Cleaning up cleaning: policy and stakeholder interventions to put household formulations on a pathway to net zero

Katherine. A. Collett, Emily Fry, Sophie Griggs, Cameron Hepburn, Gloria Rosetto, Nadia Schroeder, Anupama Sen, Charlotte Williams

Oxford Smith School of Enterprise and the Environment | **Working Paper No. 23-07**

The Smith School of Enterprise and the Environment (SSEE) was established with a benefaction by the Smith family in 2008 to tackle major environmental challenges by bringing public and private enterprise together with the University of Oxford's world-leading teaching and research.

Research at the Smith School shapes business practices, government policy and strategies to achieve net-zero emissions and sustainable development. We offer innovative evidence-based solutions to the environmental challenges facing humanity over the coming decades. We apply expertise in economics, finance, business and law to tackle environmental and social challenges in six areas: water, climate, energy, biodiversity, food and the circular economy.

SSEE has several significant external research partnerships and business fellows, bringing to the university experts from industry, consulting firms and related enterprises who seek to address major environmental challenges. We offer a variety of open enrolment and custom executive education programmes that cater to participants from all over the world. We also provide independent research and advice on environmental strategy, corporate governance, public policy and long-term innovation.

For more information on SSEE, please visit: www.smithschool.ox.ac.uk

Suggested citation: Collett, K. A., Fry, E., Griggs, S., Hepburn, C., Rosetto, G., Schroeder, N., Sen, A., and Williams, C. (2023). Cleaning up Cleaning: policy and stakeholder interventions to put household formulations on a pathway to net zero. Oxford Smith School Working Paper 23-07.

Acknowledgments: We thank Unilever for supporting the research carried out for this report. We are grateful to an internal referee for comments, and to Lucy Erickson, Liliana Resende and Tom Pilsworth in the SSEE Communications team for their support.

Front cover design and figure illustrations: Liliana Resende, Oxford Smith School.

Executive summary

This report presents a portfolio of policy interventions to address the end-of-life emissions of chemicals used in Fast-Moving Consumer Goods (FMCG), to put the sector on a pathway to net zero and align with the Paris Agreement. It focuses on the *fossil-based carbon* found in everyday cleaning products such as laundry powder, fabric detergent, and dishwashing detergent and soaps. The carbon in the chemical formulations ('surfactants') used in these products is currently largely derived from the petrochemical industry, using feedstocks produced from oil and gas. If this vital sector is to move to net zero, these will either need to be replaced by sustainable carbon from bio-based feedstocks, or the petrochemical-based carbon captured at end of use and permanently removed from the atmosphere.

This transition is unlikely to occur in the absence of policy intervention. This is because FMCG companies operate in a highly competitive market, with little to no excess economic returns in the sector, and bio-based inputs are currently estimated to be between 1.2 and 4.2 times more expensive than fossil-based counterparts. There is little to no incentive for any single company to voluntarily switch to a more expensive feedstock in this market, as this would put it at a competitive disadvantage. Therefore, policy intervention to ensure the environmental costs of using fossil fuel derived inputs are paid, and regulation or structural support for bio-based inputs, is likely to be needed, along with policies to protect vulnerable consumers from price increases. Furthermore, with competition for bio-based feedstocks from other sectors as they also transition towards net zero (for example, aviation), a holistic policy framework is desirable to address the interconnected challenges and opportunities in cross-sectoral pathways to net zero which involve the substitution of fossil-based with bio-based feedstocks.

The main recommendation of this report is for policymakers to work with researchers, consumers and stakeholders from across industry, civil society and the financial community to create *national strategies for sustainable carbon used as feedstock*. Such strategies would draw from a portfolio of policy interventions – for instance, to narrow the cost differential between sustainable and fossil-based carbon and remove other barriers – to help facilitate a *pathway to net zero* for surfactants and the chemicals industry, covering the vast number of products that use carbon in their composition. A 'portfolio-based approach' is one in which technology-specific and sector-specific policies, such as R&D incentives, along with financing mechanisms and risk-mitigation instruments, can be deployed alongside more traditional carbon prices, to motivate a timely transition. The report also highlights cross-country and cross-sectoral synergies and opportunities for international coordination.

Context and scale of the policy issue

Approximately 2.2 billion tonnes of (fossil-based) carbon emissions are produced each year in the chemical and petrochemicals sector overall, which one academic study suggests accounts for 6% of global (direct and indirect) CO_2 emissions (Saygin & Gielen, 2021). Within this, industry sources suggest that household chemical formulations could account for around 10% of carbon emissions (Bott, 2023). Moreover, the carbon contained within the chemicals entering wastewater systems degrades into carbon-based greenhouse gases, meaning that the use of fossil-carbon feedstocks in their production (even those that are recycled) will not achieve net zero. Critically, these emissions are often overlooked. These 'hidden' emissions released at product end of life can account for two-thirds of the emissions of the products they are used in (Fogliatti, et al., 2014). According to industry sources, surfactants can make up a large proportion of procurement costs for many products: up to 50% in some cases (Biosolutions, 2022). To align with climate targets while also reducing exposure to volatile petrochemical prices linked to the cost of oil, the FMCG sector will need to shift to sustainable sources of carbon in order to make the formulations for the cleaning products that consumers buy.

Key findings

Bio-feedstocks likely offer the best opportunity (in terms of technological alignment with net zero, and policy-driven intervention) for reducing greenhouse gas emissions from household formulations. However, they have a current market share of only 6% (SystemIQ; University of Tokyo; Center for Global Commons, 2022). The petrochemicals sector consumes about 14% of oil and 8% of natural gas production annually to supply the chemicals industry (International Energy Agency (IEA), 2018). Replacing petrochemicals with bio-carbon as a feedstock creates a circular loop: the CO_2 released from biodegradation of formulations is equivalent to the CO_2 absorbed from the atmosphere to grow the crop. In contrast, closing a petro-based carbon loop would require capturing the equivalent CO_2 and permanently storing it back in the lithosphere (not merely the biosphere), from whence it came. Bio-based sources of carbon include virgin vegetable oils, byproducts and waste materials, offering emissions savings of between 39% and 86% compared to their fossil-based alternatives (Adom, et al., 2014). Each has different considerations, such as emissions, availability, competition, land requirements, cost and crop-to-chemical efficiency.

This report suggests that, in theory, a carbon price ranging from US$144-711/tCO2eq is currently needed to make bio-based surfactants cost competitive. This is given current technologies, and on a cradle-to-grave lifecycle-emissions basis. Our calculations are limited by data availability; full lifecycle analysis data would be needed to improve the accuracy of these estimates. Irrespective, carbon prices at the upper end of this range are unlikely to be economically optimal or politically feasible. The shift to bio-carbon in chemicals is hindered by higher prices, challenges associated with scaling up and the need for global *cross-sectoral coordination* around the demand for bio-based feedstock in reducing greenhouse gas emissions. Bio-based chemicals are estimated to be between 1.2 and 4.2 times more expensive than fossil-based counterparts. In the context of factors such as distributional impacts, political acceptability, fiscal policy goals and land use changes, carbon prices for formulations should be aligned with the range of existing carbon prices (Stiglitz, 2019; Stern & Stiglitz, 2017); the latter lie at the lower end of this range. Carbon prices will not necessarily be equal for all countries due to equity considerations, economic structures and different elasticities (Stern, et al., 2021; Stiglitz, 2019; Stern & Stiglitz, 2017). In low-income countries, a lower carbon price is likely to be more appropriate (Stern & Stiglitz, 2017). In practice, a carbon price alone is unlikely to resolve all barriers; *reducing the cost differential will require other policy interventions* to incentivise innovation, with a longer-term eye on land-use constraints and chemical-biofuel competition for supply (for example, in aviation).

Technological advances in bio-feedstocks could deliver cost competitiveness, as demonstrated for other technologies, such as renewable power. This report employs *learning curves* to estimate bio-feedstock costs under several scenarios. We consider bio-naphtha, bio-ethanol and bio-kerosene, which are each important feedstocks for surfactants. Although bio-ethanol is already cost competitive, learning rates for bio-naphtha and bio-kerosene would need to be 20% per annum in order to be competitive with today's costs by 2050. To put this in context, renewable energy generation, lithium-ion batteries and transistors have followed learning rates of 10%, 12% and 40-50%, respectively (Way, et al., 2022). This emphasises the potential for policy intervention to help rapidly level the playing field between bio-based and fossil-based feedstocks and accelerate a transition.

Policy interventions could make bio-carbon more competitive on the supply side. For example, a combination of policy instruments based on structural support have been successfully deployed in other sectors, notably in the switch from fossil fuels to clean energy. *Subsidies*, though subject to criticism, have been used to successfully deploy clean energy technologies through private sector investment, thereby reducing clean energy costs. For instance, global renewable subsidies stood at $166bn in 2017 (far lower than the $3tn subsidies to fossil fuels); in a more recent example, the US Inflation Reduction Act is expected to pump $369bn into clean energy subsidies (in various forms) over the coming decade, and early estimates suggest that this could boost renewable investment to a further $114bn per year (Chu, 2023) (Liu, 2023). Similarly, *contracts-for-difference (CfDs)* are a form of structural support used to scale up novel clean energy-generation technologies – mainly solar and wind, which are now the cheapest sources of new electricity generation globally (Way, et al., 2022).

Carbon CfDs are a form of CfD applied to carbon prices, to help mitigate price uncertainty (European Commission, 2023). *Innovation* around conversion efficiencies, improved properties and design for end of life could also be funded through *grants*, *R&D investment credits* and *green loans*. Other supply-side interventions include more accurate forecasts of (and planning for) bio-feedstock demand, *sustainable feedstock certification* schemes and *research into new sustainable carbon sources.*

Similarly, policy interventions could be used to shift feedstock demand towards sustainable sources. Policymakers could adopt *portfolio standards* and/or *composition mandates* to catalyse a shift. For example, renewable portfolio standards in the US have been found to be one of the most effective policies in increasing the use of solar energy (Ryan, et al., 2019). This sends a strong signal to suppliers that demand will be present, de-risking investment in scaling up supply. More broadly, *green public procurement* can help to create stable demand, especially if coordinated across multiple governments (Swedish Energy Agency, Smith School of Enterprise and the Environment, 2023). General public procurement represents an important proportion of the overall market, accounting for an average of 12% of GDP in OECD countries and up to 30% of GDP in developing countries (United Nations Department of Economic and Social Affairs, 2021).

Policymakers can deploy measures from a portfolio of possible interventions, working with key stakeholder groups to minimise trade-offs. Experience elsewhere has shown that *stakeholder coalitions* built around specific environmental targets and SDGs can be a powerful driver of policy action. This report discusses policy interventions corresponding to an overall category of barriers corresponding to cost, scale and coordination across a broad range of stakeholder groups that are likely to be involved in enabling a pathway to net zero for household formulations. *Capacity building* and *workforce upskilling and reskilling* will need to be an integral part of any successful strategy.

International coordination based on synergies with biomass production, carbon removal and job creation can play a key part in the industry's pathway to net zero. This is of strategic importance to governments as it tends to align with the environmental aims set out in both national legislation (such as net-zero targets) and international agreements (e.g. the Paris Agreement). For instance, the reduction of greenhouse gas emissions from formulations is closely linked to the availability of biomass feedstocks. Similarly, eliminating greenhouse gas emissions from the chemicals industry as a whole could create an additional 29 million new jobs globally by 2050, compared to a business-as-usual trajectory (SystemIQ; University of Tokyo; Center for Global Commons, 2022). This would more than compensate for the shift of around five million workers away from fossil fuel sectors required in the net-zero transition (International Energy Association, 2022).

Contents

1 Introduction

Introduction: At a glance

Approximately 2.2 billion tonnes of (fossil-based) carbon is emitted each year in the chemical and petrochemicals sector, which one academic study suggests accounts for 6% of global CO_2 emissions (Saygin & Gielen, 2021). Within this, industry sources suggest that household chemical formulations could account for around 10% of emissions (Bott, 2023). This report focuses on *the fossil-based carbon* found in everyday cleaning and home care products' formulations such as laundry powder, fabric detergent, and dishwashing detergent and soaps. This is not a report about fossil-carbon in packaging; instead, we focus on what is inside the container.

The lifecycle of the carbon in formulations is unique compared to the carbon in plastics. These formulas are designed to be disposed of down wastewater systems after use, meaning there is negligible opportunity for recycling. Critically, there are 'hidden' emissions released at the product end of life, which can account for a significant proportion of the emissions associated with their manufacture – estimated to be nearly two-thirds in one academic study (Fogliatti, et al., 2014). These emissions are often overlooked.

The report is intended to bring this discussion to the attention of policymakers and stakeholders. Through novel research and critical analysis, it presents a portfolio of policy interventions to shift chemical use in the fast-moving consumer goods (FMCG) industry away from fossil-carbon to more sustainable sources of carbon to align with the Paris Agreement. This is vital for achieving net-zero emissions, and particularly important in a time of volatile oil and gas prices, when manufacturers may be considering diversifying their feedstocks to reduce exposure to fossil-carbon prices.

The current system

The fossil-carbon used in chemicals to produce formulations[1] for FMCG represents the often-neglected side of the petrochemicals industry. In addition to damage to natural ecosystems, the fossil carbon in these products largely ends up in the atmosphere as carbon dioxide (CO_2).

[1] In this report, formulations refer to the contents of the bottle. Within the FMCG context examples of formulations used for cleaning and personal hygiene include shampoo, conditioner, washing-up liquid, soap and washing detergent.

Historically, the source of the carbon embodied in consumer household cleaning products has been the petrochemical industry. Fossil fuels are processed by the chemicals industry to create the feedstocks for formulations. Globally, the chemicals industry is significant in the economy, making up 4% of global GDP and accounting for an estimated 15 million jobs worldwide (SystemIQ; University of Tokyo; Center for Global Commons, 2022). To supply this industry, the petrochemicals sector consumes about 14% of oil and 8% of natural gas production annually (International Energy Agency (IEA), 2018). With the decarbonisation of energy, the IEA forecasts that, by 2050, petrochemicals could account for 55% of all oil demand (International Energy Agency (IEA), 2021). An existing estimate for the total cost of mitigating emissions of petrochemicals (including plastics) across energy and feedstocks in 2050 is calculated at more than 35% of the entire energy and feedstock costs of the 2050 petrochemicals industry (Saygin & Gielen, 2021).

The cost of petrochemicals is highly interconnected with the cost of oil because petrochemicals are derived from oil and gas. Every barrel of oil extracted contains carbon chains used as fuel as well as carbon chains which are used by the chemicals industry. Often, household cleaning formulations use carbon chains from the kerosene and naphtha fractions of a barrel of oil, shown in Figure 1.

As has been evident in recent months and years, the prices of oil and gas, and thus of petrochemicals, are volatile, and can be influenced by supply shocks such as international conflict and demand shocks like the fast recovery from Covid-19 (Rogoff, 2022; Kelly & Browning, 2022). As the pathway to net zero progresses, with both reduced demand for and reduced supply of fossil fuels, it is likely that the price of oil will be more volatile than in periods of relative equilibrium before it eventually declines, as only the cheapest barrels (with the lowest costs of extraction) are extracted and produced. The US Energy Information Administration forecasts that under a high price scenario, Brent crude could increase to US$190/bbl by 2050 (almost 2.5 times the 2023 price) (Energy Information Administration, 2023). The risk of such a scenario, on top of potential fossil-fuel price volatility to geopolitical disruptions, offers an incentive for industries dependent on petrochemicals to diversify their feedstocks and incorporate sustainable chemicals to protect their business models from long-term increases in feedstock costs (Bosch, et al., 2017).

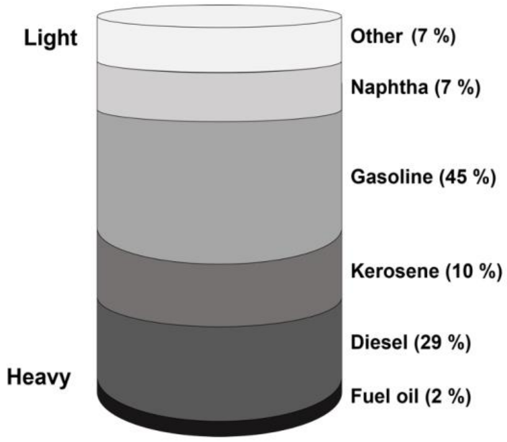


Figure 1. Stylised fractions of a barrel of oil. Based on Thomson Reuters data (Reuters, 2022)

As discussed, carbon emissions[2] associated with the chemical and petrochemical sector are reported to account for around 6% of the global total, with industry sources placing household chemical formulations at around 10% of this (Saygin & Gielen, 2021) (Bott, 2023). Emissions are released during production, through methane leakage during oil and gas extraction (Tollefson, 2013; Schneising, et al., 2020), during use, through chemical waste and degradation of chemicals into carbon dioxide at product end of life. These emissions can be categorised into Scope 1, 2 & 3 (Carbon Trust, 2023) (see Figure 2). Additionally, there is also the risk of pollution to land, sea and even food chains (European Environment Agency, 2023).

[2] 'Emissions' in general can be defined as any greenhouse gas, which typically includes methane, water vapour, carbon dioxide, nitrous oxide and ozone. They can also include any other harmful gases released, such as carbon monoxide, particulates and volatile organic compounds (VOCs).

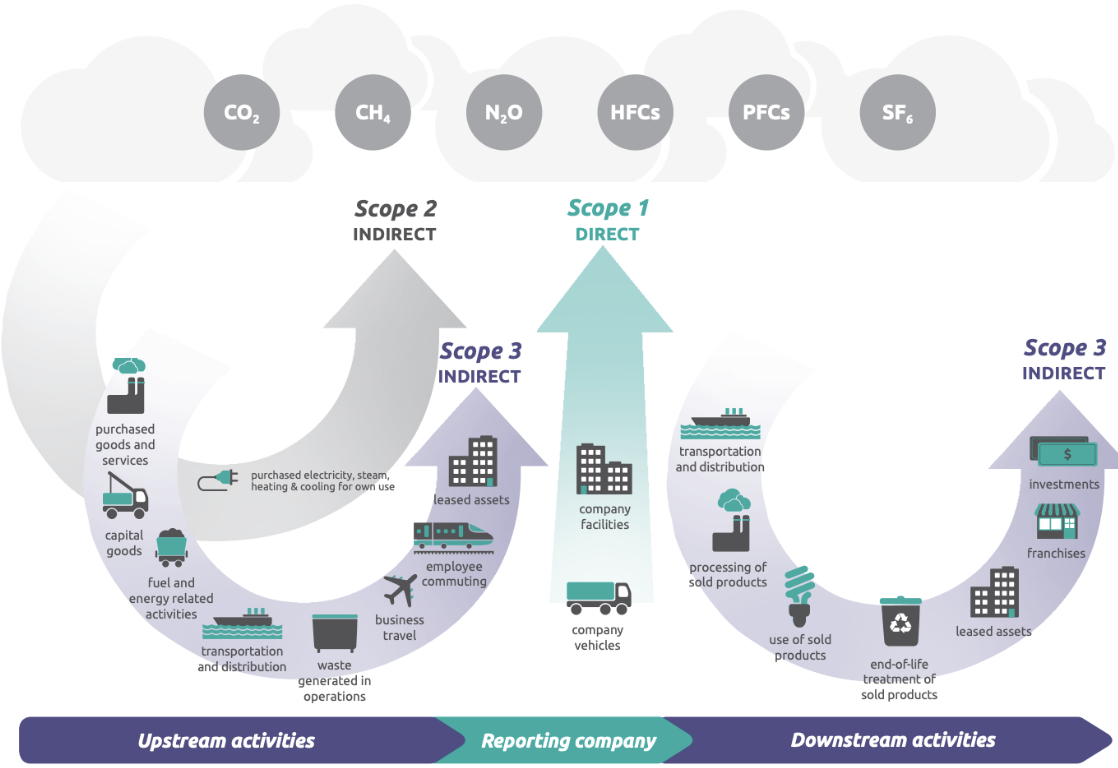


Figure 2. Overview of emission scopes across the value chain (with illustrative examples) (Greenhouse Gas Protocol, 2011)

One of the key messages of this report is that these formulations have non-energy emissions associated with them, sometimes termed 'hidden' emissions. Unlike plastics, formulations cannot be recycled.

These hidden emissions have so far 'slipped under the radar' (Lim, 2022) and are linked to the life cycle of the carbon that is embedded within the chemical structures of the formulation. Figure 3 shows the different stages of emissions during formulation production, highlighting the 'hidden' emissions in red[3].

[3] This diagram does not show other pollutants, which are defined as any substance that has a negative impact on the environment – for example, microplastics found in waterways or chemicals from fertilisers, such as phosphorus and nitrogen, which can cause soil acidification and erosion. In the literature, these pollutants are sometimes referred to as waterborne emissions (Sauter, E. & Van Hoof, 2002).

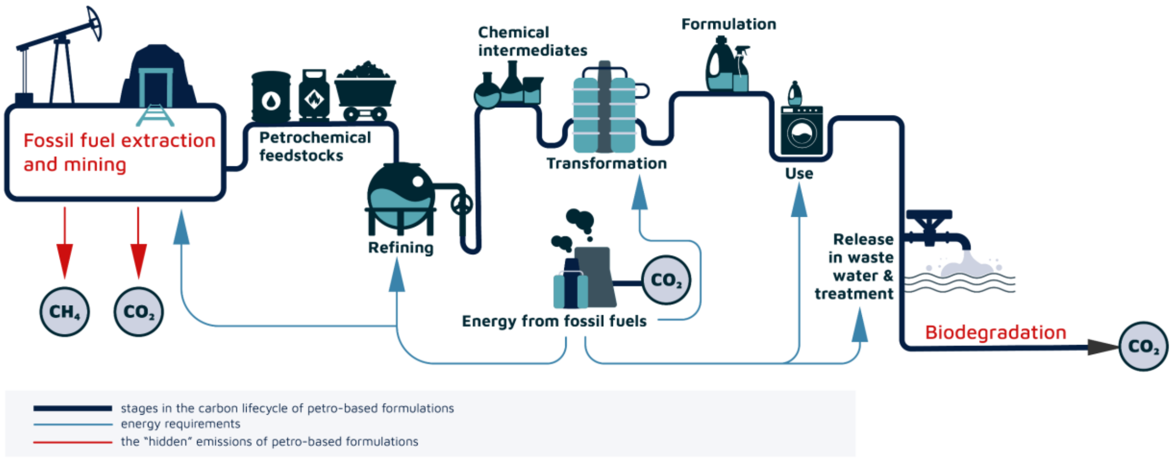


Figure 3. Schematic showing emissions related to formulation production using fossil-carbon. The "hidden" emissions are highlighted in red.

The hidden emissions predominantly occur at two stages in the process: oil and gas extraction, and product end of life. In this way, they relate to Scope 3. For the former, methane leakage during oil and gas extraction can be poorly reported, as well as challenging to monitor and assess (Tollefson, 2013). Recent advances in the field, using satellite imagery, have demonstrated that these emissions are often underestimated (Schneising, et al., 2020; Franklin, 2022). For the latter, for example, the end-of-life pathway often creates emissions upon disposal in water treatment plants, where formulations result in non-cyclical forms of carbon, such as carbon dioxide. This is not insignificant; in some cases, two-thirds of the emissions associated with a product are released at the end of life (Fogliatti, et al., 2014).

Currently, due to a combination of factors including a lack of awareness, measurement techniques, and data, these sources of emissions remain hidden (Schowanek, et al., 2018). The damage caused by these emissions is not considered in taxation or incentive schemes, such as the EU Emissions Trading Scheme (ETS), and to the extent that it is covered, the chemicals industry as a whole has historically received free allocations to pollute (Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council (notified under document C(2, 2011)). Measures such as Extended Producer Responsibility (EPR) have historically applied mainly to end-of-use packaging and tend not to include lifecycle emissions of household formulations. While EPR rules have incentivised producers to meet (rather than exceed) their recycling targets, they are being reformed (e.g. the Extended Producer Responsibility in the UK) to place responsibility on businesses for the environmental impact of their products and for the costs of managing products at end of life (Department for Environment Food and Rural Affairs, 2021). Even with these reforms, household formulations are not suited to the scope of EPR due to emissions not being captured within traditional end-of-life considerations. A robust climate policy needs to account for these hidden emissions.

To limit global temperature increases to 1.5°C, as laid out in the Paris Agreement, emissions from FMCG must be cut drastically by the end of the decade and then follow a pathway to net zero. The International Energy Agency (IEA) clearly indicates that a shift away from fossil-derived carbon sources in the chemical sector is critical (International Energy Agency (IEA), 2021). While there may be some levers to pull on the demand side, changes in consumer behaviour alone cannot solve this problem. Fundamentally, alternative non-fossil sources of carbon are required (European Commission, 2023).

The focus of this report is on surfactants in cleaning products as they are a key component of many household cleaning products. They also make up a large proportion of procurement costs for many products – up to 50% in some cases (Novozymes, 2022).

Sustainable alternatives

Fortunately, effective and sustainable alternatives to fossil carbon exist and it is technically viable to create products that are compatible with a circular economy. For the cleaning formulations considered in this report, circularity must start with the recognition that these products will inevitably end up in the wastewater system before they biodegrade. This creates a different system to that of plastics, where some capture and recycling is frequently feasible. Achieving net-zero emissions either requires the industry to pay for Direct Air Capture (DAC) or other permanent carbon removal methods to compensate for its emissions, or to employ sources of carbon for formulation production from the biosphere, likely from plants which remove carbon dioxide from the atmosphere during their growth.

Using DAC (plus utilisation) or other permanent carbon removal methods to properly offset the emissions of fossil carbon dioxide is theoretically possible, but there are challenges[4]. First, and most significantly, the cost of extracting fossil carbon and then utilising DAC to compensate for the associated carbon dioxide emissions is currently energy intensive and very expensive. These costs are likely to fall in future (State of Carbon Dioxide Removal, 2023), but it is unclear at this stage whether they will fall to levels that make DAC an economic option to offset

[4] Note that biological offsetting (for instance, using nature-based solutions), while valuable, does not provide a like-for-like offset, because it moves atmospheric carbon to the biosphere, not back to the lithosphere where it came from. There are equilibrating processes between flows of carbon between biosphere and atmosphere, implying that such offsets are not permanent, and hence do not represent full compensation for carbon extracted from the lithosphere (Smith School, 2022).

emissions from this sector. And second, DAC would need to compensate not only for CO_2 emissions, but also for unavoidable methane leakage from oil and gas extraction during raw materials production. Methane is a potent greenhouse gas, and these leaks would need to be estimated and offset at additional cost. Further, the fossil supply chain creates environmental damage beyond that from climate change – there are damages to human health caused by associated pollution, and damages to natural ecosystems along the value chain. Any use of biogenic carbon would also have to take these issues into consideration.

For these reasons, this report focuses on the use of bio-derived chemicals made using carbon from plants, which one lifecycle analysis from the academic literature suggests gives a reduction in emissions (on a cradle-to-grave basis) of between 39% and 86% compared to conventional fossil feedstocks (Adom, et al., 2014). This is because using bio-carbon creates a circular loop: the CO_2 released from biodegradation of formulations is equivalent to the CO_2 absorbed from the atmosphere to grow the crop. To ensure bio-carbon has lower associated emissions than fossil-carbon, it is critical that energy requirements to cultivate the source are met through renewable energy generation, and that any land-use changes do not release essential naturally stored carbon into the atmosphere (i.e. no deforestation for crop growth).

There are many sources of bio-carbon, including virgin vegetable oils, byproducts and waste materials. Each has different considerations such as emissions, availability, competition, land requirements, cost and crop-to-chemical efficiency. These bio-carbon sources are often classified in different ‘generations’, as defined by the biofuels industry. First-generation feedstocks are crops in the food chain, such as corn and sugarcane, and edible oils such as palm and soy. Second-generation feedstocks include non-edible crops such as agricultural waste, wood and used cooking oils. The third-generation category is for algae, including seaweed. CO_2 itself is also considered as a potential sustainable source of carbon. The circular carbon cycle for using bio-based feedstocks is shown in Figure 4.

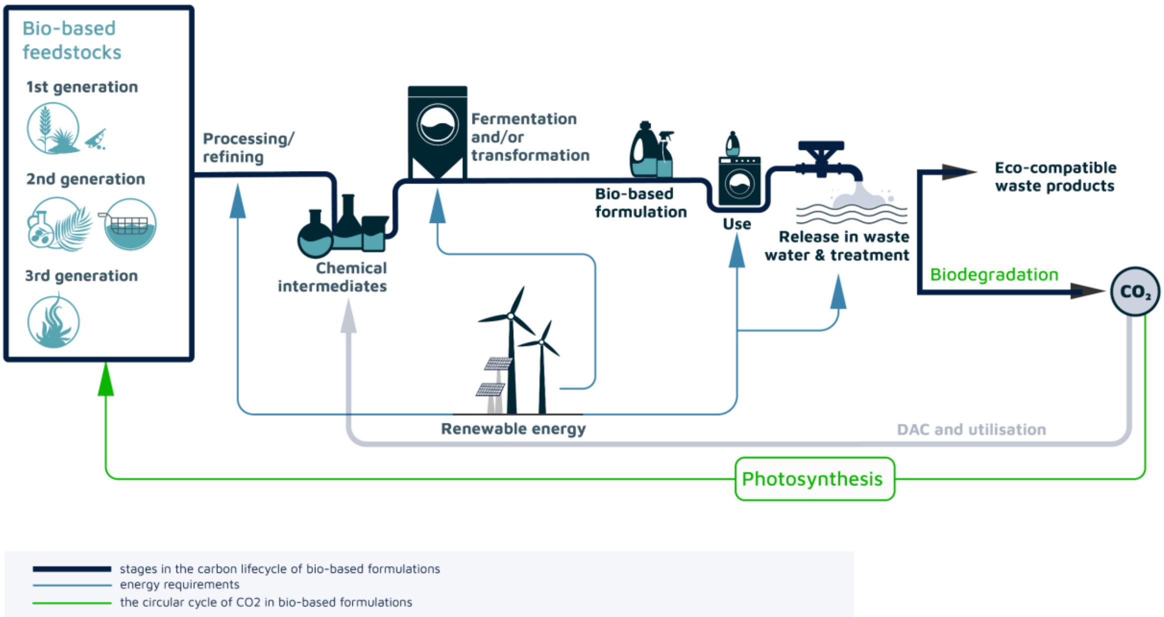


Figure 4. Schematic showing emissions related to formulation production using bio-carbon. Provided biodegradation to CO_2 is matched with photosynthetic capture of CO_2 (both in green), the system can be circular.

Achieving a sustainable formulations industry

At present, bio-based feedstock chemicals are relatively expensive compared to fossil-based chemicals (World Bio Market Insights, 2022; Wellenreuther, et al., 2022), and bio-feedstocks make up only 6% of chemical feedstocks (SystemIQ; University of Tokyo; Center for Global Commons, 2022). Until sustainable feedstocks are cost competitive with fossil-based feedstocks, policy measures will need to be employed to even the playing field and facilitate this transition.

This report focuses on the policy mechanisms that could shift the formulation industry from fossil-carbon to bio-carbon and complimentary supporting measures to lower related barriers. This includes the relative benefits and trade-offs of economic incentives, regulations and carbon prices across the supply chain. The report aims to identify a portfolio of interventions that could support this transition.

Structure of the report

The report is structured as follows: In Section 2 we identify three key barriers related to (i) cost, (ii) scale and (iii) coordination, that hinder the adoption of sustainable carbon by the FMCG sector. Section 3 outlines the broad objectives of well-rounded policy for sustainable formulations. Section 4 evaluates policy options to address the barriers, and to accelerate the transition to sustainable sources of carbon. Section 5 discusses policy implementation and the development of a sustainable carbon strategy in different contexts, and Section 6 concludes.

2 The barriers to adopting sustainable carbon alternatives

Barriers: At a glance

- **Cost**: sustainable carbon is currently up to five times more expensive than its fossil-based equivalent (Section 2.1).
- **Scale**: the technical state of knowledge for production of bio-based products is generally small-scale. Scaling up sustainable carbon would require changes in land use, and further innovation to ensure that sustainable carbon could be substituted into products (Section 2.2).
- **Coordination**: for the transition to occur effectively, procurers of bio-based feedstocks might need to coordinate on standards and approaches, potentially internationally (Section 2.3).

This section considers the three major barriers to transitioning away from fossil carbon to sustainable alternatives in surfactants.

2.1 Higher cost of sustainable carbon

The cost of bio-based chemicals is a major barrier to widespread adoption in place of petrochemicals (Hillmyer, 2017). Sustainable feedstocks can currently cost significantly more than fossil-based feedstocks (World Bio Market Insights, 2022; Wellenreuther, et al., 2022).

2.1.1 The cost difference between fossil- and bio-based

The range of price differences between bio-based alternatives and the dominant fossil-based feedstock chemical is substantial, and also varies for each feedstock type – with the difference highest for naphtha (a widely used solvent for cleaning) and its bio-based alternative, and bio-ethanol being the most cost competitive. Figure 5 below shows current price differences between select feedstocks commonly used to produce household products (IndexBox, 2017; Trading Economics, 2023; Global Petrol Prices, 2023; Argus, 2023; ICIS, 2023; Bloomberg, 2023).

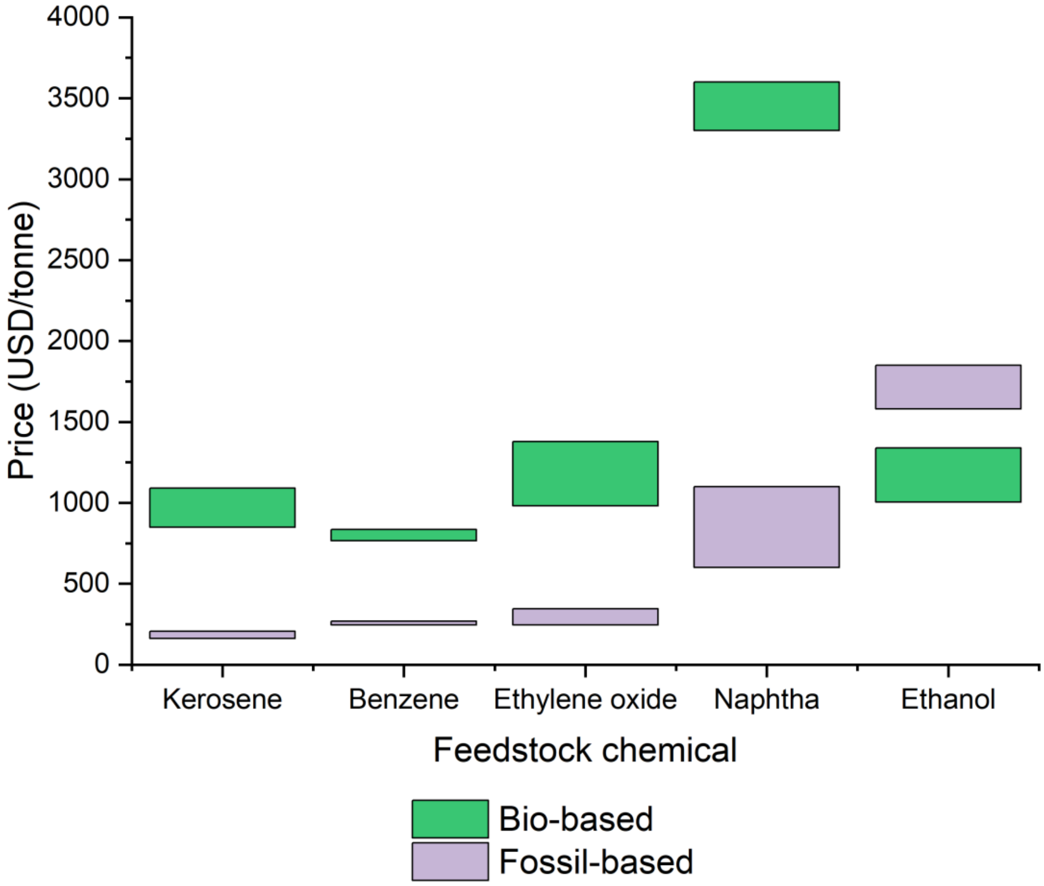


Figure 5. Bar chart indicating the absolute price ranges of bio-based feedstocks compared to the same chemical derived from fossil fuels. Data from references (IndexBox, 2017; Trading Economics, 2023; Global Petrol Prices, 2023; Argus, 2023; ICIS, 2023; Bloomberg, 2023).

Once the feedstock is obtained from either bio-based or petrochemical sources, the processing costs to transform the feedstock into the surfactant are equal.

It is notable that bio-based feedstocks whose processes are powered by energy-intensive processes may also be affected by fossil prices, where fossil fuels remain their primary energy source.

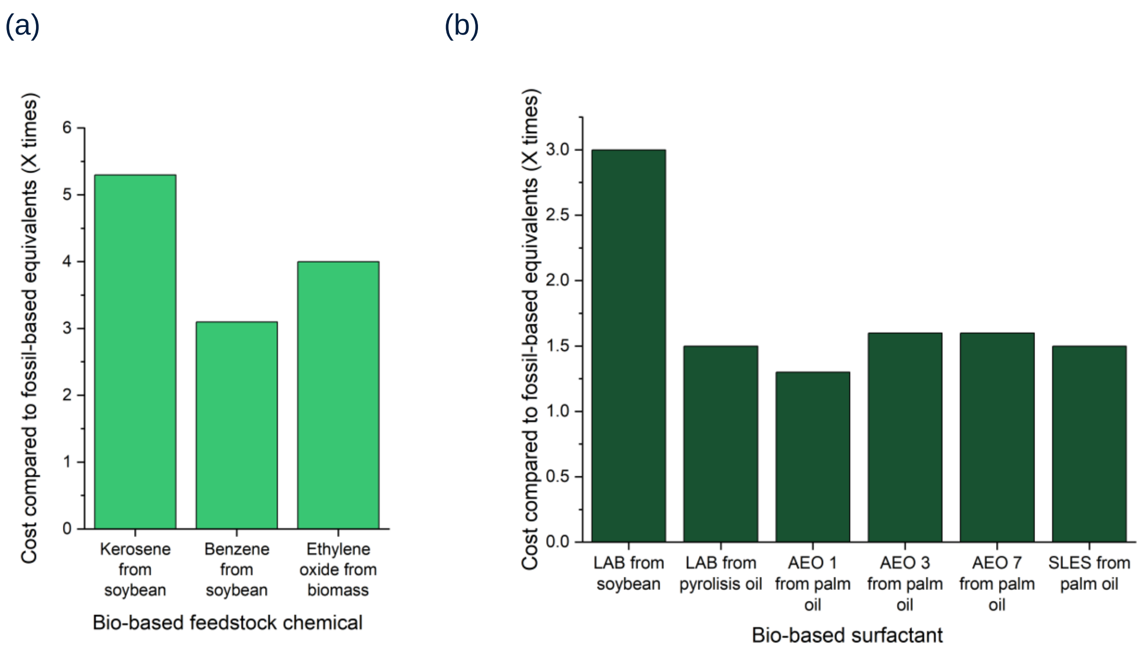


Figure 6. Illustrative bar chart to highlight the price increase of a) feedstock chemicals and b) surfactant chemicals when derived from bio-based sources, compared to traditional petrochemicals, considering only direct replacement of feedstock. Data from references (ICIS, 2023; Bloomberg, 2023; Bloomberg, 2023)

2.1.2 Why bio-carbon is currently more expensive than fossil-carbon

There are four key reasons why fossil-based formulation has historically been so cheap. First, fossil-based carbon comes from petrochemicals, which effectively originated as a byproduct from oil and gas extraction that could otherwise have been waste. Capitalising on a byproduct has resulted in it being very cheap and readily available – at least for as long as the global energy supply is reliant on fossil fuels.

Second, the petrochemical industry is mature, optimised and efficient, with refinery processes having been established in the 1850s, resulting in almost 200 years of knowledge and research. This, along with economies of scale, contributes to bring down the cost of refining processes. Additionally, all refined products are used by different industries, resulting in a cost-effective process with almost no waste products.

Third, fossil fuel extraction still receives significant subsidies from governments to incentivise cheap energy production (Coady, et al., 2017). This has a knock-on impact of reducing the cost of petrochemicals.

Fourth, environmental externalities from fossil-carbon are not priced into the cost of carbon used for plastics or formulations. The consequence is that fossil-derived carbon appears, at present, to be the cheapest source for formulations and plastics. To some extent, this is due to the hidden nature of these emissions, as this report highlights.

2.2 The feasibility of scaling up

Due to their higher cost, sustainable feedstocks are not yet commonplace. However, as the market develops, and supply needs to scale, there may be challenges related to the state of knowledge, land use and financing the necessary R&D.

2.2.1 State of knowledge

The use of biogenic sources of carbon is advancing in the field of formulations, as it has for biofuels and bio-derived polymers. However, the technology is not yet mature. There is a need to advance the state of knowledge in the field to benefit from learning curves and develop efficient solutions and investigate opportunities to overcome land-use constraints.

Different forms of biomass contain different substances such as sugars, oils, starch, cellulose, proteins and lignin. This means that some plants are more useful than others for producing specific chemicals. Oils and sugars are the key platform chemical intermediates for bio-refineries. Their sources, along with the type of molecules useful for the surfactant industry that can be obtained, are summarised in Figure 7. The process maturity level is indicated by the type of line. Details of the different bio-based sources are offered in the appendix.

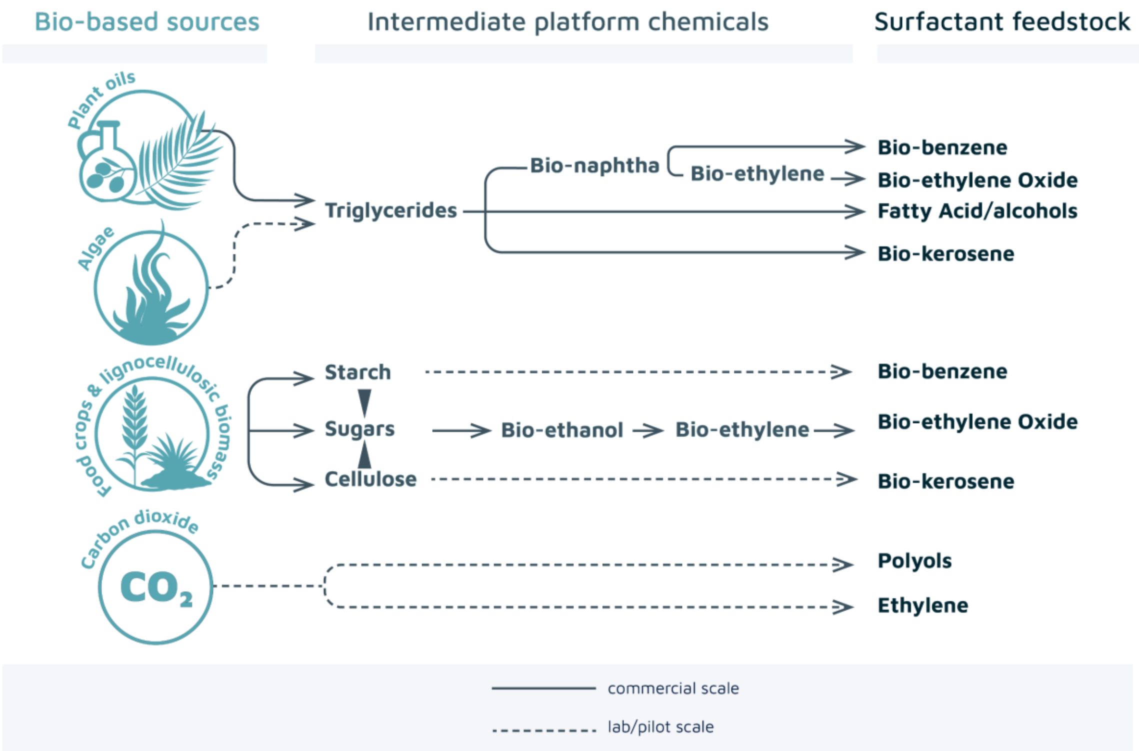


Figure 7. Four key sustainable sources of carbon and the platform chemicals they can produce. Process maturity level indicated by type of line (dashed or solid). Original graphic based on references (Coady, et al., 2017; IEA Bioenergy, 2020).

2.2.2 Land use

Globally, around 23-25% of greenhouse gas emissions come from agriculture, forestry and land use (IPCC, 2019). To avoid an increase in emissions, any land use changes caused by a shift to bio-based carbon sources must be sustainably managed (IPCC, 2019). As an example, palm oil is the most widely used vegetable oil replacement for fossil-derived carbon in formulations. It has a huge range of applications, including in around 50% of supermarket items, biofuels and animal feed (Yue, et al., 2020). Academic literature on sustainable palm oil states that it should be possible to 'fulfil the present and future demands without impairing the ecosystem or environment' (Khatun, et al., 2017). However, at present, only 19% of palm oil is produced sustainably, as verified by the Roundtable on Sustainable Palm Oil (RSPO, 2021). In light of the deforestation concerns related to palm oil, the EU is planning to phase out the use of palm oil (and soyabean oil) in biodiesel by as early as 2023 (brought forward from 2030) due to concerns about the crop growth being linked to deforestation (Mintec, 2022). This demonstrates the need to understand the practical and sustainable land use constraints for bio-feedstock production when developing transition pathways. Long-term planning approaches for the scale-up of sustainable palm oil production are required, in conjunction with investigations to diversify carbon sources. This combination will be necessary to mitigate the risk of sustainable palm oil price inflation impacts on formulation costs.

Practical land use constraints can introduce challenges related to price inflation of bio-carbon sources, especially for crops which can only be grown in specific geographical regions. This is intensified by climate change, the transition to global net-zero emissions, and competition between sectors for sustainable sources of carbon.

There are no clear assessments of the overall land use requirements if all FMCGs were to be made using sustainable carbon. Due to the need to maintain and re-nature carbon-capturing ecosystems, such as rainforests, along with requirements for food crops and biofuel feedstocks, there will inevitably be some degree of land use competition. Use of waste sources of carbon and carbon that can be efficiently grown will be crucial. Unless carefully considered, sustainable land use constraints could cause price inflation of bio-carbon supply or regulatory intervention to prohibit use, as with palm oil.

2.3 International coordination across demand

Forums for international coordination have to date not focused on the lack of sustainable chemicals for formulations. But international coordination across both countries and companies is necessary, given the competition for sustainable kerosene from the aviation industry, as well as the need for FMCG companies to create stable demand for these chemicals as an alternative to aviation.

2.3.1 Chemical-biofuel competition

The challenges surrounding food-biofuel competition have been well documented. Yet, as other sectors decarbonise, competition may emerge between the chemical and biofuel sectors. The chemicals industry utilises feedstocks such as kerosene, naphtha, benzene and ethanol, which are also important feedstocks in biofuel production. Unless the supply of sustainable versions of these chemicals can keep up with demand, this may cause further price increases for bio-based feedstocks, making them even less competitive. A case study on bio-kerosene, a good example of cross-sectoral competition, is given in Box 1.

Box 1: Bio-kerosene and the aviation sector

Bio-kerosene is a feedstock used by both the aviation and FMCG industries, making it a good case study for competition. Historically, kerosene from crude oil has served both the chemical industry as a feedstock as well as the aviation industry as fuel. As both sectors look to decarbonise, bio-kerosene is an attractive drop-in alternative to fossil kerosene; a supply-chain connection across the sectors which must be monitored.

Aviation fuel is primarily composed of kerosene. It is estimated that Sustainable Aviation Fuel (SAF) can reduce up to 80% in carbon emissions compared to traditional jet fuels (Dray, et al., 2022). The EU has mandated for sustainable fuels, requiring that all aviation fuel used in EU airports must comprise 63% sustainable fuels by 2050 (International Air Transport Association, 2022). Therefore, there are large efforts to find such alternative fuels and accelerate the deployment of SAF. It has been reported that 'one of the key reasons airlines give for an interest in biofuels is to reduce exposure to the price volatility of fossil-kerosene' (Bosch, et al., 2017, p. 2).

Bio-based kerosene is an obvious candidate to directly replace petroleum-based kerosene. It can be derived from the various treatments of biomass, including thermal processing of plant oils. The current premium price for bio-kerosene is five times that of conventional kerosene (ICIS, 2023). The price of conventional kerosene is similar to that of crude oil, although in the last year it has increased significantly, reaching 35% higher in June 2022 (S&P Global Commodity Insights, 2022). The cost of bio-based kerosene depends on the availability of feedstocks and the development of production technology, the cheapest using waste cooking oil and plant oils (Dray, et al., 2022). Currently there is one process, hydrogenation of fatty acids (HEFA), produced at commercial scale, which can be cost competitive with jet fuel (Doliente, et al., 2020; Wei, et al., 2019).

There are concerns that within the next few years demand for sustainable aviation fuel (due to regulations and voluntary market demand) will surpass supply, which will be unable to scale fast enough (S&P Global Commodity Insights, 2022). This is just from the aviation sector; demand from the chemical sector for the same raw materials must also be considered. This supply shortage may be aggravated by restrictions on feedstocks, with the EU phasing out palm oil for bio-fuel production as well as capping crop-based fuels to 7% by 2030 (S&P Global Commodity Insights, 2022). Under business-as-usual, there could be a shortage of feedstocks to meet these ambitious targets of the aviation sector. It is expected that prices will remain high if the demand cannot be met.

2.3.2 Sectoral co-ordination

Creating cost reductions and the economies of scale necessary to make sustainable feedstocks cost competitive for the FMCG sector will require sectoral coordination. The FMCG sector needs to create long-term stable demand to encourage the chemicals industry to diversify from biofuel products to FMCG-specific offerings. Currently, a lack of sectoral co-ordination is a barrier to investments in innovation.

The rate of transition away from fossil-based formulations will likely significantly impact the overall cost of this transition. For example, a fast transition to decarbonise the energy sector is predicted to save up to $12 trillion, because it realises the cost savings due to cheaper technology sooner (Way, et al., 2022). A transition away from all fossil-based carbon products is necessary, thus the sooner this is achieved, the sooner the cost savings will be realised for the market and the consumer. Sectoral collaboration to accelerate this transition could achieve cheaper sustainable feedstocks sooner.

3 Why policy intervention is necessary

Why policy is needed: At a glance

A move to bio-based carbon is unlikely to occur in the absence of policy intervention, for three related reasons: first, FMCG companies operate in a highly competitive market for products, with little to no excess economic returns (‘rent’) in the sector. Second, bio-based chemicals are more expensive than fossil-based counterparts; in a highly competitive market, there may be little incentive for a single firm or company in this sector to switch to a more expensive feedstock on its own, as this would put it at a competitive disadvantage. And third, due to the competitive nature of the market in which the sector operates, price increases are likely to be passed through to consumers with vulnerable consumers and low-income households particularly likely to be impacted from price increases. Therefore, policy intervention in the form of regulation or structural support for bio-based inputs, and support for vulnerable consumers and households, is likely to be needed.

Currently, the cost of bio-based feedstocks can be up to five times that of equivalent fossil-based feedstocks. A transition to sustainable feedstocks will incur an increase in production costs, at least initially. Research presented in this report shows that, although bio-ethanol is already cost competitive with its fossil counterpart, this is not the case for most feedstocks. If the cost of oil were to remain the same, bio-naphtha would need to see a high learning rate of 20% to be price-competitive by 2050 and bio-kerosene would need to see a learning curve which would exceed even this. The chances of achieving these learning rates will benefit from policy and stakeholder intervention.

Without stimulus and policy intervention, this transition may occur inefficiently and be too slow to limit global warming in line with Paris Agreement targets.

Reducing greenhouse gas emissions in surfactants used in formulations effects critical everyday items that are vital to public health. Bio-derived alternatives reaching price parity with fossil-derived products will be fundamental in achieving a significant shift to sustainable alternatives.

In this section, to better understand the cost reductions required over time for bio-carbon feedstocks to reach the cost of fossil-based feedstocks, we present new research on the necessary *learning curves of bio-based feedstocks*. This is accompanied by discussion of *the need for a sector-wide transition*, the *global relevance* of such a transition, the *benefits of a coordinated response,* and finally, a note on the *opportunity for job creation* that a transition to sustainable feedstocks in the formulations sector could offer.

3.1 Possible learning curves for bio-feedstocks

As with many new technologies and processes, bio-derived products have the potential to reduce in cost over time through scaling and learning effects. Accumulated experience in the production of bio-derived products can highlight opportunities for process efficiencies and establish new production capacities. In turn, this can reduce average costs and improve competitiveness. The cost reductions can be modelled using learning curves, based on Wright's law, where the cost reduction is a function of cumulative production (Way, et al., 2020). These models have been demonstrated as representative forecasts for other green technologies, including renewable energy sources and bioplastics (Schmidt, et al., 2017; Creutzig, et al., 2017; Creutzig, et al., 2017; Bogdanov, et al., 2019; Lewis, 2016).

A previous study (Ellen MacArthur Foundation, 2021; SystemIQ; University of Tokyo; Center for Global Commons, 2022) indicated that, with favourable market conditions and suitable policy intervention, as much as 82% of chemicals containing carbon could originate from renewable resources by 2050. However, in more conservative markets this could be closer to 18%. To achieve the 82% scenario, a significant decrease in the price of bio-based chemicals will be required, along with supportive policy measures.

As an emerging market, the learning rate of bio-derived feedstocks is yet unclear and there is insufficient data on historical price points, but lessons can be taken from other technologies. Renewable energy generation and lithium-ion batteries, along with transistors and optical fibres, followed learning rates of 10%, 12% and 40-50% respectively (Way, et al., 2020). To achieve these learning curves, a variety of policy mechanisms such as taxation, mandates and regulatory standards have been employed – for example, carbon taxes, subsidies and portfolio standards (Lam & Mercure, 2021; Ryan, et al., 2019).

If bio-based feedstocks are to follow a similar learning rate as advanced biofuels, it is possible that production costs may fall by between 5% and 27% in the next 10-15 years (IEA, 2020). If this is also combined with lowering the capital cost of a processing plant, there could be additional reductions of between 5% and 16% (IEA, 2020).

The IEA also identifies the development of integrated biorefineries as an effective potential intervention to reduce production costs in the bioeconomy, whereby biofuels and bio-based products (chemicals, materials) are produced in single product processes. In this approach, producing bio-based energy, materials and chemicals alongside biofuel can facilitate bioeconomy-wide learning effects to achieve cost-effective processing of biological raw materials (IEA Bioenergy, 2020).

Figure 8 presents original visualisations of what could happen to the price of bio-based feedstocks under various learning curve scenarios. The range of learning curves shown are similar to those seen in the renewable energy sector. The cumulative demand by 2050 is marked with a dashed vertical line and the current cost of the fossil-carbon alternatives is shown by the grey horizontal range. Notes and methodology are included in the appendix.

Conservatively, the current price for fossil-based feedstocks is used due to the uncertainty in future costs, which could increase towards 2050. It is possible that the cost of crude oil could increase 2.5-fold by 2050 (Energy Information Administration, 2022), resulting in a knock-on effect to the cost of petrochemical feedstocks. This increase in oil cost would mean that bio-based feedstocks would reach price parity with fossil-based ones sooner.

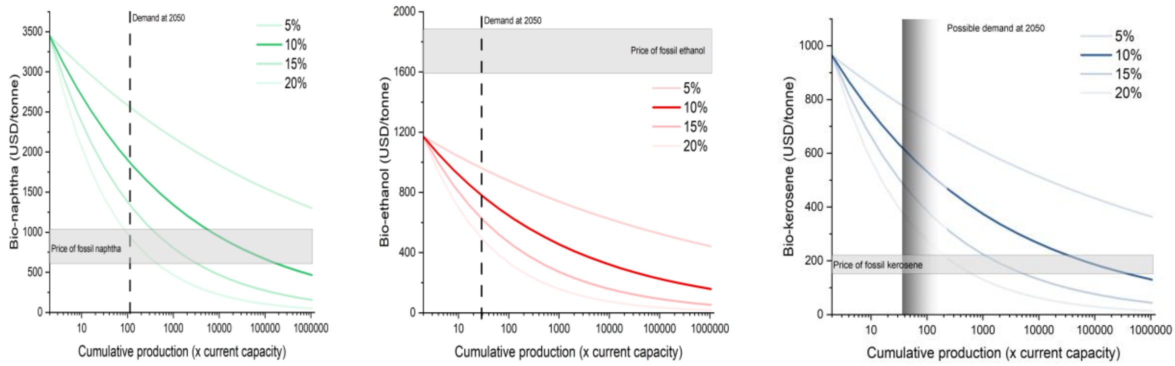


Figure 8. Learning curves for bio-naphtha, bio-ethanol and bio-kerosene (from left to right) with a 5, 10, 15 and 20% learning rate using the current spot price as 0 for the cumulative production (Argus, 2023; IndexBox, 2017; International Energy Agency (IEA), 2020). Fossil price ranges shown do not incorporate carbon prices.

These figures indicate that bio-ethanol is already cost competitive with its fossil counterpart. In contrast, if the cost of oil were to remain the same, bio-naphtha would need to see a high learning rate of 20% to be price-competitive by 2050 and bio-kerosene would need to see a learning curve which would exceed even this. These learning curves are steep and will require political and stakeholder support to achieve a timely transition.

These results emphasise the importance of policy measures – for example a carbon price – to level the playing field between bio-based and fossil-based feedstocks. A carbon price could be most effective in conjunction with other policies to offer well-rounded support for such a transition.

3.2 The need for sector-wide transition

To eliminate emissions from the cleaning formulations sector completely, the entire sector will need to transition. This shift needs to allow time for necessary steps such as sufficient scale-up of supply, innovation in processing and sustainable carbon sources, and workforce upskilling, among others. Given the urgency of the climate crisis and the time necessary to conduct a financially efficient and sustainable transition, action is needed now.

As in any sector, given concerns around industrial competitiveness, no producer is likely to make the first move to bio-feedstocks and incur the associated higher costs. Especially considering research that shows that despite 65% of consumers saying they want to buy from brands that advocate for sustainability, only 26% actually do so (White, et al., 2019). A sector-wide incentive to adopt sustainable feedstocks is required.

Policy and stakeholder interventions which are applied to the industry as a whole will enable this shift in feedstocks to commence. Interventions will need to be announced with lead times to allow a steady transition, signalling intent to companies and facilitating appropriate investment decisions in the long term.

3.3 Benefits of a coordinated international response

The net-zero transition of the formulations sector would benefit from careful planning and coordination with governments around the globe. While government approaches and models of coordination with industry will vary between states, a response of this kind offers a considerable range of benefits across geographies. This section provides an overview of a selection of advantages of governments addressing the greenhouse gas pollution of formulations at scale, showcasing particular opportunities across geographies.

The importance of formulations in government environmental commitments

The reduction in emissions of the formulations sector is of strategic importance to governments, as it tends to align with the environmental aims set out in both national legislation and international agreements such as the Paris Agreement. As states move to address residual emissions, the chemical sector (and formulations segments within it) will become a significant issue due to its comparatively high volume of emissions (International Energy Agency (IEA), 2021).

Centralised government planning benefits the reduction of greenhouse gas emissions of formulations as it offers a mechanism to strategically assess societal needs across sectors through demand prioritisation, direct innovation and investment, and pace scale-up. This approach should de-risk investment for industry due to guaranteed demand and allow efficient use of public money. We propose developing a *Sustainable Carbon Strategy*, as discussed in the following sections. Government planning on the reduction of greenhouse gas emissions from formulations is also linked to a variety of issues that are important for the net-zero transition as a whole, including the development and scaling of carbon capture, use and storage (CCUS), biomass strategies to provide sustainable feedstocks, and 'just transition' considerations involving upskilling and reskilling of workers and job creation in green sectors.

3.3.1 Scaling up emissions trading and carbon pricing

Around the globe, governments are taking a stand on emissions. Explicit carbon prices exist in 68 jurisdictions[5], as shown in Figure 9. Although they predominantly apply to carbon from energy generation across national and sub-national jurisdictions, these same countries could be turning the conversation to the hidden emissions of the formulations sector, chemicals industry, and petrochemicals more generally. The extension of carbon prices to formulations can generate significant comparative advantages for early adopters of zero-emission formulations, for example by easing market access for products that could be impacted by carbon border adjustment mechanisms. Countries and firms that are able to meet more rigorous carbon standards could experience enhanced market access while contributing to the net zero agenda many states have committed to both domestically and internationally.

[5] Notes on the Map: Map shows national schemes, although there are more than 42 subnational schemes, including Alberta, British Columbia, Baja, Beijing, California, Catalonia, Chongqing, Fujian, Guangdong (except Shenzhen), Hawaii, Hubei, Jalisco, Manitoba RGGI, New Brunswick, Newfoundland and Labrador, Northwest Territories, Nova Scotia, Ontario, Oregon, Pennsylvania, Prince Edward Island, Quebec, Saitama, Sakhalin Saskatchewan, Shanghai, Shenyang, Shenzhen, TCI, Tamaulipas, Tianjin, Tokyo, Washington and Zacatecas.

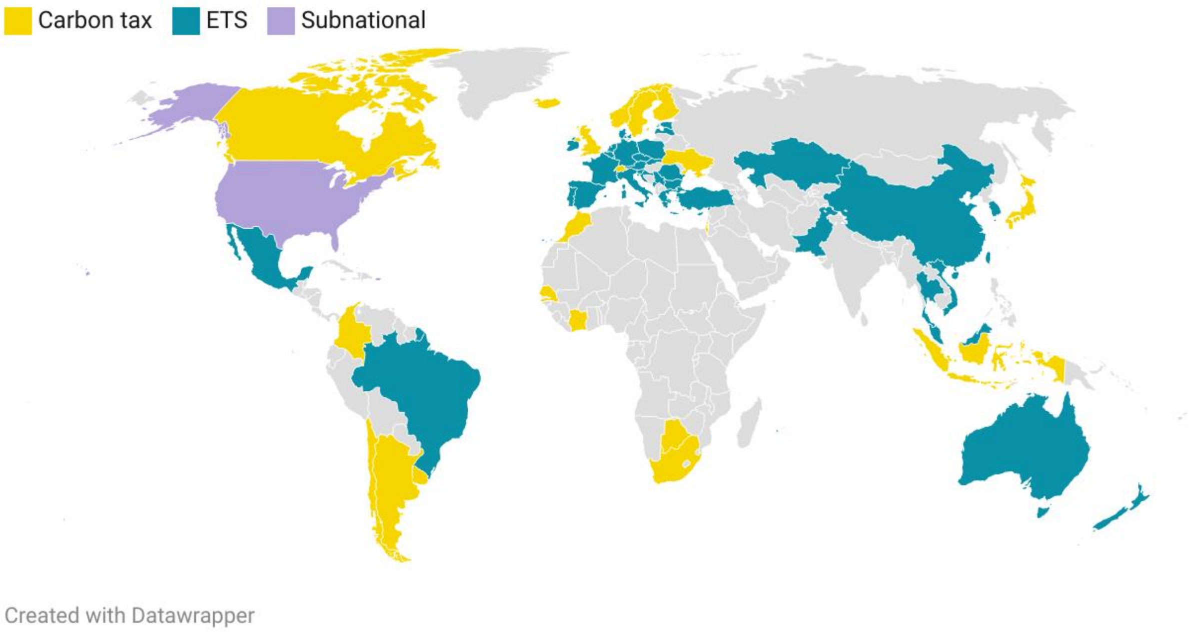


Figure 9. Map showing countries with carbon taxes and emissions trading schemes. Data source: World Bank (2022).

3.3.2 Biomass production

Reducing greenhouse gas emissions for formulations is closely linked to the availability of biomass feedstocks. There is consequently a significant opportunity for states to develop both their biomass volumes (from waste as well as purpose-grown crops) and biomass processing capacity and become critical suppliers to the future formulations market.

Figure 10 presents an overview of where biomass is currently distributed in vegetation globally, indicating potential hubs of purpose-grown production (European Space Agency, 2019). However, the capacity of states and regions to use waste as feedstock products for surfactants should not be overlooked, as this can provide a significant share of feedstocks or energy sources for surfactant production (Black & Richter, 2010).

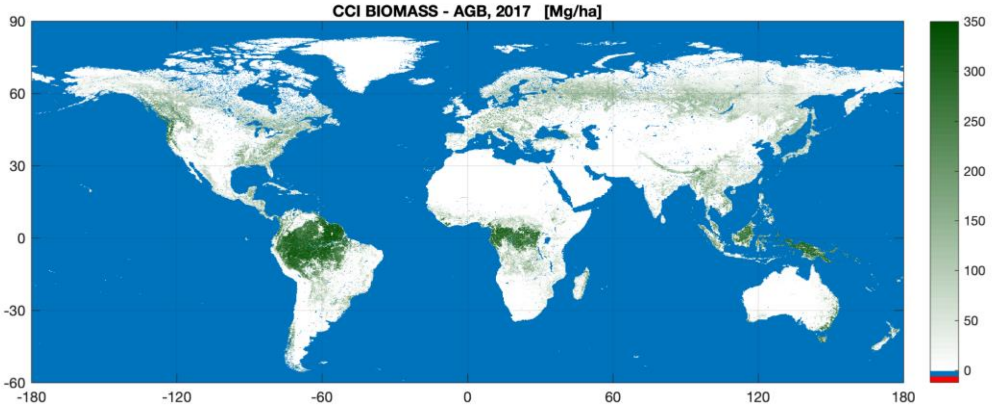


Figure 10. Overview of global biomass distribution (European Space Agency, 2019).

The biomass strategy of states (as well as sectoral practices) must carefully consider the competing uses of land that can be used to produce biomass, such as food production, conservation, biodiversity projection or living space for humans. These considerations should take on particular weight in developing economies, where biomass makes up a large share of the energy mix, and a diversion of resources could cause significant harm. For example, fuel wood provides almost 90% of the energy in rural areas of Kenya, and biomass accounts for 97% of total primary energy supply in Malawi (Black & Richter, 2010). It is therefore essential to identify the most feasible and efficient portfolio of biomass tailored to specific states and regions (Sertolli, et al., 2022).

3.3.3 Job creation

Throughout the transition to net zero, jobs are a central theme for government consideration. As with the movement towards renewable energy, the literature suggests that a shift to sustainable chemical feedstocks will create new jobs.

According to a 2022 report by SystemIQ (SystemIQ; University of Tokyo; Center for Global Commons, 2022), eliminating greenhouse gas emissions from the chemicals industry as a whole could create an additional 29 million new jobs globally by 2050, compared to a business-as-usual trajectory. Compared to 2020, this would include 11 million new jobs directly related to the production of chemicals, more than compensating for the shift of around 5 million workers away from fossil fuel sectors required in the net-zero transition, as estimated by the IEA (International Energy Association (IEA), 2022). Reducing greenhouse gas emissions in the FMCG sector would contribute to the demand for these sustainable chemicals and the associated jobs.

4 Policy and stakeholder interventions

Policy and Stakeholder Interventions: At a glance

To encourage a shift from fossil-carbon to sustainable carbon in cleaning formulations, the first action from policymakers will need to be the development of a *sustainable carbon strategy*. Interventions which may be included in this strategy relate to increasing the cost of carbon; making bio-carbon more competitive; funding innovation; demand-pull, encouraging a shift in feedstock demand; supply-push, sustainably scaling-up supply; and, capacity building.

Figure 1111. Portfolio of policy and stakeholder interventions to support sustainable carbon in cleaning formulations.

The previous section established the need for policy intervention supported by action from other stakeholders. A carbon price alone is unlikely to be sufficient to enable a sustainable and feasible transition to sustainable-carbon feedstocks. A portfolio of interventions, which address the cost, feasibility of scale up, and need for co-operation, will need to be adopted to support a well-rounded transition away from fossil-based carbon. This approach of adopting a combination of policies has been advocated by Stern, Stiglitz, and Hepburn (2021), who emphasise the value of such an approach given the urgency of reducing emissions, the political feasibility of implementing high carbon prices, and the potential for rapid gains from innovation.

Designing well-rounded policy portfolios will require the first action from policymakers to be the development of a *sustainable carbon strategy*. Strategies will need to be context specific and contain a range of appropriate interventions. Before we discuss the design and implementation of a sustainable carbon strategy, we describe a range of interventions which may be valuable to include in such a strategy. These fall within five aims: increasing the cost of fossil carbon, making bio-carbon more competitive, funding innovation, demand pull, supply push, and capacity building.

4.1 Increasing the cost of fossil-carbon

Increasing the cost of fossil-carbon is a strong political signal to reduce the use of fossil-carbon in formulations.

To incentivise a shift from high carbon-emitting products to lower or zero-carbon products, economists have largely favoured carbon pricing, despite this often being met with public unpopularity (Carattini, et al., 2018). Carbon pricing alters relative prices, leading to an automatic adjustment in behaviour by firms and consumers, and creating a continuous incentive for investments in low-carbon technological improvement (Carattini, et al., 2018).

There are different theoretical foundations for carbon pricing (see Box 2). Explicit carbon prices already exist in 68 jurisdictions, although they predominantly apply to carbon from energy generation across national and sub-national jurisdiction. In 2022, these initiatives covered 12 $GtCO_2eq$, representing 23% of global GHG emissions (World Bank, 2022).

Carbon pricing can be a powerful tool if designed correctly. In this section we present *novel calculations of the theoretical carbon tax for feedstocks* to aid in setting a carbon price, as well as the possibility of combining this with a *carbon-border adjustment mechanism*. Implementing these taxation policies requires information about *cradle-to-grave lifecycle analysis*. Any taxation policy must involve careful consideration of *'just' pricing* to protect low-income consumers. [Reinvesting taxation revenue] to aid the sustainable transition or support citizens may make these taxation policies more politically popular.

Throughout this report, it is noted that the adoption of a carbon price should be accompanied by other policy interventions to create a politically well-rounded environment for such a transition.

4.1.1 Carbon price

Chemicals would be a new industry for many jurisdictions to add to their carbon pricing systems – only the EU covers the bulk organic chemicals sector, to some extent, as part of its European Emissions Trading Scheme (EU-ETS). However, exceptions or generous allowances mean that coverage is not as comprehensive or effective at bringing down emissions as it is in other sectors (European Commission, 2022; Carbon Market Watch, 2021). For example, between 2019 and 2020 the EU chemicals sector reduced emissions by just 1.9%, far below other industrial counterparts such as iron and steel, whose emissions reduced by 11.5% and 8% respectively (European Environmental Agency, 2023).

The ineffectiveness of the current EU-ETS application to the chemicals industry offers evidence that the carbon prices for the chemicals sector must be addressed. To aid this, we present in this paper calculations for the *theoretical carbon price* on formulations and discuss considerations for a *practical carbon price*.

A theoretical carbon price for formulations today

For bio-chemicals, Saygin et al. (Saygin & Gielen, 2021) estimate that a carbon price would need to be US$100-400/t$CO_2$eq. This is higher than typical carbon prices, which range from US$1-137/t$CO_2$eq (World Bank, 2022). For the analysis conducted in this section, in a deductive exercise we calculate the tipping point theoretical carbon price; the price at which it immediately becomes optimal to switch from fossil-based to bio-based feedstocks.

Primary work, showing specific examples of carbon price calculations relevant to the FMCG sector, are presented in this report for bio-kerosene (a feedstock) and LAB (a formulation ingredient). A cradle-to-grave lifecycle approach is taken to calculate the carbon price because this accounts for the hidden emissions of formulations. Tables 1 and 2 show calculations of the theoretical carbon price per tonne which, other things equal, would equalise the post-tax price between fossil and bio-based feedstocks.

Table 1. Theoretical carbon price for kerosene (a feedstock for the FMCG sector) using cradle-to-grave lifecycle emissions

Kerosene	Fossil	Bio-based	Difference
Price[6] (US$/tonne)	242 Range: 215–270	1282 Range: 1000–1250	1040 Range: 871–1209
Emissions (Dray, et al., 2022) [7] (tCO_2eq/tonne)	5.2	2 Range: 1.4–2.6	3.2 Range: 2.6–3.8
		Carbon price: (US$/$tCO_2eq$)	325 Range: 230–460

Table 2. Theoretical carbon price for LAB (an FMCG formulation ingredient) cradle-to-grave lifecycle emissions

LAB	Fossil	Bio-based	Difference
Price[8] (US$/tonne)	1007 Range: 564–1450	1716 Range: 1694–1738	709 Range: 244–1174
Emissions (Fogliatti, et al., 2014)[8] (tCO_2eq/tonne)	3.48	1.81 Range: 1.79–1.83	1.67 Range: 1.65–1.69
		Carbon price: (US$/$tCO_2eq$)	424 Range: 144–711

The calculations in Tables 1 and 2 suggest theoretical carbon prices of US$144-711/$tCO_2eq$ to immediately make sustainable chemicals cost competitive with fossil-carbon.

One must acknowledge that these calculations have been conducted with the available data, something which has been highlighted as limited. Once full lifecycle analysis data has been collected, these will need to be updated to improve their accuracy. As the cost of bio-based feedstocks reduce, following the learning curves discussed in Section 3.1, the theoretical carbon price will also reduce.

[6] From ICIS data. Assuming exchange rate of €1 = US$1.14
[7] Conversion from gCO_2eq/MJ (as in reference) to tCO_2eq/tonne, assuming 43,920MJ/tonne (BP, 2022)
[8] LAS emissions with sulfonation step removed. Equivalent to 0.1kgCO_2eq/kg (Fogliatti, et al., 2014)

A practical carbon price

The theoretical carbon prices calculated for the formulations sector are above the current ones applied to other sectors. To put these numbers into context, in existing carbon regimes, prices vary from less than US$1/t$CO_2$eq, in the US state of Massachusetts, to US$137/t$CO_2$eq in Uruguay (World Bank, 2022). The largest carbon market in the world is EU-ETS, and the European Allowance (EUA) price was trading around €80-90/tCO_2eq (US$90-100/t$CO_2$eq) in early 2023. Research by a group of leading economists (Stern, et al., 2022) found that an explicit target consistent global average price level should be US$50-100/t$CO_2$eq by 2030, with prices in high-income countries expected to be higher than in low-income countries.

Carbon prices represent a balance between the social costs, the national or jurisdictional appetite of applying a carbon price, the macro-economic conditions such as GDP and oil prices, and whether there are complementary policies targeting innovation (Kaufman, et al., 2020).

Adopting a uniquely high carbon price for the chemicals industry, in line with the theoretical carbon price, is not likely to be the immediate answer for most governments. The internalisation of significant price increases in the formulations sector, as in other sectors, would likely lead to concerns about industrial competitiveness (Novozymes, 2022; Statista, 2023; Kearney, 2022). These essential everyday items need to remain affordable, and the businesses that produce them need to remain functional. Therefore, it may be more appropriate for governments to adopt a carbon price at the lower end of the theoretical range, if not altogether lower, as a signal to industry. Ensuring that the sector is not exempt from a carbon price sends a strong signal for change to the industry.

One approach could be to include the wider chemicals sector within existing carbon pricing regimes – removing existing exemptions for the sector – and then complement the carbon price with structural support measures for R&D and innovation. In 2022, carbon prices around the world reached record highs. The EU-ETS reached almost €100/tCO_2eq (approximately US$114/t$CO_2$eq) in both February and August in 2022 as the EU's ambitions for emissions reduction grew, and the post-Covid recovery saw demand for emissions credits increase (Trading Economics, 2022). At these levels, the carbon price would enable the industry to change its behaviour.

However, the EU-ETS is also highly volatile, meaning there is no price certainty for industry. Making the general carbon price regime stricter, including quickly phasing out free allowances and incorporating the chemicals – and formulations sectors – into these regimes, would provide more certainty of a reasonable carbon price going forward.

Alternatively, to demonstrate government intent and encourage long-term planning by industry in the feedstock transition, a separate carbon price could be announced for the FMCG or chemicals industry. This could be designed to increase over time in a pre-agreed schedule shared with industry well in advance to enable businesses to prepare and invest as necessary. To be publicly acceptable, a carbon price for fossil-based formulations would likely need to start low and then be scaled up (Burke, et al., 2019). Naturally, the running of a separate carbon pricing regime may create additional administrative burden compared to including chemicals in a pre-existing structure.

4.1.2 Carbon border adjustment mechanism

A Carbon Border Adjustment Mechanism (CBAM) can help address supply chain emissions by addressing the carbon embedded in a nation's imports; it also reduces carbon leakage and ensures fair competition for domestic producers reducing their own emissions. CBAMs can take one of three forms: (i) border taxes (as tariffs on imports and, less commonly, rebates on exports); (ii) mandatory emissions allowances purchased by importers; and (iii) embedded carbon product standards. CBAMs may incentivise consumers to opt for low-carbon products. Any distributional impacts (on low-income countries or households, for example) can be addressed through the recycling of CBAM revenues to mitigate adverse impacts (Adams, Axelsson and Parr, 2021).

CBAMs are not a silver bullet – for them to be effective across multinational supply chains, a substantial proportion of economies (e.g. representing the majority of traded goods importers) would have to implement them. For example, it has been estimated that a 'carbon club' of countries implementing the CBAM that includes the EU, UK, US, Canada and Japan would cover 44% of global international trade (Adams, Axelsson and Parr, 2021). Key barriers to the implementation of CBAMs include the need for comprehensive and universally verifiable systems of carbon accounting and measurement, as well as compatibility with world trading regulations (e.g. WTO). The UK, US, Canada and Japan are countries that have been discussing the potential for CBAMs, although no formal intentions have been declared (Adams, Axelsson and Parr, 2021). The prospects of a CBAM may have prompted developing countries to begin developing their own internal (voluntary) carbon markets (India recently passed legislation to set up a carbon market), in an effort to pre-empt losses of export competitiveness (Government of India, 2023).

The EU is currently developing a CBAM. However, the organic chemicals industry, which includes those feedstocks used in cleaning formulations, are at present not to be included. This is because of uncertainty regarding the embedded emissions of these goods at import (European Commission, 2021). In the CBAM proposal produced by the European

Commission, the authors explicitly call out the requirement for more data and analysis of this sector before a targeted allocation to the chemicals sector can be considered. This is another example of the need for full lifecycle analysis and investment to advance understanding.

Box 2: "Carbon pricing 101"

Carbon pricing is used to disincentivise the use of products, processes or fuels containing fossil-carbon, and to incentivise cleaner alternatives. Carbon prices force companies to internalise the costs associated with the negative repercussions of using fossil-carbon (also known as negative externalities). They can be calculated to factor into account the additional healthcare costs of climate change, higher risks to the food system, and damage from increased extreme weather events (Stern, 2007). Some theoretical approaches to carbon pricing emphasise that polluters should pay the full 'social cost' of carbon (SCC), broadly defined as the cost that accounts for the total damages of emissions. The carbon price may increase demand for cheaper abatement techniques such as bio-derived substitutes in the long run (Stern, 2007; LSE, Vivid Economics, 2020), by increasing the relative cost of fossil-containing components.

Carbon prices can be explicit or implicit. Explicit prices can be created through carbon taxes or cap-and-trade systems. Carbon taxes are sometimes described respectively as being 'price-based', because the price of carbon is fixed by the tax, while trading schemes are described as being 'quantity-based', because they fix the quantity of carbon dioxide emitted each year, which typically falls over time, and the price emerges as a result of trades on the market between participants of 'allowances' to emit (Hepburn, 2006). Companies which are able to reduce carbon emissions more cheaply than the price of a carbon allowance will sell their allowances to companies where it is more costly to reduce their carbon emissions. Certain industries are provided with 'free allocations' (which they do not have to buy on the market) which they can then sell if they are able to reduce emissions cheaply. Other industries have to purchase allowances on the market for each tonne of carbon they emit. In a cap-and-trade system, the emissions reductions are set by the government or regulator, but the carbon price will be unknown and varies until the market clears (Stern & Stiglitz, 2017). The largest carbon market in the world is the European Emissions Trading Scheme (EU-ETS), and the European Allowance (EUA) price was trading around € 80-90/tCO2eq (US$90-100/tCO2eq) in early 2023.

Implicit carbon prices can be created through regulations and standards (Hepburn, et al., 2020). For example, road vehicle emission standards, for which an implicit carbon price can be calculated. The price does not explicitly appear anywhere, and does not need to be paid, but can be determined by working out the carbon price that, if imposed, would lead to the same outcome. In some instances, implicit carbon price can be created by other taxes. For instance, a consumption tax on meat might (in part) be seen as forcing companies to pay for the climate damages from their agricultural emissions (Funke, et al., 2022).

4.1.1 Full lifecycle analysis

Lifecycle calculations are in the very early stages of being incorporated into carbon pricing, such as for heating oil pricing in Finland (World Bank, 2022b). In many sectors there is current debate about lifecycle analysis methodologies and boundary setting. For example, should the lifecycle analysis be cradle-to-gate or cradle-to-grave, given the challenges associated with quantifying end-of-life emissions.

Given the end-of-life emissions from formulations, a cradle-to-grave lifecycle emissions approach needs to be taken to calculate carbon prices for the chemicals used by the FMCG sector. Without this, the hidden emissions of this sector remain unaccounted for, and attempts to price in the externalities associated with these products will be inaccurate. This intervention is supported by the IPCC in their 2023 Sixth Assessment Report, in which lifecycle analysis is mentioned as one of the key activities in reducing emissions from the production and use of chemicals (Intergovernmental Panel on Climate Change, 2023).

Limited cradle-to-grave lifecycle analysis for cleaning formulations has been conducted to date. Fogliatti et al. (2014) offer one of the limited lifecycle assessments of a bio-based FMCG feedstock called LAS. They demonstrate that it is critical to include end-of-life emissions in lifecycle assessment and comparison; without these, the emissions benefits of bio-based can be overlooked (Fogliatti, et al., 2014).

Reaching a stage where we confidently understand the possible range of full lifecycle emissions of formulations produced worldwide will require additional data collection and funding to advance the state of knowledge, particularly with regard to the end-of-life emissions of these products.

Standards have been developed by international collaborations such as through the World Business Council on Sustainable Development (WBCSD) to fully assess lifecycle emissions of the chemicals sector (World Business Council on Sustainable Development, 2014). These types of cradle-to-grave assessments should be institutionalised in carbon pricing regimes to accurately price the hidden emissions of formulations.

Full lifecycle analysis of these goods and the necessary collection of data will be critical in the adoption of any carbon price or carbon border adjustment mechanism.

4.1.2 'Just' pricing and managing distributional impacts

The introduction of fiscal mechanisms such as a carbon price or CBAM will potentially increase the cost of producing a fossil-carbon based formulation. If these costs are not internalised fully by producers, this could lead to increased product prices, with adverse impacts for consumers and households if costs are passed through.

These distributional effects must be carefully considered in designing a carbon price or CBAM on formulations. This is especially critical as the products discussed in this report are essential goods with relatively inelastic demand. Consumers are unlikely to be able to substitute away to cheaper alternatives; this is particularly pertinent during times of rising inflation.

When designing a taxation regime, consideration must be given to the impact on low-income consumers, who spend a slightly higher percentage of their income on these products. In the UK, for example, the lowest income quintile spends 3.3% of their total expenditure on these products (UK Office for National Statistics, 2021).

Price cap regimes, which limit the pass-through of higher costs, or other policies which require the taxation cost to be internalized by the manufacturers, could be considered – although targeted support is usually more efficient, based on experiences from other types of mitigation policy such as direct cash payments. Alternatively, rebates for low-income consumers may be a possibility, or consumers could benefit from pay-outs through recycling or reinvesting the taxation revenue where low-income households benefit most (Carattini, Kallbekken and Orlov, 2019).

Introducing a carbon tax or CBAM will result in taxation revenue being collected by the government. While there is no specific reason in economic theory why funds raised through carbon pricing should be hypothecated to subsidise clean alternatives, this is a publicly and politically popular policy (Carattini, et al., 2018). This revenue, for example, could be reinvested to support low-income customers, fund innovation, and improve access to capital.

Some groups advocate for ‘climate dividends’, which are per-capita pay-outs to citizens from the carbon tax collected (Carattini, et al., 2018). This is already in practice in Switzerland through their tax on heating fuel and in Canada in relation to the carbon tax scheme. The two systems are run differently and can be designed to best suit the context (Mildenberger, Lachapelle, Harrison & Stadelmann-Steffen , 2022; Burke, 2021).

When considering reinvestment of fiscal revenues, policymakers and treasuries must be cognisant that there is no economic theory which equates the revenue generated through taxation to the investment required for the benefit of society. Policymakers need to, independently from the tax structure, assess the investment needed and should not superficially limit expenditure to align with tax revenue.

4.2 Making bio-carbon more competitive

Implementing a fossil-carbon taxation regime will indirectly reduce the cost of sustainable-carbon feedstocks by shifting demand and enabling the cost of these emerging alternatives to proceed down the learning curve. There are other interventions which could be considered to make biocarbon competitive.

In this section we cover contracts for difference and subsidies and structural support measures, which both have an immediate impact on the cost of bio-feedstocks. In addition, innovation in processing is discussed, which can, in the mid-term, result in permanent reductions in costs, independent of ongoing financial support.

4.2.1 Subsidies and structural support measures

Subsidies have been extensively used as an instrument to deploy clean energy technologies, and to incentivise private investment in scaling them up further. These have included, for instance:

- Feed-in-Tariffs for developers of renewables
- Capital subsidies for clean technologies (e.g. for heat pumps and EVs)

Total subsidies to renewables stood at $166bn in 2017 (Taylor, 2020)[9]. In a more recent example, the US Inflation Reduction Act is expected to pump $369bn into clean energy subsidies (in various forms) over the coming decade, under the Renewables Obligation scheme.

Subsidies have often come under scrutiny, with policies criticised for creating market distortions or leaving governments exposed to long-term expenditure, due to the uncertainty of learning curve trajectories, or other exogenous factors such as the exposure of the subsidy mechanism to external shocks. For instance, the energy price spikes of 2022 (triggered by the Ukraine war) fed through to *all* electricity prices (which were being set by the cost of fossil gas at the margin), increasing the costs to both consumers and the exchequer (Evans, 2022).

4.2.2 Portfolio Standards

Portfolio Standards are a market-based support instrument that has been used to scale clean technologies. For example, the UK Renewable Obligation (introduced in 2002) was designed to support electricity suppliers to procure a proportion of their supplies from renewable sources. Renewable Obligation Certificates were issued free of charge to electricity generators by

[9] Fossil fuel subsidies were estimated to be far higher, at nearly $3tn.

Ofgem (the administrator of the scheme). These could be sold at a premium to traders or suppliers who were required to meet the Obligation, or instead make a fixed payment into a cash payment fund in lieu of each ROC. Cash payments were recycled back to suppliers who met their obligation with ROCs, so giving ROCs additional value. The cost of the RO to suppliers was, however, passed on to consumers through their electricity bills. This eventually prompted further reform to support mechanisms; there was a move to Feed-in-Tariffs (FiTs) from 2010-2019, under which 'FiT-accredited' electricity generators received support for between 10 and 25 years, depending on technology type and capacity when their installation was commissioned, and whether it was previously accredited contracts for difference (CfD).

4.2.3 Contracts-for-Difference (CfDs)

CfDs are policy mechanisms that have been successfully used to scale up novel clean energy-generation technologies – mainly solar and wind, which are now the cheapest sources of new electricity generation globally (Way, et al., 2022; Evans, 2020). By extension, sectors which use these technologies as inputs have also undergone rapid cost declines – for example, in some countries including the UK, Electric Vehicles (EVs) are now cheaper to run than petrol of diesel cars (Office for Zero Emission Vehicles , 2022).

A CfD mitigates the market risks faced by suppliers of a new, high-cost commodity by paying the supplier the difference between a predetermined reference price reflecting the old technology (for example, a fossil carbon-based feedstock) and a 'strike price' set at the value required for the new technology to be viable. The strike price can be determined administratively (for example, in its first renewable CfD round in 2014, the UK government set the strike price), or through competitive reverse-auctions. The counterparty to a CfD is usually a public sector agency or enterprise (in the UK renewable CfD auctions, for example, it is the Low Carbon Contracts Company). CfDs are now being considered in the decarbonisation of other sectors, such as maritime shipping (Clark, et al., 2021).

The difference in cost between zero-emissions chemicals-production technologies and other more polluting alternatives in global market prices are still significant. This difference could be bridged through several CfD-based options, such as carbon CfDs (where the EU would subsidise producers, covering the difference in cost between zero-carbon technologies and more polluting ones, for example) (European Commission, 2023). Research shows that the success of UK CfDs was partly due to the policy landscape that preceded it; CfDs replaced the Renewable Obligation on electricity suppliers to source an increasing proportion of their electricity from renewable sources (Clark, et al., 2021), which meant the CfD was introduced when an emerging renewables industry already existed, and strike and market prices could be assessed against some benchmarks.

4.2.4 Innovation in processing and properties

Research is necessary for diversifying raw material carbon sources (covered in Section 4.5.4) and the processing stage. In this section we discuss the need for innovation in processing with respect to *improving conversion efficiencies* and the *long-term opportunities to improve properties*. In addition, the concept of design for end of life is discussed.

Improving conversion efficiencies

Methods to improve the chemical processing of plant matter can also assist in reducing the cost of bio-derived 'drop-ins'. For example, higher biomass-to-chemical yields could be achieved by investigating catalysts (e.g. bacteria and enzymes) with high activity and selectivity to the desired renewable feedstocks (Hayes, 2012)[10]. Product separation may also contribute to poor yields, and this can be improved with better technology as well as keeping a high O/C atomic ratio in the product (Huang, et al., 2021).

Long-term opportunities to improve properties

In the short term, fossil-derived formulations will likely be directly replaced with the exact bio-based alternative as 'drop-ins', as has been the focus of this report. For example, the use of bio-naphtha, bio-kerosene and established sugar fermentation processes to make platform chemicals. Adopting 'drop-ins' makes use of established refinery infrastructure and avoids additional costs (e.g. an industrial plant could be made use of to the end of its design life). There are also benefits due to existing data on product health and safety (e.g., REACH), efficacy and biodegradation.

Long term, new formulation recipes could be developed for use in the FMCG sector which use more efficient chemical compositions for formulations. This change in ingredients could exploit alternative raw-material sources of carbon (to reduce competition and land use constraints) and produce products with superior properties, which boast lower environmental impacts. For example, these new products may be 100% sustainable carbon, biodegradable, produce better outcomes, and, for example, work effectively at low temperatures.

Design for end of life

Although extended producer responsibility mandates will be challenging to implement in a sector where waste is not captured, design for end of life can be encouraged, or even mandated. Research can be conducted into the decomposition of waste products under

[10] Environmental impact of disposal of such catalysts must be accounted for in lifecycle analysis.

different conditions to provide data on the impact of product at the end of life and inform lifecycle analysis. Based on this research, measures could be put in place to mandate bio-compatible waste.

4.3 Funding Innovation

Advancing the state of knowledge is critical to achieve the learning curves presented in Section 3.

4.3.1 Innovation grants

Public support for early-stage R&D can take the form of innovation funds, such as those created by Innovate UK. These public grants can support riskier, early-stage ventures which have significant potential but are not yet market-ready and thus may not attract sufficient private investment.

These grants can be used to direct private investment and must ensure sustainability and positive land use outcomes at the same time as advancing bio-feedstock knowledge – for example, funding investigations into land-efficient bio-feedstocks deployed in appropriate locations. In an example from the plastics sector, the UKRI 'Smart Sustainable Plastic Packaging' supports a portfolio of more than 70 funded projects in sustainable plastics research, with a total budget of £60m over six years (UKRI , 2023). In aviation, the EU-ETS 'free allocation' of EUAs beyond Europe will be phased out in the coming years under the new 'Fit for 55' package. To increase the supply of, and demand for, high-quality sustainable aviation fuels (SAF), the EU plans to support innovation into alternative fuels through R&D funding combined with regulation to mandate the share of SAF in aviation by particular dates (European Parliament Think Tank, 2022).

4.3.2 R&D investment credits

R&D investment credits can be introduced in order to incentivise private investment in R&D to advance the state of knowledge and scale up bio-carbon alternatives. A scheme of this sort entitles the company conducting the relevant R&D to receive some degree of tax relief. For example, the US Research and Experimentation Tax Credit is a federal benefit that provides companies across a variety of industries dollar-for-dollar cash savings for performing activities related to the development, design or improvement of products, processes, formulas or software (GovGrant, 2023).

If this policy is adopted in conjunction with a fossil-carbon taxation regime, the design of fiscal policy must account for the risk of leakage. For example, by investing in R&D, companies which continue to use fossil-based feedstocks are unaffected by the relevant carbon taxation scheme.

4.3.3 Green loans

To scale existing ventures, green or national investment banks such as the Connecticut Green Bank in the US, and KfW in Germany can help to scale up companies operating in novel industries. These banks can leverage private capital by overcoming upfront costs, asymmetric information and technology costs to help new sustainable chemicals gain market traction and reach new customers.

4.4 Demand pull: Encouraging a shift in feedstock demand

In the absence of a financially competitive edge, private investment can be secured by introducing requirements and communicating reliable future demand to de-risk investments.

4.4.1 Portfolio standards and composition mandates

By setting clear and achievable targets well in advance, regulators can enforce the integration of sustainable bio-feedstocks. For example, renewable portfolio standards in the US have been found to be one of the most effective policies in increasing the use of solar energy (Ryan, et al., 2019). This sends a strong signal to suppliers that demand will be present, de-risking investment in scaling up supply. This sign-posting of mandates has been seen to be effective with the current transition to EVs as they provide a transition period to make the adjustment (Lam & Mercure, 2021). In the UK, the Renewable Fuel Transport Obligation (RTFO) has been deployed to decarbonise the transport sector by mandating that suppliers of relevant transport fuel in the UK must be able to show that a percentage of the fuel they supply comes from renewable and sustainable sources (Department for Transport, 2021). Another example is the EU strategy for plastics in a circular economy, which proposes that all plastic packaging placed on the EU market should contain a certain minimum amount of recycled content recovered from post-consumer plastic waste (European Parliament, 2023).

4.4.2 Green public procurement

Green public procurement (GPP) can help to create stable demand, especially if coordinated across multiple governments (Swedish Energy Agency, Smith School of Enterprise and the Environment, 2023). Through GPP policies, public entities can drive markets in sustainable directions by prioritising environmentally and socially responsible purchases when exercising large-scale purchasing power in contracts for goods, services and infrastructure development.

General public procurement represents an important proportion of the overall market, accounting for an average of 12% of GDP in OECD countries and up to 30% of GDP in developing countries (One Planet Network, 2023). GPP programmes utilise this purchasing power to choose goods, services and works with a reduced environmental impact, making an important contribution to sustainable production, consumption and re-use. In addition to reducing environmental impacts, GPP programmes drive innovative sustainable directions for bio-feedstock markets by identifying future priorities, sharing best practices on bio-based procurement, and increasing local innovation capacity where they are used (Orsatti, et al., 2020). This can speed up market demand for bio-based products at a regional and national level. To engage the bio feedstock market and promote demand in end-use industries for bio-based products, public bodies should set bio-specific strategies in GPP. Coordinating public procurement efforts alongside R&D support for bio technologies can effectively promote the development and market deployment of sustainable feedstocks.

4.4.3 Demand prioritisation and planning

The prospect of the chemical sector becoming largely bio-based remains challenging. It will be difficult to achieve given: (i) the limited availability of sustainable primary biomass; (ii) the fierce competition for biomass resources from other sectors (in particular, the energy and transport sectors); and (iii) the sheer scale of demand. Increased pressure on biomass demand therefore requires careful assessment of trade-offs by adopting the biomass-use prioritisation principle on the national or regional level. The 'cascading' principle for biomass is proposed in RED III (the revised version of the EU Renewable Energy Directive), which aims to ensure that biomass is used first where it has the highest economic added value and the lowest environmental impact (European Commission, 2023).

Those using sustainable feedstocks will need to compete with other industries looking to reduce their greenhouse gas emissions, will need to create stable long-term demand so that innovation is worthwhile, and ensure that information on sustainable chemicals is shared widely around the world.

In order to compete with aviation (and other industries) for bio-feedstocks, the chemicals industry will have to engage with international forums beyond an FMCG focus, such as through the Marrakesh Partnership, which brings together a wide range of businesses, investors and cities to discuss achieving the goals of the Paris Agreement (UNFCC, 2023).

The formulations sector is not the only sector looking to reducing its greenhouse gas emissions. For example, aviation is under increasing pressure to find sustainable biofuels in order to have the social license to operate. Forecasts predict that the demand for aviation, the largest market for bio-kerosene, will grow at between 2.4% and 4.1% per year, which translates to a doubling or tripling of the market by 2050 (Dray, et al., 2022). If policy is forthcoming and well designed, governments can leverage the multiplier effects to scale technologies faster.

This shared demand for bio-kerosene creates the biofuel-chemical nexus discussed in Section 2.3.1. However, there are some analyses which have shown that the amount of available biomass for bio-kerosene production could produce double the bio-kerosene needed by the aviation sector in 2050 under a high-demand scenario (Dray, et al., 2022; Staples, et al., 2018)[11]. Under combined-technology scenarios, where the aviation industry adopts multiple technologies, the sector is assigned one-third of global potential bio-kerosene production (21.7 EJ of 63.4 EJ) and is able to meet customer demands under the low-demand scenario (World Economic Forum, McKinsey and Company, 2020). Given this, the absolute production capability of bio-kerosene may be less constrained than expected.

4.5 Supply push: Sustainably scaling up supply

In conjunction with encouraging demand of bio-based feedstocks, there is a need to make sure that there is sufficient and sustainable supply of bio-carbon. To achieve this, the demand must be quantified and forecast across sectors that will be competing for bio-carbon sources. To sustainably meet this demand across sectors, governments can assist with improving access to capital, introducing sustainable feedstock certifications, and encouraging research into carbon sources, focusing on overcoming land use constraints and diversifying carbon sources.

4.5.1 Demand quantification and forecasting

Forecasts show that, in certain sectors, demand for bio-feedstocks may outstrip supply, causing the price to rise due to demand competition. Policy should encourage appropriate scale up of sustainable supply, carefully considering the knock-on effects of limiting supply options for the bio-fuels industry (for example, the EU decision to phase out palm oil for bio-fuel production as well as capping crop-based fuels to 7% by 2030 (Anon., 2022)). If supply limitations are necessary to achieve truly sustainable products, public funding could be directed to advance the state of knowledge of alternative supply options, such as CAM plants, which are able to grow in semi-arid regions (Collett, et al., 2021).

Policymakers should have an awareness of supply chain competition and constraints. Policy to incentivise a transition to sustainable aviation fuels may have unintended consequences for

[11] Production of bio-kerosene could equate to 63.4 EJ of jet fuel per year, while the aviation industry under this high-demand scenario will require less than 30 EJ per year in 2050.

the chemical sector. In sectors where competition challenges are foreseen, public funding could be directed towards R&D of alternative carbon sources. Introducing carbon prices will also encourage the private sector to invest where appropriate and adjust their business model accordingly to be in line with the Paris Agreement.

4.5.2 Improving access to capital

As R&D in sustainable feedstock develops, government can facilitate market growth through targeting production capacity and stable demand. They can do so through financial and regulatory incentives that balance two objectives: i) a reduction in financial risks and costs for processing innovative sustainable feedstock and ii) an increase in returns from producing such feedstocks.

One identified strategy to facilitate efficient production at scale is for the support of integrated biorefineries with the process flexibility to co-produce different bio-based products. To increase the economic viability of bio-based feedstocks and reduce financial risks, production must expand and diversify. Co-producing value-added products such as bio-based chemicals alongside biofuels can reduce overall production costs and scale supply. It can do so through achieving process efficiencies and reducing financial risks for innovators of sustainable bio feedstock. Integrated biorefineries thereby encourage take-up of bio feedstock end uses beyond biofuels.

Financial tools can assist in the development of new refineries as well as the expansion of existing infrastructure. These include:

- *Public co-financing for pilot/demonstration plants:* to overcome high upfront capital barriers and de-risk further developments through proof of concept
- *Green bonds:* providing access to funding for capital expenses and improving financial stability of early investments.

4.5.3 Sustainable feedstock certification

Standards or codes to coordinate efforts on land use can ensure that the burden is divided equitably, creating fair standards for local citizens and the environment. For example, the EU recently passed a bill that restricts the importation of soy, beef, palm oil, timber, cocoa and coffee that was grown on deforested lands (News Mongabay, 2022). This code requires the exact coordinates of the product's growth location to be reported so that the origin of these crops can be precisely traced (European Commission, 2021). This will impact the bio-based formulations industry, arguably making it more sustainable, as soybean and palm oils are both used as bio-based sources for surfactant feedstocks. Another example is where a collective of companies creates a code to improve the industry standards, such as the roundtable on sustainable palm oil (RSPO), where participating members voluntarily aim to improve the standard farming practices for palm oil, through education and transparency (RSPO, 2021).

Certification of sustainable feedstocks must consider the energy-related emissions to ensure not only that the carbon source is sustainable, but that the production process also has low emissions.

4.5.4 Research into sustainable carbon sources

Research into sustainable carbon sources covers better understanding land use constraints, impacts on ecosystems, as well as investigating new ones to diversify.

Land use constraints and emissions

Transitioning land from use as a bio-sink to a bio-source is not an option. How land is used has a significant impact on its carbon emissions (UNFCCC, 2022). If land is managed poorly, it can release substantial greenhouse gas emissions, for example through deforestation for agriculture or crops. If lands and oceans are managed sustainably, they can provide valuable carbon sinks and make an important contribution to mitigating climate change.

Currently the most useful bio-carbon source for formulations is palm oil. In many aspects, palm is the optimal oil crop for bio-feedstock production for the FMCG sector. Yet, there are significant challenges surrounding sustainability and land use (Meijaard, et al., 2020).

Understanding the availability of biomass now and into the future is a challenge, given current land use, the uncertainty created by climate change, and biodiversity loss (European Commission, 2023). For the formulations industry (and chemicals industry more widely) to be able to confidently transition away from fossil-carbon, research to quantify this will be crucial.

Ecosystem mapping

Ecosystem mapping will be invaluable in assessing sustainability and selecting appropriate land. As innovation in identifying sustainable alternative sources and where to grow them advances, ecosystem mapping will be crucial in conducting full lifecycle analyses of the alternatives.

For example, compared to palm crops, rapeseed and sunflower crops are able to grow in much larger areas of land, across central and southern Europe and western Asia. Ecosystem mapping can assist in assessing environmental and biodiversity impact of crop growth in different regions, prioritising use of low-impact areas (such as brownfield sites) and assessing risks, for example to flooding, as is done by Natcap Research (Natcap Research, 2022). This can assist in developing specific land-management practices, which, when implemented, can maximise the yield of the crop. Furthermore, good practices can ensure proper waste management and the optimal use of pesticides and fertilisers to ensure the soil health is maintained, emissions are minimised and neighbouring water systems are safe.

Brazil offers a case study of ecosystem service policies that can be used to encourage sustainable land use, including conditional cash-transfer programmes called Bolsa Floresta[12] and Bolsa Verde, which support rural families in conserving the forests in which they live. Alongside this, the National Institute for Space Research runs a satellite imaging system[13] to monitor the five million km^2 of Brazilian rainforest, requiring only one enforcement official per 11,000 km^2 (OECD, 2015).

Diversifying bio-carbon sources

New, available and reliable sources of bio-carbon need to be investigated which meet sustainability goals. Both waste and virgin sources must be considered. Research should be directed towards diversifying bio-carbon sources (raw materials) to minimise cost, exploit availability, maximise growth rate and potential for conversion, and overcome land use constraints. Possible sources include: vegetable oils other than palm – for example sunflower and rapeseed oils, particularly relevant for markets where they can be grown locally; CAM plants, which can utilise land that is not suitable for agriculture, overcoming land use constraints (Collett, et al., 2021); and algae, which is already used on an industrial scale in food, biofuels, fertilisers and pharmaceuticals (White & Ryan, 2015).

Palm and coconut oil contain the desirable fatty acids (of chain length C12-C14), useful for surfactants given their physical and biodegradation properties, whereas oils produced by other plants are slightly larger (Hayes, et al., 2019). Novel techniques to convert other vegetable oils, both virgin and waste, into the desired carbon length need to be devised and work at large scales. Genetic engineering of plants to be richer in certain fatty acids or sugars would also improve efficiency.

[12] Bolsa Floresta requires the attendance of a two-day environmental awareness training course, as well as enrolling their children in school, in return for monthly payments of 50 reais (~$30) (United Nations Department of Economic and Social Affairs, 2021). This programme alone has improved the health and education outcomes of more than 35,000 people and recorded a dramatic decrease in the rate of deforestation (OECD, 2015).

[13] This programme, called DETER, provides updates on deforestation violations, as well as running a training centre on satellite monitoring, and is being further developed to self-detect deforestation and degradation throughout the country (OECD, 2015) (P. H. May, 2012).

Although greenhouse gas emissions are typically lower for waste feedstocks as no emissions are allocated to their cultivation/production, these are mostly cellulose and hemicellulose, which require further processing to obtain sugars, are less efficient (~60%) and require more feedstock. In contrast, sugar beet and sugar cane are high-yielding crops per hectare of land (12.5 and 11.0 tonne/hectare, respectively) and the sugars are more easily extracted (100% efficiency). Selecting the source of carbon must be carefully considered across the lifecycle of the carbon, for which there is a lack of academic literature. The optimal scenario may be to combine first and second-generation feedstocks, as using all parts of a plant would lead to the highest fermentable sugar yield.

4.6 Capacity building

4.6.1 Formation of an international body for sustainable formulations

As the global net-zero transition picks up pace, industry coalitions have emerged across hard-to-abate sectors to collectively shift their operational standards towards sustainability. The Science-Based Targets Initiative (a part of the 'We Mean Business' Coalition) is an example of initiatives that support private sector organisations in setting science-based targets. Organisations such as the International Council of Chemical Associations, which support the Paris targets – could provide similar platforms for collaboration around net-zero strategies for the chemical industry – although they tend to include a broad remit.

Companies need a collaborative approach to develop policy, as well as signposting from governments across sectors so that supply can keep up with demand. Governments' support of low-carbon alternatives can act as a market signal for the private sector to develop and incorporate net-zero policies. This can happen effectively through multi-national enterprises which operate in multiple jurisdictions, bringing a lesson from one country into its operations in another. As discussed earlier, different carbon pricing policies might work in different regions, but sharing lessons and success stories from implementing policy can enable a faster and more effective transition. Leakages in carbon emissions across borders can be prevented through border adjustment mechanisms, or climate clubs which enable a bilateral partnership on specific industries to reduce emissions (Helm, 2015; Helm, Hepburn and Ruta, 2012; World Bank, 2022b), or through regulations on multi-national enterprises which purchase chemicals from suppliers.

Industry forums such as the Consumer Goods Forum can provide the environment for companies to coordinate on standards and identify the support that they would need in order to transition. One of the leading voices in standards for companies to align with the Paris

Agreement and Net Zero is SBTi, a partnership between CDP, the United Nations Global Compact, World Resources Institute (WRI) and the World Wide Fund for Nature (WWF).

> Box 3: Science-Based Targets initiative (SBTi)
>
> The SBTi aims to provide companies with a clear route to reduce emissions in line with the Paris Agreement targets, by setting goals to limit global warming to below 1.5°C. By setting out a five-step process, private-sector companies can embed science-based targets into the sustainability management process.

4.6.2 Workforce upskilling

The chemical industry is significant in size and employment. For instance, it is the fourth largest industry in the EU, accounting for around 7% of manufacturing output by turnover. The industry directly employs 1.2 million highly skilled workers and supports 3.6 million jobs indirectly. It also supports a further 19 million jobs across all other supply chains in the EU. The EU chemical industry has 67% greater labour productivity than the average for the manufacturing sector (European Commission, 2023).

Stakeholders report that the chemical industry may lack future skilled workers in the transition to sustainable carbon. New, effective and inclusive training approaches are therefore essential in swiftly integrating new workers into the job market. Examples may include expanded access and programmes in relevant disciplines; incentives for education; training-related movement to develop skills; and reskilling and retraining programmes for workers in adjacent industries (Zhou, et al., 2022). Major employers such as ‘bpost’ in Belgium have successfully trialled such schemes at scale in a post-pandemic setting (bpost, 2022).

4.6.3 Upscaling renewable energy infrastructure

For bio-based feedstocks to be considered sustainable, the energy required to produce them will need to be sourced from renewable sources.

The emissions of bio-based formulations can be significantly reduced by ensuring all energy requirements for production are fulfilled with renewable energy sources. This includes transportation and heating steps. For example, producing one tonne of surfactant from sustainable feedstocks requires, on average, 14 kWh of energy (D. Schowanek et al., 2018).

Continued encouragement of renewable energy integration and capacity expansion across countries will assist in achieving this, especially given the ever more cost-competitive nature of renewable energy (Our World in Data, 2020).

5 Putting this into action globally

Putting this into action: At a glance

While policymakers will need to address multiple considerations in formulating a *sustainable carbon strategy*, one of the most important objectives will be to induce learning to reduce the cost gap between bio and fossil feedstocks.

Policymakers can consider the following approach: investigating the deployment of policy options to scale up markets for sustainable carbon, identifying common trade-offs in policy implementation, determining which groups of interventions are complimentary (e.g. in designing a carbon price) and coordinating across different stakeholders to catalyse national and international action.

Given that effective policy must consider the context in which it operates, policies may vary between regions. For this reason, the primary recommendation is for governments to develop *sustainable carbon strategies*. These strategies can incorporate and adapt appropriate policy recommendations from the portfolio of approaches discussed in this report. This section sets out policymaker considerations and implementation across stakeholder groups.

5.1 Sustainable carbon strategy for cleaning products: policymaker considerations

As discussed in Section 4 of this paper, a range of policy options exists on the supply and demand sides to address the barriers (highlighted in Section 3) and unlock the market for sustainable carbon. While policy will need to address multiple different considerations, one of its most important objectives will be to induce learning to reduce the cost gap between bio and fossil feedstocks. With this in mind, and facing a range of options, in developing a sustainable carbon strategy and baseline scenario for any context, policymakers can consider adopting an approach with the following elements:

1. Investigate which policy options may be suitable to different stages of market development;
2. Identify common trade-offs that exist in policy implementation, and determine the optimal balance of outcomes;
3. Determine where interventions are complimentary so that effort can be applied efficiently;

4. Determine the range of stakeholders with whom to coordinate on different policy interventions.

Deployment of policy options to scale up markets for sustainable carbon

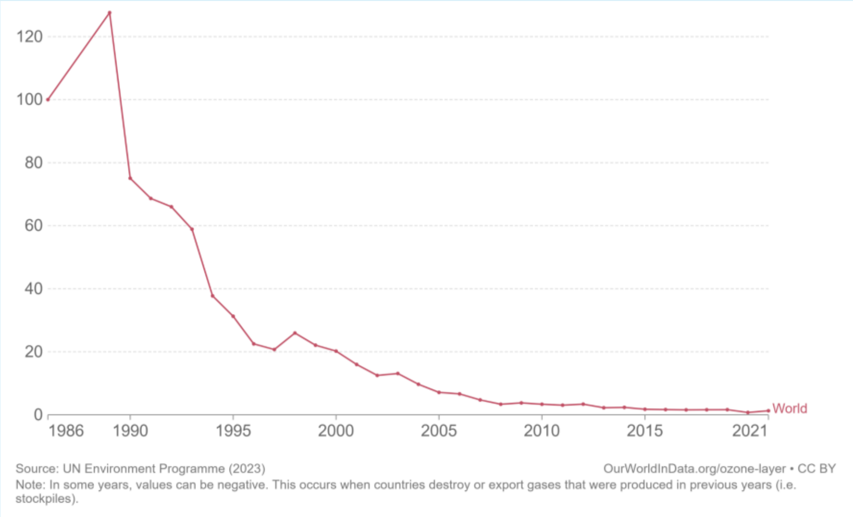
Broadly speaking, policies to support environmental innovation are well-grounded in economic theory. The more successful examples of new technologies substituting for older ones, and their eventual widespread adoption, have involved the existence or creation of *favourable initial conditions* – a critical pre-condition is the existence of some type of emerging market opportunity for the new technology (Clark, Ives, Fay et al., 2012). Other sectors provide lessons here; pertinent examples include the global phaseout of HCFCs (or CFCs), and subsequently of HFCs (Roberts, 2017), and the substitution of fossil fuels with renewable power technologies across countries.

Box 4: The Montreal Protocol and Kigali Amendment: creating baseline conditions for successful transitions

The Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in 1987, is the landmark multilateral environmental agreement that regulates the production and consumption of nearly 100 man-made chemicals referred to as ozone-depleting substances (ODS). It set out timetables for developed and developing countries to phase down the consumption and production of these substances in a stepwise manner.

The protocol was successful in the phaseout of hydrochlorofluorocarbon (HCFC) – a powerful GHG, the most commonly used of which was nearly 2,000 times more potent than CO_2 and utilised in refrigeration, air-conditioning and foam applications. Its phaseout was possible due to the existence of a viable alternative in the form of an emerging market for a substitute technology – hydrofluorocarbons (HFCs), which were introduced as non-ozone depleting alternatives. HFCs were commercialised in the 1990s, soon after the protocol was adopted.

Figure 1122. Change in the consumption of ozone-depleting substances. Consumption of ozone-depleting substances measured relative to 1986 (where consumption in 1986 is equal to 100).



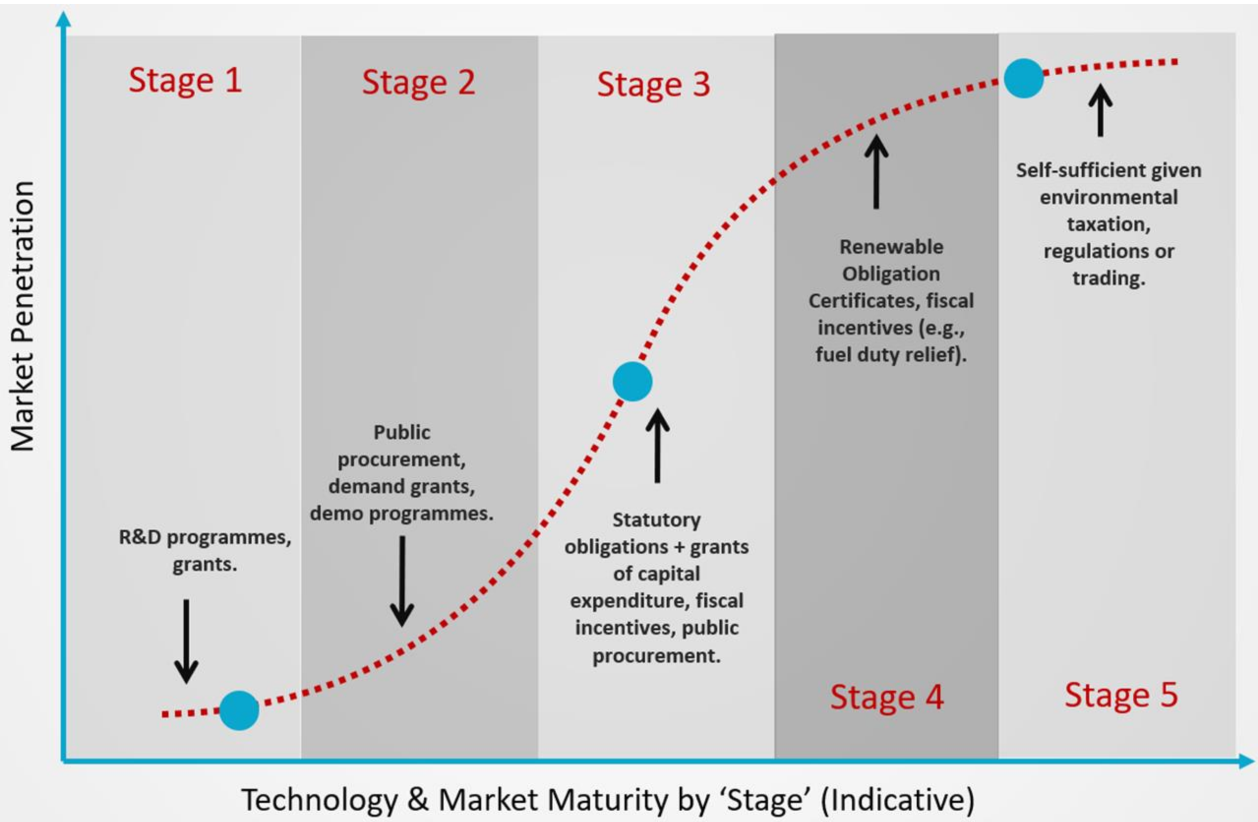
Source: Our World in Data, 2023

Over time, it became apparent that HFCs had a far higher global warming potential than initially believed, and the Kigali Amendment to the Montreal Protocol was subsequently adopted in 2016, under which parties are required to reduce HFC consumption and production by 80-85% of their baselines by the 2040s, with the first reductions coming from developed economies in the 2020s. Similar to Montreal, viable enabling alternatives existed, including:

- Additional classes of fluorinated gases (HFOs), lower GWP HFCs and HFO/HFC blends used as drop-ins or 'transitional' substitutes;
- A direct move to natural refrigerants (including hydrocarbons, ammonia, CO_2, air and water) and not-in-kind technologies.

The switch to renewables in UK power generation (and the ongoing push to electrify end-use sectors such as heating and transport) has benefited from the fact that viable alternatives either existed at the time or were supported in early stages of development using policy instruments. Policymakers in the UK deployed a raft of interventions to move early renewable technologies towards higher levels of commerciality and market penetration over time[14], as Figure 13 below illustrates. Arguably, most of the mainstream renewable technologies of today – including onshore and offshore wind, rooftop solar Photo Voltaic (PV), and Concentrating Solar Power (CSP), lie to the top right of the 'S' curve below (Stage 4 and 5), whereas newer technologies such as hydrogen produced from electrolysers, Small Modular Reactor technologies and carbon capture, use and storage (CCUS) lie to the bottom left (stages 1 through 3). These policy instruments mainly helped reduce relative price differences between fossil and renewable power technologies, though incentivising innovation to drive down costs.

Figure 13. Indicative use of policy instruments to scale renewable technologies and market penetration in the UK.



Source: Adapted from (T.J., et al., 2005) *Note*: *'Stages' are illustrative/idealised.*

[14] For the purposes of illustration, these stages could be broadly classed as: R&D, demonstration, pre-commercial, supported commercialisation, and competitive commercialisation.

UK as well as international experience has also provided examples on how sudden shifts in policy, or the lack of clear medium-term signals, could harm progress. For example, the market for solar power in the UK slowed down significantly when policymakers reduced the subsidies to rooftop solar PV in 2010 by 65%, going on to close the scheme in 2019 (while replacing it with other measures that did not result in a like-for-like incentive). Similarly, the abrupt cancellation in 2015 of a £1 billion competitive capital budget scheme aimed at commercialising CCS technologies impacted innovation and industry/investor confidence – leading to a ten-year delay in UK capability to deploy CCS (Energy Technologies Institute, 2016). In the EU, retroactive policy changes on renewable support subsidies between 2000 and 2017 are estimated to have decreased the investment rate for renewable technologies linked to those policies (for example, by 45% for solar PV and 16% for onshore wind) (Senstad, et al., 2022).

These examples yield some broad principles for policymakers seeking to design long-term strategies:

- The establishment of **baseline conditions for policy action** (for example, the environmental cost of ozone-depleting substances under Montreal and Kigali) using evidence-based research and science, on which sectoral pathways can then be built;
- The **need for perseverance on the part of policymakers** once a policy option or framework has been announced/initiated;
- The provision of **clear signals to suppliers and consumers alike** over the longevity of support measures to reinforce confidence;
- The **articulation of exit strategies**, making clear when support might be withdrawn, and why – for example, because insufficient progress has been made towards commercialisation, or because technologies have successfully progressed into competitive markets (T.J., et al., 2005);
- An understanding of **innovation as a system**, and recognition of the importance of 'joined-up' policies which support innovation through its various stages, targeted, if necessary, to address specific barriers.

It is evident that any *sustainable carbon strategy* will have synergies with both circular economy goals and net-zero targets in relation to the environmental problems that these strategies address; these synergies could be harnessed in establishing baseline conditions in the strategy (for example, a social cost of carbon).

Evaluating trade-offs in policy implementation

Policymakers in any context are likely to face a range of trade-offs when deciding which policies to implement, and in which combinations. We outline some key trade-offs below – these are not unique to sustainable surfactants, but apply for policy design in general:

- **Impact on lifecycle reductions of fossil-carbon produced by petrochemicals, versus transaction costs of monitoring, regulation and verification systems.** Effective policies to reduce emissions require (agreement on) a robust quantification of sectoral lifecycle emissions, and reporting these within a larger emissions accounting framework. There is no single, internationally harmonised method of MRV for lifecycle emissions – sectors/organisations have tended to provide their own guidelines and, for some technologies, LCA may even vary with geographical context (Nugent & Sovacool, 2014). Therefore, government-set and enforced standards around MRV will be necessary to build credible traded markets for most net-zero technologies.

- **Distributional impacts.** Experience has shown that net-zero policies are likely to have distributional implications (i.e. also referred to as 'policy costs') and policymakers may need to plan the management of such implications. For example, in the UK, 'green' technologies have been supported through a levy on household consumer bills (called the 'Environmental and Social Obligation')[15]. For low-income households that spend a higher proportion of their incomes on 'essential' goods, this may result in adverse distributional impacts – although revenues are recycled back into supporting these households or vulnerable consumers through compensation and grant schemes.

- **Political economy.** The effectiveness of policies varies across national and regional political contexts. Policies that change relative prices (e.g. carbon pricing and taxation) may face public resistance, as they may be perceived by the public to be regressive, economically damaging, opportunistic and/or have a high personal cost. However, evidence shows that the method of implementation matters: for example, the use of trial periods (i.e. soliciting public feedback prior to institutionalising a policy), tax escalators (i.e. the phase-in of a policy), environmental earmarking (i.e. hypothecating revenues to improve environmental living standards), lump-sum transfers (i.e. to mitigate distributional impacts on low-income households), tax rebates (i.e. cutting

[15] According to Ofgem, green levies made up around 15% of a dual-fuel consumer bill in February 2022 (Bartum, 2022).

taxes elsewhere for revenue neutrality) and advanced communication strategies can help remove obstacles to implementation (Carattini, et al., 2018).

- **Revenue-raising vs revenue-neutral policies.** Fiscal policies in particular are aimed at raising revenues for public spending and investment, while minimising the distortions to people's decisions. Relatively inelastic demand (i.e. when demand for goods is not very responsive to changes in price) may therefore present an attractive base for taxation.[16] While it can be regressive, the ratio of welfare gains to tax revenue of a carbon tax should be considered to understand its benefits, and whether a tax alone is welfare improving, or whether the tax combined with how the tax is spent should be considered (Kotchen, 2022).

- **Unintended consequences.** These are unique to the sector. In this instance, in order to replace petrochemicals with bio-based alternatives, land use changes and their impact on biodiversity should be considered, alongside other potential unforeseen consequences.

Considerations in the design of a carbon price – complementary interventions

Given the trade-offs above, different policies might be appropriate in different jurisdictions. Due to the imperative to act now, feasible carbon prices alone may not be sufficient to incentivise the transition (Stern, et al., 2021) and complementary policies are needed. This is especially because 'practical' carbon prices are often too low to incentivise change alone; further, there can be spillover benefits (or co-benefits) and policies can provide additional market signals (Stern, et al., 2021). For example, a carbon price combined with technology-neutral R&D investment incentives can catalyse the emergence of new sustainable feedstock sources or production processes.[17] Figure 14 below outlines other complementary interventions.

This is in part because every jurisdiction has multiple contradictory and complementary policies, creating wildly different implied carbon prices beyond the 'headline' price. Regulation, subsidies and taxes for the same industry can vary, depending on the sector and whether they are applied to households or companies, meaning that carbon is not priced consistently even within countries. In the UK, for example, research shows that emissions from electricity and road fuels are taxed at relatively high rates, while personal aviation and household gas use is effectively subsidised (Institute for Fiscal Studies, 2021).

[16] This is broadly referred to as Ramsey taxation (Ramsey, 1927).
[17] As another example, renewable support combined with an ETS has resulted in a scale up of renewable electricity in the UK, the benefits of which have spilled over into lower running costs for EVs (Department for Transport, 2022).

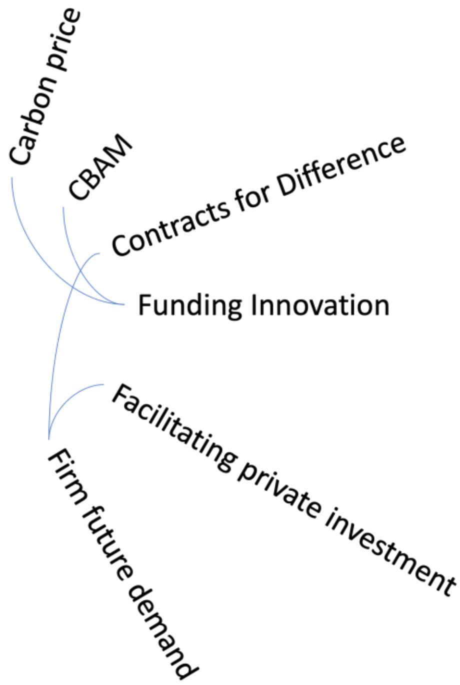


Figure 14. Complementary stakeholder interventions

In both theory and practice, carbon prices should not necessarily be equal across countries (Stern, et al., 2021). This is due to equity considerations, economic structures and different elasticities in low-income vs high-income countries for different products (Stern, et al., 2022) (Stern, et al., 2021) (Stiglitz, 2019). For example, differing capital and labour costs in low-income countries implies that production costs of formulations may differ. In addition, there is a higher price elasticity of emissions in low-income countries, meaning that a lower carbon price will have a larger impact (Stern, et al., 2022).

This is why policymakers should take the full suite of policies into account alongside the national context when determining the carbon price in formulations, and consider a carbon price in line with existing prices, rather than one representing the theoretical price that would be needed to tip demand from fossil-carbon to sustainable carbon. These theoretical values need to be complemented by a range of other considerations around appropriate carbon pricing, demonstrated in Table 3. The most effective approach for policymakers is to include a portfolio of complementary policies which have the same goal of reducing greenhouse gas emissions from formulations.

Table 3. Potential considerations of carbon price. Inspired by Funke et al. (2022)

Components of a price on formulations	Relevant effect	Impact on the tax rate
Baseline: Pigouvian environmental damages	Sum of social costs of the carbon emissions	
Distributional concerns	Tax incidence approximately equal across households, although falls slightly higher on poorer households	- / neutral
Political economy	Appetite for carbon taxes as a policy mechanism	+ if exists, - if none exists
Ramsey tax component	Fiscal revenue generation; inelastic product can be taxed more before behaviour is distorted	+
Land use changes	Shift away from agriculture to crops to produce from formulation Incentivises deforestation	- -

Source: Smith School of Enterprise and the Environment Analysis

Considered together, the feasibility of implementing a uniquely high carbon price on the formulations sector (above existing carbon prices that have been implemented), ensuring that bio-carbon chemicals are sustainably developed to minimise deforestation and competition for food crops, and that a carbon price should take into account any support to develop the sector implies that a carbon price for formulations should, at least at first, be at the lower end of the theoretical carbon price range of US$144-711/t$CO_2$eq, if not below this range.

Box 5: Examples of combined interventions in other sectors: the transition of the aviation sector to sustainable aviation fuel

Since 2012, the EU-ETS has covered aviation operating within or to European countries. Experts have calculated that a carbon price of over €200/tCO_2eq (US$228/t$CO_2$eq) would be necessary to make bio-jet fuel competitive with jet kerosene (Deane & Pye, 2018). In addition, the Biofuel Flightpath Initiative aims to encourage the uptake of 2 Mt of bio-kerosene into jet fuel annually. This could potentially add €1.20 to €4.30 (US$1.37 to US$4.90) to the per-passenger cost of a typical 1,000km flight (Deane & Pye, 2018). Part of these costs will be passed onto the consumer as a function of the market structure and price elasticity of demand (Hepburn, et al., 2013) and whether there is any public financial support. Uptake of bio-jet fuel is only just beginning, with currently 0.05% of all jet fuel made up of sustainable aviation fuel (Kallbekken & Victor, 2022). The financial incentives that were afforded to biofuel for road transport, such as subsidies, have not been so widely distributed to the aviation sector (Doliente, et al., 2020).

5.2 Interventions across stakeholder groups

Recent experience has shown that coalitions built around specific environmental targets and SDGs can be a powerful driver of policy action. Figure 15 maps each policy intervention identified in earlier sections of this report, corresponding to an overall category of barriers. There are a broad range of stakeholder groups that are likely to be involved in enabling a pathway to net zero for household formulations.

Policymakers: National, supra-national and sub-national policymakers in government and parliament, who have the power to legislate and regulate net-zero policies, as well as implement packages of incentives to shift demand and supply towards sustainability and circularity.

FMCG industry: Sectors which rely on surfactants including home care, personal care, industrial cleaning, textiles, food and beverages, plastics and others.

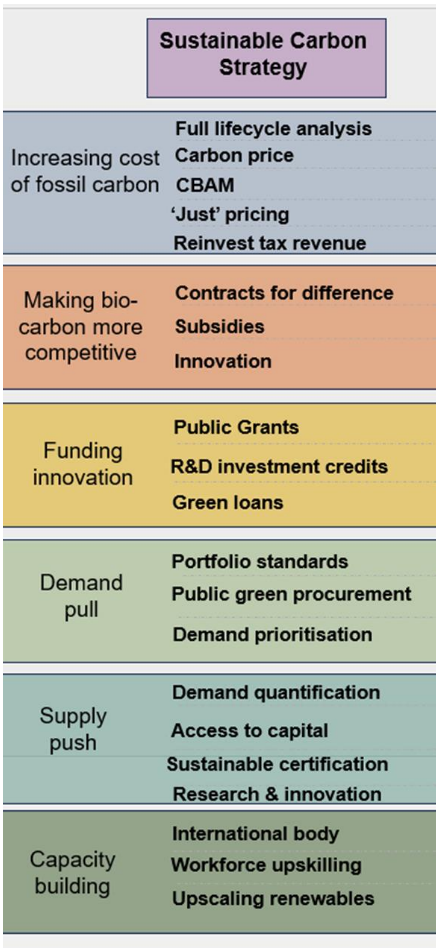
Financial bodies: Central banks, development finance institutions, infrastructure lending institutions, treasuries, financial regulators and actuarial bodies seeking to reduce asset/portfolio exposure to climate risks.

Non-governmental organisations (NGOs): Advocacy groups and think tanks working on sustainable trade and development; environment; climate; poverty and inequality; health; and just transitions for workers in 'sunset' industries (e.g. hydrocarbons).

Research institutes: Universities and publicly funded research institutions that conduct innovative research into innovative technologies, market opportunities, consumer behaviour, policy designs and socioeconomic impacts of policy pathways.

Subsequent policy work could aim to map out the names of stakeholder institutions and their roles within the policy space in greater detail, with the next step being the establishment of a convening platform (for example, spearheaded by an industry organisation or a multilateral organisation) around the elimination of greenhouse gas emissions in household formulations as a critical part of the global drive to net-zero emissions by 2050.

Figure 15. Portfolio approach – categories of interventions



Source: SSEE

Box 6: Examples of successful stakeholder coalitions

Net zero pathway for maritime shipping

In July 2023, the International Maritime Organization (IMO) set a goal of net-zero emissions from ships 'by or around, i.e. close to, 2050'. This is a major increase in the level of ambition compared to the existing 2018 strategy, which aimed at reducing emissions from ships by just 50% in the same time horizon. The goal is accompanied by strategic checkpoints at periodic intervals. It also sets a target of at least 5% – striving for 10% – uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources by 2030.

The goal was a result of a multi-year collaboration with multilateral organisations working on the environment (UN), national and supra-national governments planning their own carbon pricing and taxation pathways (EU), NGOs such as Transport & Environment that have lobbied for emissions reduction across the transportation sector, companies representing various parts of the shipping industry (e.g. shippers, brokers, bunkering) and research institutions working on techno-economic studies of sustainable shipping (e.g. UCL), as well as policy designs to enable the uptake of renewable fuels in shipping (e.g. Oxford Smith School research on the application of CfDs to incentivise green ammonia in shipping) (Clark, Ives, Fay et al., 2012).

The 'Race to Zero' coalition

Race To Zero is a global campaign to rally leadership and support from businesses, cities, regions and investors for a healthy, resilient, zero-carbon recovery that prevents future threats, creates decent jobs and unlocks inclusive, sustainable growth. It mobilises a coalition of leading net-zero initiatives, representing 11,309 non-State actors including 8,307 companies, 595 financial institutions, 1,136 cities, 52 states and regions, 1,125 educational institutions and 65 healthcare institutions. The objective is to build momentum around the shift to a decarbonised economy, where governments must strengthen their contributions to the Paris Agreement.

Box 7: The Breakthrough Agenda – a potential structure for cross-stakeholder action

To get a transition started, a niche has to be created: a place where the new technology can be deployed for the first time, following which reinforcing feedbacks kick in, making it better, cheaper and more widely adopted. Coordinated action can lead to faster innovation, larger economies of scale, stronger incentives for investment and level playing fields where they are needed (Sharpe, 2023). For example, the *Breakthrough Agenda*, established during the UK's COP26 presidency, set out a series of goals which could only be achieved with international collaboration. They were framed (as closely as international consensus would allow) in terms of 'tipping points', at which clean technologies would gain the upper hand over fossil fuels, focusing international collaboration on achieving conditions that would lead to the greatest acceleration of progress (Sharpe, 2023).

The Breakthrough Agenda: Goals

Road transport breakthrough	*To make zero-emission vehicles the new normal*
Power breakthrough	*To make clean power the most affordable and reliable option for all countries by 2030*
Steel breakthrough	*To make near-zero emission steel the preferred choice in global markets and growing in every region by 2030*
Hydrogen breakthrough	*To make affordable renewable and low carbon hydrogen globally available by 2030*
Agriculture breakthrough	*To make climate-resilient, sustainable agriculture the most attractive and widely adopted option for farmers everywhere by 2030*

Leaders of over 40 countries, covering over 70% of global GDP, signed a statement launching the Breakthrough Agenda, an endorsement of the vision of positive-sum diplomacy vis-à-vis the old paradigm of a negative-sum world in countries conflicted over a shrinking global carbon budget. Countries would 'work together in each sector … to make the global transition to a clean economy faster, lower cost and easier for all, while making solutions to adaptation more affordable and inclusive'. Smaller groups agreed to work together on sectoral solutions. For example, a group of 14 countries – the largest ever global initiative of its kind – agreed to work together to double the energy efficiency of appliances including lighting, refrigerators, air conditioning and industrial motor systems, which account for over 40% of global electricity consumption (Sharpe, 2023). On agriculture, there were agreements to work together on R&D, and to reorient subsidies and other forms of public policy support to incentivise a shift towards sustainability. Only around 5% of the $700bn spent annually in agricultural subsidies is targeted to encourage practices that regenerate ecosystems (Sharpe, 2023). On industry, a small group of countries agreed to coordinate on the public procurement of low-carbon steel and cement.

6 Conclusions

This report presents a portfolio of policy interventions to address the end-of-life emissions of chemicals used in Fast-Moving Consumer Goods (FMCG), to put the sector on a pathway to net zero and align with the Paris Agreement. It focuses on *the fossil-based carbon* found in everyday cleaning and home care products' formulations such as laundry powder and fabric detergent, hand and machine dishwashing detergent and soaps. The carbon in the chemical formulations ('surfactants') used in these products is currently largely derived from the petrochemical industry, using feedstocks produced from oil and gas. Therefore, in addition to the global challenge of decarbonising energy use, the fossil carbon feedstocks used in formulations will also need to be replaced by sustainable carbon from bio-based feedstocks, or the petrochemical-based carbon would have to be captured at end of use and permanently removed from the atmosphere, if this vital sector is to move to net zero.

This transition is unlikely to occur in the absence of policy intervention, as the highly competitive market for FMCG products, with little to no excess economic returns in the sector, and higher cost of bio-based inputs, makes it difficult for a single firm or company to switch to a more expensive feedstock on its own, as this would put it at a competitive disadvantage.

Therefore, policy intervention to ensure the environmental costs of using fossil fuel-derived inputs are paid, and regulation or structural support for bio-based inputs, is likely to be needed. Policy intervention may also be needed to protect vulnerable consumers from price increases. There will be competition for bio-based feedstocks from other sectors, as they also transition towards net-zero strategies (for example, aviation); a holistic policy framework is desirable to address the interconnected challenges and opportunities in cross-sectoral pathways to net zero which involve the substitution of fossil-based with bio-based feedstocks. This report has investigated policy interventions to move chemical use in the FMCG industry away from fossil-carbon to more sustainable sources of carbon to align with the Paris Agreement.

Bio-based sources of carbon include virgin vegetable oils, byproducts and waste materials, offering emissions savings of between 39% and 86% compared to their fossil-based alternatives (Adom, et al., 2014). Each bio-based source has different considerations such as emissions, availability, competition, land requirements, cost and crop-to-chemical efficiency. Yet, at present, bio-feedstocks make up only 6% of chemical feedstocks (SystemIQ; University of Tokyo; Center for Global Commons, 2022).

In theory, a carbon price ranging from US$144-711/tCO2eq is needed to make bio-based surfactants cost competitive. This is an estimate, given current technologies, and on a cradle-to-grave lifecycle-emissions basis, and is limited by data availability. In the context of factors such as distributional effects, political economy issues, fiscal policy goals and land use changes, carbon prices for formulations should be aligned with the range of existing carbon prices (Stiglitz, 2019; Stern, et al., 2022), and hence at the lower end of the range. Carbon prices will not necessarily be equal for all countries (Stern, et al., 2021) due to equity considerations, economic structures and different elasticities (Stern, et al., 2021; Stiglitz, 2019; Stiglitz, 2019; Stern, et al., 2022). In practice, a carbon price alone is unlikely to resolve all barriers; and reducing the cost differential will require other policy interventions to incentivise innovation, with a longer-term eye on land use constraints and chemical-biofuel competition for supply (for e.g., in aviation).

Technological advances in bio-feedstocks can deliver cost-competitiveness, as demonstrated for other technologies (e.g., renewable power). Our analysis shows that, although bio-ethanol is already cost competitive, learning rates for bio-naphtha and bio-kerosene would need to be 20% per annum in order to be cost competitive with today's costs by 2050. To put this in context, learning rates for renewable energy generation, lithium-ion batteries and transistors followed learning rates of 10%, 12% and 40-50% respectively (Way, et al., 2022). This emphasises the importance of policy intervention in order to help rapidly level the playing field between bio-based and fossil-based feedstocks and accelerate a transition. In this report, we investigated a portfolio of possible policy interventions aimed at making bio-carbon competitive on the supply side, as well as shifting demand towards sustainable sources.

Policymakers can strategically deploy interventions, working with key stakeholder groups to achieve timely results and minimise trade-offs. Experience elsewhere has shown that international coalitions built around specific environmental targets and SDGs can be a powerful driver of policy action. In this report we mapped policy interventions across a broad range of stakeholder groups that are likely to be involved in enabling *the implementation of sustainable carbon strategies as a pathway to net zero for household formulations*.

7 References

Adams, Axelsson and Parr, 2021. *The Carbon Club revisited: Harnessing enterprise and trade to decarbonise.* [Online] Available at: https://www.smithschool.ox.ac.uk/sites/default/files/2022-02/The-Carbon-Club-Revisited.pdf

Adom, F., Dunn, J., Han, J. & Sather, N., 2014. Life-Cycle Fossil Energy Consumption and Greenhouse Gas Emissions of Bioderived Chemicals and Their Conventional Counterparts. *Environmental Science & Technology,* 48(24), p. 14624–14631.

Anon., 2022. *S&P GLobal European Biofuels Conference.* s.l.:s.n.

Anon., 2022. *European Biofuels Conference.* s.l.: s.n.

Argus, 2023. *ARGUS Bionaphtha fob ARA.* [Online] Available at: https://www.argusmedia.com/en/methodology/key-prices/argus-bionaphtha-fob-ara

Barsanti, L. & Gualtieri, P., 2018. Is exploitation of microalgae economically and energetically sustainable?. *Algal Research,* pp. 107-115.

Bartum, G. T. a. O., 2022. Cost of living crisis: reducing energy bill costs, Institute for Fiscal Studies: Explainer.

Biddy, M., Scarlata, C. & Kinchin, C., 2016. *Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential,* s.l.: s.n.

Biosolutions, 2022. *"Enzymes – no compromise on formulation cost.".* [Online] Available at: https://biosolutions.novozymes.com/en/household-care/formulation-cost

Black, M. & Richter, G., 2010. *Mapping out Global Biomass Projections, technological developments and policy innovations,* s.l.: Imperial College London.

Bloomberg, 2023. [Online] Available at: https://www.bloomberg.com/markets/commodities

Bogdanov, D. et al., 2019. Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nature Communications,* Volume 10.

Böhringer, C., Fischer, C., Rosendahl, K. E. & Rutherford, T. F., 2022. Potential impacts and challenges of border carbon adjustments. *Nature Climate Change,* Volume 12, p. 22–29.

Bosch, J., de Jong, S., Hoefnagels, R. & Slade, R., 2017. *Aviation biofuels: strategically important, technically achievable, tough to deliver,* London: Grantham Institute Imperial College London.

Bott, D., 2023. *Flue2Chem.* [Online]
Available at: https://www.linkedin.com/pulse/flue2chem-story-part-1-david-bott

BP, 2022. *Approximate conversion factors: Statistical Review of World Energy,* s.l.: BP.

bpost, 2022. *bpost launches bpost boost!: a springboard for jobseekers and employees.* [Online]
Available at: https://press.bpost.be/bpost-launches-bpost-boost-a-springboard-for-jobseekers-and-employees

Burke, 2021. *Why carbon dividends are having a moment,* s.l.: LSE Grantham Research Institute on Climate Change and the Environment.

Burke, J., Byrnes, R. & Fankhauser, S., 2019. *Global lessons for the UK in carbon taxes,* s.l.: LSE.

Carattini, Kallbekken and Orlov, 2019. How to win public support for a global carbon tax. *Nature,* Volume 565, pp. 289-291.

Carattini, S., Cavalho, M. & Fankhauser, S., 2018. Overcoming public resistance to carbon taxes. *Wiley Interdisciplinary Review of Climate Change,* 5(9).

Carbon Market Watch, 2021. *New EU ETS: time for steel, cement and chemicals to (be)come clean.* [Online]
Available at: https://carbonmarketwatch.org/2021/06/30/new-eu-ets-time-for-steel-cement-and-chemicals-to-become-clean/

Carbon Trust, 2023. *Briefing: What are Scope 3 emissions?,* s.l.: s.n.

Cárdenas, J. et al., 2021. Pre-treatment of used cooking oils for the production of green chemicals: A review. *Journal of Cleaner Production,* Volume 289.

Chu, D. B. a. A., 2023. *The US plan to become the world's cleantech superpower.* [Online]
Available at: https://www.ft.com/content/e0b55820-3a16-4018-a417-

0e7c91737ffd?shareType=nongift
[Accessed July 2023].

Clark, Ives, Fay et al., 2012. *Zero Emissions Shipping: Contracts-for-difference as incentives for the decarbonisation of new shipping,* s.l.: s.n.

Clark, A. et al., 2021. *Zero-Emissions Shipping: Contracts-for-difference as incentives for the decarbonisation of international shipping,* s.l.: Smith School for Enterprise and the Environment, Institute for New Economic Thinking, Pinsent Masons.

Coady, D., Parry, I., Sears, L. & Shang, B., 2017. How Large Are Global Fossil Fuel Subsidies?. *World Development,* Volume 91, pp. 11-27.

Collett, K. A. et al., 2021. *K. A. Collett, B. O'Callaghan, M. Mason, C. L. Smith, and C. Hepburn, "Final 25% Series: Industrial need for carbon in products,* s.l.: s.n.

Collett, K., Schreiber, V., Mason, M. & Hepburn, C., 2021. *Final 25% Series: Nature-based sinks for CO2 and sources of carbon feedstocks,* s.l.: s.n.

Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council (notified under document C(2 (2011).

Creutzig, F. et al., 2017. The underestimated potential of solar energy to mitigate climate change. *Nature Energy,* Volume 2.

D. Schowanek et al., 2018. New and updated life cycle inventories for surfactants used in European detergents: summary of the ERASM surfactant life cycle and ecofootprinting project. *Int. J. Life Cycle Assess.,* April, 23(4), pp. 867-886.

Deane, J. & Pye, S., 2018. Europe's ambition for biofuels in aviation - A strategic review of challenges and opportunities. *Energy Strategy Reviews,* Volume 20, pp. 1-5.

Department for Environment Food and Rural Affairs, 2021. *Reforming the UK packaging producer responsibility system,* s.l.: s.n.

Department for Transport, 2021. *Renewable Transport Fuel Obligation.* [Online] Available at: https://www.gov.uk/guidance/renewable-transport-fuels-obligation

Department for Transport, 2022. *Common misconceptions about Electric Vehicles,* s.l.: s.n.

Diederik Schowanek, T. et al., 2018. New and updated life cycle inventories for surfactants used in European detergents: summary of the ERASM surfactant life cycle and ecofootprinting project. *The International Journal of Life Cycle Assessment,* p. 867–886.

Doliente, S. et al., 2020. Bio-aviation Fuel: A Comprehensive Review and Analysis of the Supply Chain Components. *Published in Frontiers in Energy Research,* Volume 8.

Dray, L. et al., 2022. Cost and emissions pathways towards net-zero climate impacts in aviation. *Nature Climate Change,* 12(10), pp. 956-962.

Ellen MacArthur Foundation, 2021. *The Nature Imperative: How the circular economy tackles biodiversity loss,* s.l.: s.n.

Energy Information Administration, 2022. *Assumptions to the Annual Energy Outlook 2022,* s.l.: s.n.

Energy Information Administration, 2023. *U.S. production of petroleum and other liquids to be driven by international demand.* [Online] Available at: https://www.eia.gov/todayinenergy/detail.php?id=56041#

Energy Technologies Institute, 2016. *ETI analysis of the UK energy system design implications of delay to deployment of carbon capture and storage (CCS) in the UK ', Letter to the Chair of the Energy and Climate Change Committee, House of Commons..* s.l.:s.n.

European Commission, 2019. *Insights into the European market for bio-based chemicals,* s.l.: s.n.

European Commission, 2021. *Proposal for establishing a carbon border adjustment mechanism.* [Online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021PC0564

European Commission, 2021. *Questions and Answers on new rules for deforestation-free products.* [Online] Available at: https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_5919

European Commission, 2022. *EU Emissions Trading System (EU ETS).* [Online] Available at: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission, 2023. *Transition Pathway for the chemical industry.* [Online] Available at: https://single-market-economy.ec.europa.eu/sectors/chemicals/transition-pathway_en#:~:text=In%20January%202023%2C%20the%20European,NGOs%20and%20o

ther%20interested%20parties.
[Accessed July 2023].

European Environment Agency, 2023. *Managing the systemic use of chemicals in Europe,* Brussels: s.n.

European Environmental Agency, 2023. *The EU Emissions Trading System in 2021: trends and projections.* [Online]
Available at: https://www.eea.europa.eu/publications/the-eu-emissions-trading-system-2#:~:text=In%202021%2C%20EU%20Member%20States,by%202040%2C%20relative%20to%202005.

European Parliament Think Tank, 2022. *ReFuelEU Aviation initiative: Sustainable aviation fuels and the fit for 55 package.* [Online]
Available at:
https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698900

European Parliament, 2023. *Revision of the Packaging and Packaging Waste Directive.* [Online]
Available at:
https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/745707/EPRS_BRI(2023)745707_EN.pdf

European Space Agency, 2019. *New biomass map to take stock of the world's carbon.* [Online]
Available at:
https://www.esa.int/Applications/Observing_the_Earth/Space_for_our_climate/New_biomass_map_to_take_stock_of_the_world_s_carbon

Evans, S., 2020. *Solar is now 'cheapest electricity in history', confirms IEA,* s.l.: IRENA.

Evans, S., 2022. *Analysis: Why UK energy bills are soaring to record highs – and how to cut them,* s.l.: Carbon Brief.

Fogliatti, D. et al., 2014. Life Cycle Carbon Footprint of Linear Alkylbenzenesulfonate from Coconut Oil, Palm Kernel Oil, and Petroleum-Based Paraffins. *ACS Sustainable Chemical Engineering,* 2(7), p. 1828–1834.

Foley, P., Beach, E. & Zimmerman, J., 2011. Algae as a source of renewable chemicals: Opportunities and challenges. *Green Chemistry.*

Franklin, J., 2022. *The MethaneSAT Mission: Progress and Future Plans.* Chicago, s.n.

Funke, F. et al., 2022. Toward Optimal Meat Pricing: Is It Time to Tax Meat Consumption?. *Review of Environmental Economics and Policy,* 16(2).

Geden, O. et al., 2023. *State of Carbon Dioxide Removal Edition 1,* s.l.: s.n.

Global Petrol Prices, 2023. *Ethanol prices.* [Online] Available at: https://www.globalpetrolprices.com/ethanol_prices/

Government of India, 2023. *Indian Carbon Market (ICM) to spur mobilization of investments for transition to low-carbon pathways,* s.l.: s.n.

GovGrant, 2023. *USA R&D tax credits scheme.* [Online] Available at: https://www.govgrant.co.uk/usa-rd-tax-credits-scheme/

Greenhouse Gas Protocol, 2011. *Corporate Value Chain (Scope 3) Accounting and Reporting Standard: Supplement to the GHG Protocol Corporate Accounting and Reporting Standard,* s.l.: s.n.

Hayes, D., 2012. Bioprocessing Approaches to Synthesize Bio-based Surfactants and Detergents. In: *Food and Industrial Bioproducts and Bioprocessing.* s.l.:Wiley-Blackwell, p. 243–266.

Hayes, D. G., Solaiman, K. & Ashby, R. D., 2019. *Biobased Surfactants: Synthesis, Properties, and Applications.* s.l.:s.n.

Helm, Hepburn and Ruta, 2012. Trade, climate change, and the political game theory of border carbon adjustments. *Oxford Rev. Econ. Policy,* 28(2), pp. 368-394.

Helm, D., 2015. *The Carbon Crunch,* s.l.: Yale University Press.

Hepburn, C., 2006. Regulation by prices, quantities, or both: A review of instrument choice. *Oxford Review of Economic Policy,* 22(2), pp. 226-247.

Hepburn, C., Quah, J. & Ritz, R., 2013. Emissions trading with profit-neutral permit allocations. *Journal of Public Economics,* Volume 98, pp. 85-99.

Hepburn, C., Stiglitz, J. & Stern, N., 2020. Carbon pricing' special issue in the European economic review. *European Economic Review.*

Hillmyer, M., 2017. The promise of plastics from plants. *Science,* 358(6365), pp. 868-870.

Huang, K. et al., 2021. Greenhouse Gas Emission Mitigation Potential of Chemicals Produced from Biomass. *CS Sustainable Chem. Eng,* 9(43), p. 14480–14487.

ICIS, 2023. *ICIS Insight.* [Online]
Available at: https://www.icis.com/explore/commodities/chemicals/?cmpid=PSC%7cCHEM%7c2022-EURO%7cgeneral_chemicals&sfid=7014G000000j6M2QAI&gclid=CjwKCAjw2K6lBhBXEiwA5RjtCd0IXrtq6GZH8pklfgAChpKL5cbljKTCjaGpMDUANBqEX-AYdyfMPBoCdXAQAvD_BwE

IEA Bioenergy, 2020. *Bio-Based Chemicals: A 2020 Update ,* s.l.: s.n.

IEA, 2020. *Advanced Biofuels – Potential for Cost Reduction,* s.l.: s.n.

IndexBox, 2017. *U.S. Ethanol Market: Prices Are Soaring, Bioethanol Displaces Synthetic Alcohol.* [Online]
Available at: https://www.globenewswire.com/en/news-release/2021/12/08/2348225/0/en/U-S-Ethanol-Market-Prices-Are-Soaring-Bioethanol-Displaces-Synthetic-Alcohol-IndexBox.html

Institute for Fiscal Studies, 2021. *Tax policies to help achieve net zero carbon emissions ,* s.l.: s.n.

Intergovernmental Panel on Climate Change, 2023. *Synthesis Report of the IPCC Sixth Assessment Report Longer Report,* s.l.: s.n.

International Air Transport Association, 2022. *Fact Sheet: EU and US policy approaches to advance SAF production,* s.l.: IATA.

International Energy Agency (IEA), 2018. *The future of petrochemicals: towards more sustainable plastics and fertilisers,* s.l.: IEA.

International Energy Agency (IEA), 2020. *Fossil jet kerosene market price compared with HEFA aviation biofuel production cost, 2019-2020.* [Online]
Available at: https://www.iea.org/data-and-statistics/charts/fossil-jet-kerosene-market-price-compared-with-hefa-aviation-biofuel-production-cost-2019-2020

International Energy Agency (IEA), 2021. *Net Zero by 2050: A Roadmap for the Global Energy Sector,* s.l.: IEA.

International Energy Agency (IEA), 2021. *Renewables 2021: Analysis and forecasts to 2026,* s.l.: s.n.

International Energy Agency (IEA), 2021. *World Energy Outlook 2021,* s.l.: IEA.

International Energy Agency (IEA), 2022. *World Energy Outlook 2022,* s.l.: IEA.

International Energy Association (IEA), 2022. *World Energy Employment,* s.l.: IEA.

IPCC, 2019. *Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems,* s.l.: s.n.

Kallbekken, S. & Victor, D., 2022. A cleaner future for flight — aviation needs a radical redesign. *Nature,* Volume 609, pp. 673-675.

Kaufman, N. et al., 2020. A near-term to net zero alternative to the social cost of carbon for setting carbon prices. *Nature Climate Change,* Volume 10, p. 1010–1014.

Kearney, 2022. *How inflation is reshaping margins for commodity and specialty chemicals.* [Online]
Available at: https://www.kearney.com/industry/chemicals/article/-/insights/how-inflation-is-reshaping-margins-for-commodity-and-specialty-chemicals

Kelly, S. & Browning, N., 2022. *Analysis: Oil prices turn more volatile as investors exit the market,* s.l.: s.n.

Khalil, A. et al., 2017. Seaweed based sustainable films and composites for food and pharmaceutical applications : A review. *Renewable and Sustainable Energy Reviews,* Volume 77, pp. 353-362.

Khatun, R., Reza, M. I. H., Moniruzzaman, M. & Yaakob, Z., 2017. Sustainable oil palm industry: The possibilities. *Renewable and Sustainable Energy Reviews,* Volume 76, p. 608.

Kotchen, M., 2022. *Taxing Externalities: Revenue vs. Welfare Gains with an Application to U.S. Carbon Taxes,* s.l.: s.n.

Lam, A. & Mercure, J.-F., 2021. Which policy mixes are best for decarbonising passenger cars? Simulating interactions among taxes, subsidies and regulations for the United Kingdom, the United States, Japan, China, and India. *Energy Research & Social Science,* Volume 75.

Laurens, L. et al., 2017. Development of algae biorefinery concepts for biofuels and bioproducts; a perspective on process-compatible products and their impact on cost-reduction. *Energy & Environmental Science.*

Lewis, N., 2016. Research opportunities to advance solar energy utilization. *Science,* 351(6271).

Lim, X., 2022. How the chemicals industry's pollution slipped under the radar. 22 November.

Liu, D., 2023. *Boom time: What the Inflation Reduction Act means for US renewables.* [Online] Available at: https://go.woodmac.com/l/131501/2023-01-13/2ylxq2/131501/1673885417KLtmn0hZ/Horizons_January_2023_Whitepaper_Final_16th.pdf

Li, Y. et al., 2022. Redox-mediated electrosynthesis of ethylene oxide from CO2 and water. *Nature Catalysis,* Volume 5, p. 185–192.

LSE, Vivid Economics, 2020. *Distributional impacts of a carbon tax in the UK Report 2: Analysis by income decile,* s.l.: London School of Economics.

Markets and Markets, 2021. *Sucrose Esters Market.* [Online] Available at: https://www.marketsandmarkets.com/Market-Reports/sucrose-esters-market-191170937.html

Mathimani, T. & Pugazhendhi, A., 2019. Utilization of algae for biofuel, bio-products and bio-remediation. *Biocatalysis and Agricultural Biotechnology,* Volume 17, pp. 326-330.

Meijaard, E. et al., 2020. The environmental impacts of palm oil in context. *Nature Plants.*

Mildenberger, Lachapelle, Harrison & Stadelmann-Steffen , 2022. Limited impacts of carbon tax rebate programmes on public support for carbon pricing. *Nature Climate Change,* Issue 12, pp. 141-147.

Mintec, 2022. [Online] Available at: https://www.mintecglobal.com/top-stories/eu-to-discontinue-soyabean-oil-and-palm-oil-as-biodiesel-feedstock-from-2023#:~:text=EU%20to%20Discontinue%20Soyabean%20Oil%20and%20Palm%20Oil%20as%20Biodiesel%20Feedstock%20from%202023,-back%20to%20insight&text=On

Natcap Research, 2022. *Advanced nature and climate intelligence,* s.l.: s.n.

News Mongabay, 2022. *European bill passes to ban imports of deforestation-linked commodities.* [Online] Available at: https://news.mongabay.com/2022/09/european-bill-passes-to-ban-imports-of-deforestation-linked-commodities/.

Novozymes, 2022. *Enzymes – no compromise on formulation cost.* [Online] Available at: https://biosolutions.novozymes.com/en/household-care/formulation-cost

Nugent, D. & Sovacool, B. K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy,* Volume 65, pp. 229-44.

OECD, 2015. *Environmental Performance Reviews: Brazil Highlights,* s.l.: s.n.

Office for Zero Emission Vehicles , 2022. *Common Misconceptions About Electric Vehicles,* s.l.: Department for Transport.

One Planet Network, 2023. *Factsheets on Sustainable Public Procurement in National Governments.* [Online] Available at: https://www.oneplanetnetwork.org/knowledge-centre/resources/factsheets-sustainable-public-procurement-national-governments-1

Orsatti, G., Perruchas, F., Consoli, D. & Quatraro, F., 2020. Public Procurement, Local Labor Markets and Green Technological Change. Evidence from US Commuting Zones. *Environmental and Resource Economics,* Volume 75, pp. 711-739.

Our World in Data, 2020. *Cheap Renewable Energy.* [Online] Available at: https://ourworldindata.org/cheap-renewables-growth.

P. H. May, M. F. G. B. R. C. a. G. R. L., 2012. *"The ' Ecological ' Value Added Tax (ICMS-Ecológico) in Brazil and its effectiveness in State biodiversity conservation : a comparative analysis,* s.l.: 12th Biennial Conference of the International Society for Ecological Economics.

Ramsey, F., 1927. A Contribution to the Theory of Taxation. *Econ. J.,* Volume 37, pp. 47-61.

Randhawa, K. K. S. & Rahman, P. K. S. M., 2014. Rhamnolipid biosurfactants-past, present, and future scenario of global market. *Frontiers in Microbiology.*

Reuters, 2022. *Breaking down a barrel.* [Online] Available at: http://fingfx.thomsonreuters.com/gfx/rngs/1/1409/2220/index.html

Richie, H. & Roser, M., 2021. *Palm Oil.* [Online] Available at: https://ourworldindata.org/palm-oil

Roberts, R., 2017. Finishing the job: The Montreal Protocol moves to phase down hydrofluorocarbons. *Review of European, Comparative and International Environmental Law,* Volume 26, pp. 220-230.

Rogoff, K., 2022. *Global oil and gas prices have been highly volatile – what will happen next?,* s.l.: The Guardian.

RSPO, 2021. *Annual Communication of Progress.* [Online] Available at: https://rspo.org/acop-2020--latin-america-and-north-america-report-robust-results/

Ryan, A. J., Donou-Adonsou, F. & Noble Calkins, L., 2019. Subsidizing the sun: The impact of state policies on electricity generated from solar photovoltaic. *Economic Analysis and Policy,* Volume 63, pp. 1-10.

Sauter, E. & Van Hoof, G., 2002. A database for the life-cycle assessment of procter & gamble laundry detergents. *Int. J. Life Cycle Assess,* 7(2), pp. 103-114.

Saygin, D. & Gielen, D., 2021. Zero-Emission Pathway for the Global Chemical and Petrochemical Sector. *Energies,* 14(3).

Schmidt, O., Hawkes, A., Gambhir, A. & Staffell, I., 2017. The future cost of electrical energy storage based on experience rates. *Nature Energy,* Volume 2.

Schneising, O. et al., 2020. Remote sensing of methane leakage from natural gas and petroleum systems revisited. *Atmospheric Chemistry and Physics,* 20(5), p. 9169–9182.

Schowanek, D. et al., 2018. New and updated life cycle inventories for surfactants used in European detergents: summary of the ERASM surfactant life cycle and ecofootprinting project. *The International Journal of Life Cycle Assessment,* Volume 23, p. 867–886.

Senstad, L. H., Hagspiel, V. & Mikkelsen, W., 2022. The impact of subsidy retraction on European renewable energy investments. *Energy Policy,* Volume 160, p. 112675.

Sertolli, A., Gabnai, Z., Lengyel, P. & Bai, A., 2022. Biomass Potential and Utilization in Worldwide Research Trends—A Bibliometric Analysi. *Sustainability,* 14(9).

Sharpe, S., 2023. *Five Times Faster: Rethinking the Science, Economics, and Diplomacy of Climate Change.* s.l.:Cambridge University Press.

Smith School, 2022. *The Oxford Principles for Net Zero Aligned Carbon Offsetting,* s.l.: s.n.

Staples, M. et al., 2018. Aviation CO2 emissions reductions from the use of alternative jet fuels. *Energy Policy,* Volume 114, pp. 342-354.

State of Carbon Dioxide Removal, 2023. *State of Carbon Dioxide Removal: A global, independent scientific assessment of Carbon Dioxide Removal,* s.l.: s.n.

Statista, 2023. *Operating margin of the United States chemical industry from 2002 to 2019.* [Online]
Available at: https://www.statista.com/statistics/302004/us-chemical-industry-operating-margin/

Statista, 2023. *Volume of used cooking oil collected in the European Union from 2011 to 2019, with a forecast for 2020.* [Online] Available at: https://www.statista.com/statistics/1297092/uco-volume-collected-in-europe/

Stern, N., 2007. *The Economics of Climate Change: The Stern Review,* s.l.: Cambridge University Press.

Stern, N. & Hepburn, C., 2007. *The Economics of Climate Change: The Stern Review.,* s.l.: Cambridge University Press.

Stern, N. & Stiglitz, J., 2017. *Report of the High-Level Commission on Carbon Prices,* s.l.: Carbon Pricing Leadership Coalition.

Stern, N., Stiglitz, J. & Hepburn, C., 2021. Carbon Pricing. *European Economic Review.*

Stern, N., Stiglitz, J., Karlsson, K. & Taylor, C., 2022. *A Social Cost of Carbon Consistent with a Net-Zero Climate Goal,* s.l.: Roosevelt Institute.

Stiglitz, J., 2019. Addressing climate change through price and non-price interventions. *Eur. Econ. Rev,* Volume 119, pp. 594-612.

Swedish Energy Agency, Smith School of Enterprise and the Environment, 2023. *The role of Ministries of Finance in driving and shaping the low-carbon energy transition,* s.l.: s.n.

SystemIQ; University of Tokyo; Center for Global Commons, 2022. *Planet Positive Chemicals: Pathways for the chemical industry to enable a sustainable global economy,* s.l.: SystemIQ.

T.J., F., Gross, R., Chase, A. & al., e., 2005. 'UK innovation systems for new and renewable energy technologies. *Energy Policy,* Volume 33, pp. 2123-2137.

Taylor, M., 2020. *Energy Subsidies: Evolution in the Global Energy Transformation to 2050,* s.l.: IRENA.

Tollefson, J., 2013. Methane leaks erode green credentials of natural gas. *Nature,* 492(12).

Trading Economics, 2022. *Carbon Commodity Price.* [Online] Available at: https://tradingeconomics.com/commodity/carbon.

Trading Economics, 2023. *Naptha.* [Online] Available at: https://tradingeconomics.com/commodity/naphtha

Transport & Environment, 2021. *Used Cooking oil demand likely to double, and EU can't fully ensure sustainability,* s.l.: s.n.

UK Office for National Statistics, 2021. *Dataset. Family spending workbook 1: detailed expenditure and trends,* s.l.: s.n.

UKRI , 2023. *Smart sustainable plastic packaging.* [Online] Available at: https://www.ukri.org/what-we-do/our-main-funds-and-areas-of-support/browse-our-areas-of-investment-and-support/smart-sustainable-plastic-packaging/

UNFCC, 2023. *Background.* [Online] Available at: https://unfccc.int/climate-action/marrakech-partnership/background?gclid=Cj0KCQjwzdOlBhCNARIsAPMwjby3eH_Hj0bPnj8B1INmEKQM-cp6m7fi8sokDLRgEOQyu3GF0iYpcC4aAu0LEALw_wcB

UNFCCC, 2022. *Introduction to Land Use,* s.l.: s.n.

United Nations Department of Economic and Social Affairs, 2021. *Bolsa Floresta (The Forest Conservation Grant Fund).* [Online] Available at: https://sustainabledevelopment.un.org/index.php?page=view&type=99&nr=272&menu=1449

Vivid Economics, 2009. *Advance Market Commitments for low-carbon development: an economic assessment. Final Report.,* s.l.: Department for International Development.

vonHedemann, N. et al., 2020. Forest policy and management approaches for carbon dioxide removal. *Interface Focus,* 10(5).

Wang, P., Deng, X., Zhou, H. & Yu, S., 2019. Estimates of the social cost of carbon: A review based on meta-analysis. *Journal of Cleaner Production,* Volume 209.

Way, R., Ives, M., Mealy, P. & Farmer, D., 2022. Empirically grounded technology forecasts and the energy transition. *Joule,* 6(9), pp. 2057-2082.

Way, R., Mealy, P. & Farmer, D., 2020. *Estimating the costs of energy transition scenarios using probabilistic forecasting methods,* s.l.: Institute of New Economic Thinking Oxford University.

Wei, H. et al., 2019. Renewable bio-jet fuel production for aviation: A review. *Fule,* Volume 254.

Wellenreuther, C., Wolf, A. & Zander, N., 2022. Cost competitiveness of sustainable bioplastic feedstocks – A Monte Carlo analysis for polylactic acid. *Cleaner Engineering and Technology,* 6(1).

White, K., Hardisty, D. & Habib, R., 2019. The Elusive Green Consumer. *Harvard Business Review*, July-August.

White, R. L. & Ryan, R. A., 2015. Long-Term Cultivation of Algae in Open-Raceway Ponds: Lessons from the Field. *Ind. Biotechnol.,,* August, 11(4), pp. 213-220.

World Bank, 2022b. *State and Trends of Carbon Pricing 2022,* Washington D.C: s.n.

World Bank, 2022. *Carbon Pricing Dashboard.* [Online]
Available at: https://carbonpricingdashboard.worldbank.org/

World Bio Market Insights, 2022. *The chemicals companies decarbonising with bio-feedstocks.* [Online]
Available at: https://worldbiomarketinsights.com/the-chemicals-companies-decarbonising-with-bio-feedstocks/

World Business Council on Sustainable Development, 2014. *WBCSD Chemicals - Life Cycle Metrics for Chemical Products,* s.l.: s.n.

World Economic Forum, McKinsey and Company, 2020. *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation,* s.l.: s.n.

Yue, G. H., Ye, B. & Suwanto, A., 2020. The Unavoidable Palm Oil Can Be Sustainable. *International Journal of Oil Palm,* 3(2), p. 29–39.

Yusuff, A. S. et al., 2023. Valorization of used cooking oil as a source of anionic surfactant fatty acid methyl ester sulfonate: process optimization and characterization studies. *Biomass Conversion and Biorefinery,* Volume 13, p. 8903–8914.

Zhang, Q.-Q.et al., 2015. The Rebirth of Waste Cooking Oil to Novel Bio-based Surfactants. *Nature,* Volume 5.

Zheng, J. & Suh, S., 2019. Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change,* p. 374–378.

Zhou, N. et al., 2022. *Deployment support for geological Greenhouse Gas Removals in the UK,* s.l.: s.n.

8 Appendix

Details of bio-based alternatives

Plant and animal fats

Surfactants based on oil and fats date back to 2,500BC, when soap was being used for hygiene and washing clothes, up until the mid-20th century. Since then, more effective and sensitive products have been commercialised to replace soap. Plant or animal fats and oils (i.e. lipids) are composed of triglycerides. They can be sourced from oilseed crops such as palm, rapeseed, sunflowers and tallow from ruminant animals. Triglycerides can undergo conversion into fatty acid alcohols/acids or even bio-naphtha.

Fatty alcohols/acids are linear alcohols/acids which contain more than 12 carbons. They are primarily used to make surfactants (50% of the market) (Biddy, et al., 2016). Palm oil and coconut oil are often raw materials of choice as they contain a large proportion of saturated carbon chains with optimum specificity for surfactant production (C12-C14). In addition, palm oil is a very attractive natural source as the oil is high yielding and easy to grow. Oil palm is a tropical species; therefore, it grows best along a narrow band around the equator. The leading producers are Indonesia and Malaysia, accounting for 84% of the global production. However, in recent years it has been over-exploited and mis-managed; extensive land is cleared for plantations in tropical areas, leading to deforestation and loss of biodiversity. Some life cycle analyses calculate that this oil derivative has a higher environmental impact than crude oil; this is largely dependent on land use change and cultivation practices. If managed properly, oil derived from palm is a highly desirable bio-derived source. In 2018, the global production of palm oil was 71.5 million tonnes, with 27% being used for industrial applications for consumer products (Richie & Roser, 2021). The primary use (68%) is in food products. Substituting palm with coconut oil would require five times more land, putting more land pressure on tropical countries.

The alternatives to palm oil and coconut are soybean, sunflower, rapeseed and olive oil, which can be grown in milder areas of the world. They are rich in fatty acids with a high degree of unsaturation and longer carbon chains, and hence require more steps to make useful intermediates for surfactant production.

Fossil-fuel derived chemical feedstocks come from naphtha, a liquid hydrocarbon mixture usually obtained from the refinement of crude oil, natural gas or coal. From it, an extensive range of platform chemicals can be obtained. It is also possible to produce bio-based naphtha via treatment of lipids. Bio-naphtha can hence access the same traditional chemicals for use in current industries while lowering the carbon footprint.

Waste cooking oils are also an attractive source of non-edible fatty acids. With collection schemes in place for households, industry and restaurants, the resource is cheap and offers significant GHG emission savings as a waste product. After appropriate treatment, it can be used like a regular vegetable oil and turned into bio-naphtha or directly into surfactants (Cárdenas, et al., 2021; Zhang, et al., 2015). In the EU, collection increased by 750,000 metric tons between 2011 and 2019, reaching 1,100,000 metric tons (Statista, 2023). Nevertheless, industries cannot solely rely on this resource, as the volume is limited to how much vegetable oil people and industry consume (Transport & Environment, 2021).

As it stands, the most widely produced bio-based surfactants are Methyl Ester Sulfonates (MES), which have similar and competitive properties to fossil-fuel based LAS. It is procured mostly from palm oil, but other oils as well as used cooking oil have been reported (Yusuff, et al., 2023). This surfactant is tolerant to water hardness, easily biodegrades- and has potential to be used for cold-water washing. In 2020, the production volume reached 0.7 Mt, primarily used for laundry detergents (~70 %) (Markets and Markets, 2021).

Algae

Algae is a fast-growing aquatic plant which converts CO_2 into carbohydrates and oils through photosynthesis. It can be farmed on land unsuitable for agriculture, with low carbon, water and land use impact. Originally envisioned for conversion into biofuels for energy, the applications are now primarily for food, nutrition and personal care. Algae can produce useful lipids, surfactants and polymers (Mathimani & Pugazhendhi, 2019; Khalil, et al., 2017; Laurens, et al., 2017; Foley, et al., 2011). It has been possible to genetically engineer algae to maximise oil yield and change the oil composition. Similar to plant oils/fats, the algal oil can be converted into bio-naphtha and fatty alcohol/acid. Challenges exist associated with efficient growth and scale up of microalgae production (Barsanti & Gualtieri, 2018).

Lignocellulosic biomass

Lignocellulosic biomass is agricultural waste (straw, husk and stalks) and non-edible plants (wood) rich in lignin, hemicellulose and cellulose, which through a pre-treatment process can be converted into sugars. Sugars are important bio-based intermediate platform molecules for the chemical industry. Dedicated sugar crops such as sugar beet require fertile land, but the product is more readily isolated.

Microbial fermentation of sugars is the most common method of obtaining chemical building blocks from bio-derived feedstocks. Biological conversions can be tailored to obtain specific molecules, depending on the fungi, yeast or bacteria used. A study showed that significant greenhouse gas savings can be made if platform chemicals are derived from the fermentation of biomass instead of fossil fuels. For chemicals of interest for the surfactant industry, the GHG savings for benzene, ethylene oxide and ethylene are 3.6kgCO_2eq/kg product, 2.25kgCO_2eq/kg product and 2.25kgCO_2eq/kg product respectively, assuming a 50% conversion of biomass feedstock to product (Huang, et al., 2021).

Sugar-derived surfactants are also made from the chemical coupling of a sugar and lipid, termed saccharide-fatty acid esters. These surfactants are already produced at scale, and the market is expected to grow with a compound annual growth rate of 6% (Markets and Markets, 2021). Saccharide-fatty acid esters are an important class of surfactants, as they are biodegradable, biocompatible and non-toxic.

Microbial surfactants are also gaining industrial attention as bio-surfactants, the most common being rhamnolipids and glycolipids. They look similar to the sugar-derived molecules mentioned above, although they are produced by microorganisms such as bacteria and yeast by providing them with sugars and fatty acids. It is a desirable process as fermentation conditions are mild, and various fatty acid substrates can be used, including sunflower and rape seed oil. However, costs are still high: the downstream processing, including purification of the lipid, accounts for 70-80% of the entire production cost (Randhawa & Rahman, 2014). More selective and productive bacteria strains are required and could be achieved by genetic engineering.

Carbon dioxide

Using CO_2 emissions as a chemical feedstock is a prominent mitigation strategy for climate change and reduces the need for fossil fuels. Carbon dioxide can be converted electrochemically or by fermentation into ethylene gas, which is a key intermediate chemical in surfactant synthesis (Li, et al., 2022). Ethylene oxide can be obtained from ethylene gas, which is then used to make surfactants. Carbon dioxide can also be used as a co-monomer in polymer production. The economic bottleneck is carbon capture technology, which is still in its infancy.

There are many reported bio-based surfactants in the literature, some of which are commercialised. Nearly all can be traced to the same biological origins, typically a sugar, such as glucose, and triglycerides from oilseed crops, converted by traditional chemistry or microbial fermentation. Currently, in the EU, 84% of bio-based surfactants are derived from vegetable oil and 16% from sugars (European Commission, 2019). Despite the existence of many bio-based surfactants, they are not widely used due to the costs and limited accessible feedstock supply. Improved transformations of biomass into sugar-based feedstocks, exploitation of by-products and residues as feedstocks, and genetic engineering of algae and high-yielding crops are examples of how the economics and scope of bio-based surfactants can overcome current barriers and warrant widespread use of biomass in this sector.

Palm oil production

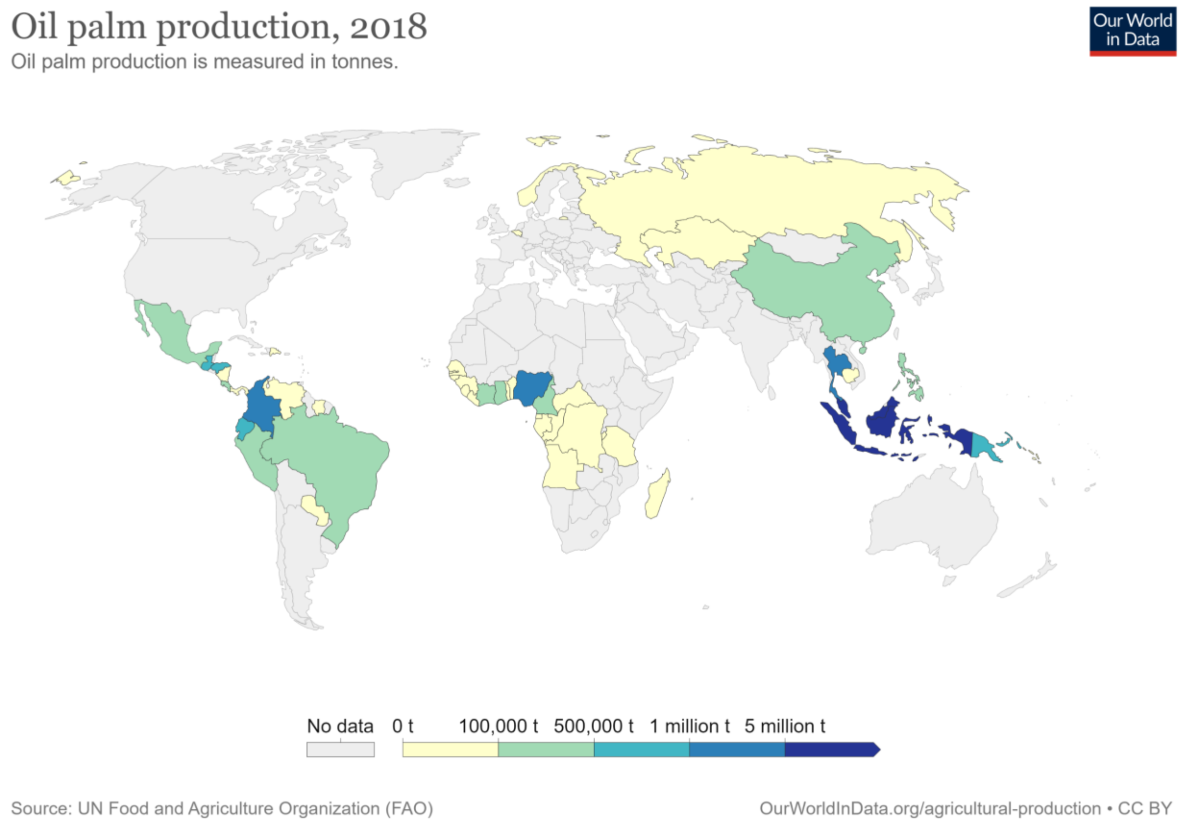


Figure: 13 Oil palm production in 2018. Graphic from Our World in Data (Richie & Roser, 2021)

Assumptions on learning curves

Notes on learning curve assumptions: The predicted 2050 demand for bio-naphtha is calculated by extrapolating the data suggesting the demand will grow by 1.7 times by 2030 (Trading Economics, 2023). The demand for bio-ethanol is predicted such that demand doubles to align with the IEA Net Zero by 2050 Scenario (International Energy Agency (IEA), 2021). The predicted demand for bio-kerosene is calculated using the forecast demand for the use of bio-kerosene by the aviation industry only, which is predicted to be a two to three-fold increase on current demand by 2050 (low-end demand) to a six-times increase on current demand (high-end demand, which are the predicted limits of supply) (Dray, et al., 2022). Bio-naphtha is used to produce bio-based LAB, bio-ethanol is used in the production of bio-based ethylene oxide derivatives and bio-kerosene can be transformed into bio-derived LAB and LAS. This assumes that supply can keep up with demand.