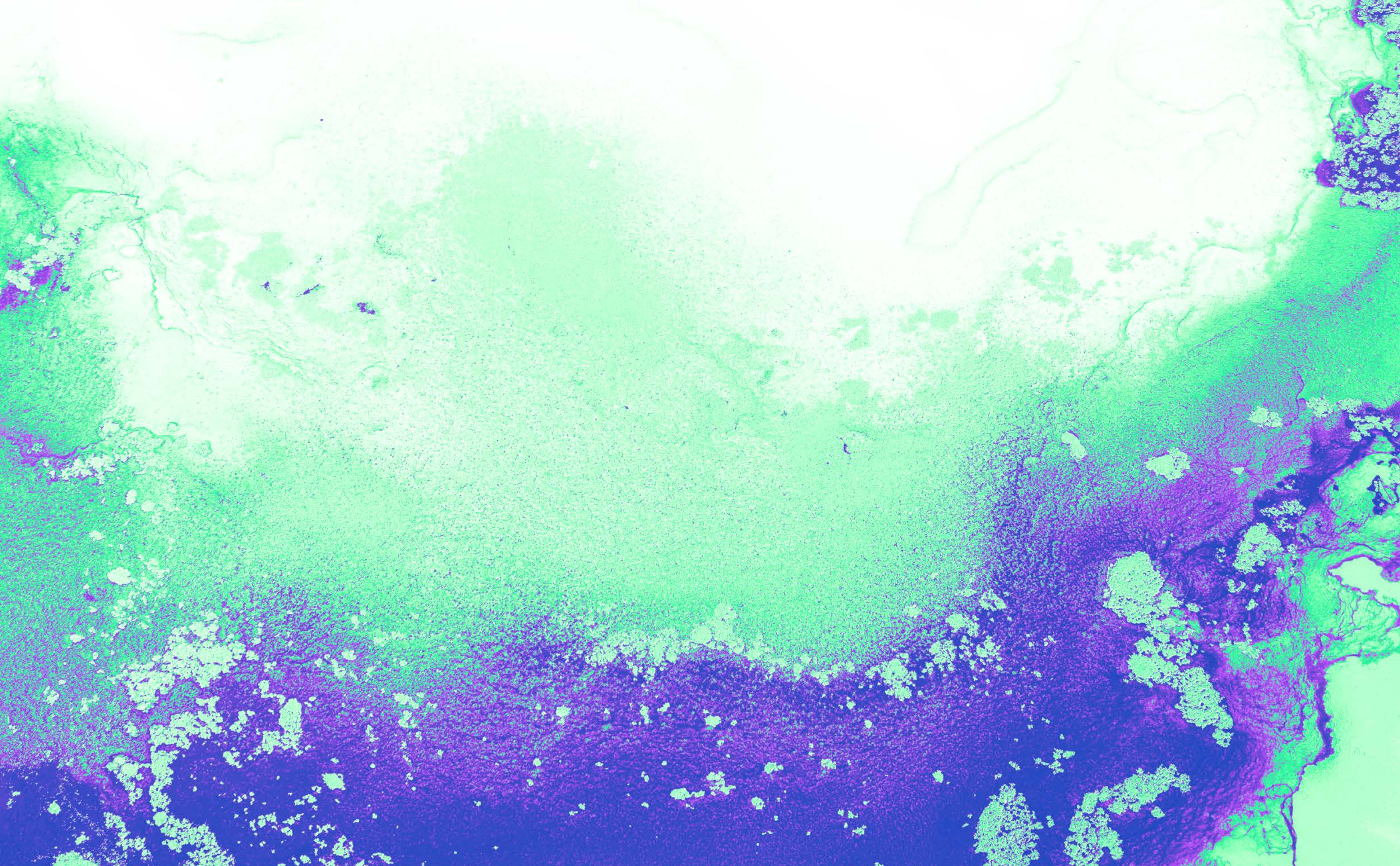
CENTER FOR GLOBAL COMMONS

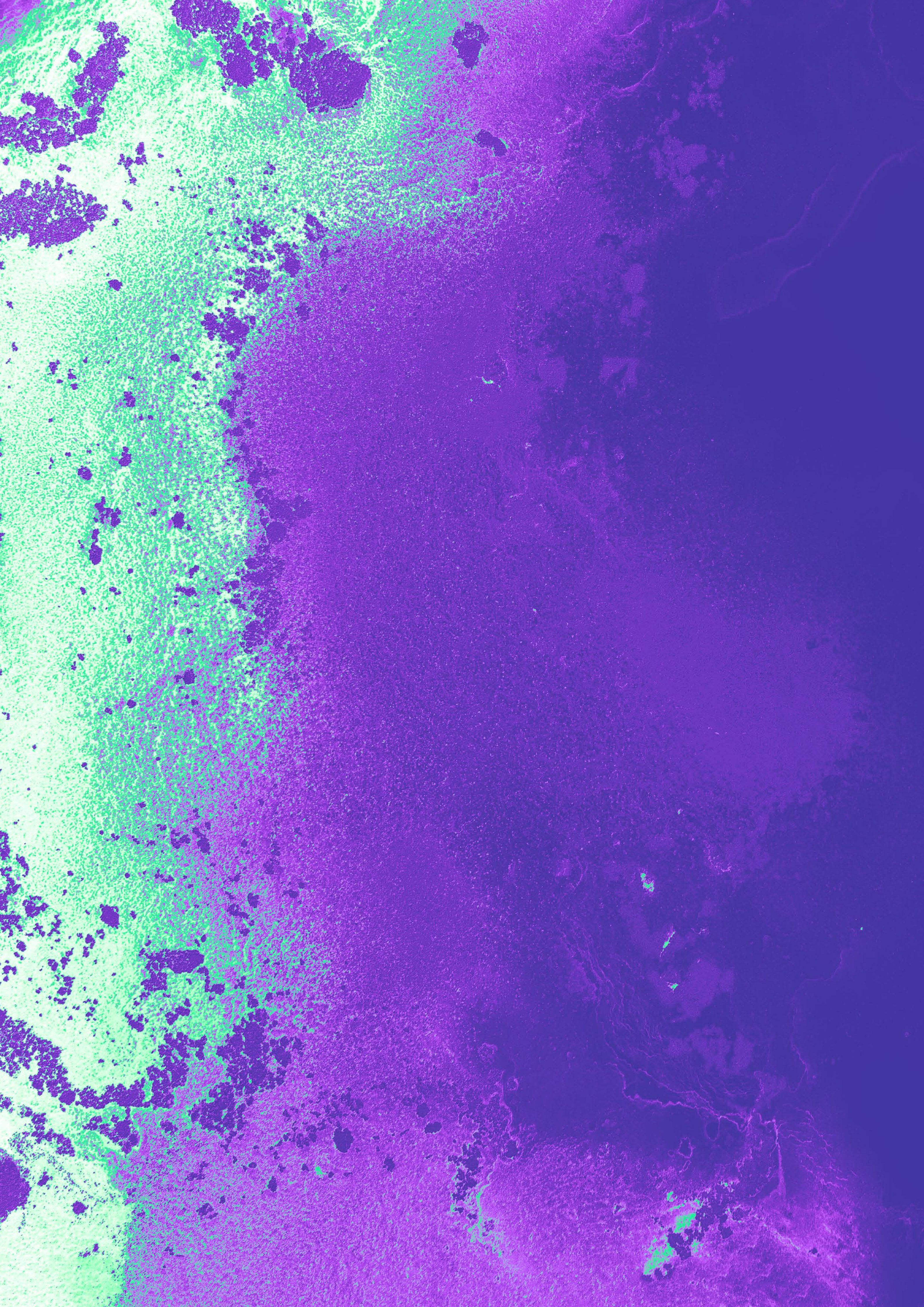
SYSTEMIQ

September 2022

Planet Positive Chemicals

Pathways for the chemical industry to enable a sustainable global economy





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Preface – the reasons for writing this report

Climate action in the global chemical industry is lagging compared to other sectors. As of August 2022, only seventeen industry players had committed to targets in line with a 1.5 degrees future as part of the Science Based Targets initiative (SBTi). That represents just 17% of the companies in the sector that have made commitments; less than half the global cross-sector average of 35%. This report by the Center for Global Commons, University of Tokyo & SYSTEMIQ aims to create clarity aroundhow the global chemical industry can transition to operate within planetary boundaries. This, in turn, seeks to catalyse action and clarify the industry's role in safeguarding the global commons.[1]

Three main uncertainties are delaying this transition: uncertainty around demand for net zero chemicals; uncertainty around the most suitable technology to produce net zero chemicals; and uncertainty around the best pathway to achieve overall net zero Scope 1-3[2] emissions. To address these uncertainties, the report defines possible pathways to net zero Scope 1-3 emissions by 2050 for the global chemicals system and outlines its future role in helping other sectors of the global economy reach net zero. It is unique in scope as it addresses the bulk of emissions in the sector at a global level, analyses how both demand and supply side interventions can be used to abate them and seeks to do so within planetary boundaries.

A detailed quantitative analysis[3] was conducted by the core project team in collaboration with a panel of international experts. The resulting report is not only about whether the chemicals system can reach net zero Scope 1-3 but **how**. The analysis suggests that the chemicals value chain has multiple pathways to reach net zero if action is taken soon enough, but each of these pathways present varying degrees of risk and opportunity. Therefore, the global chemicals system requires a more nuanced set of metrics by which to determine success that consider:

How fast net zero is achieved. This is critical for determining the use of the global carbon budget as, without rapid abatement, the current global annual emissions rate of 59 Gt CO_{2eq} per year will exhaust the budget for 1.5 degrees of global warming shortly before 2030 and for 2 degrees by 2040.[4] That means the speed of abatement and cumulative emissions to 2050 per pathway is a key determinant of success.

How reliably the chemicals system can transition to a planet positive model.[5] Even if many of the technologies considered in this report have already reached commercial maturity, it remains uncertain whether they will attain the massive scale required to abate the chemicals value chain over the 30-year timeframe of the analysis. Some technologies may fail to scale and some feedstocks may become scarcer than anticipated. This makes it essential to de-risk the transition as far as possible by avoiding dependence on a limited number of, or less mature, technologies.

How strategically the global chemicals system can position itself in a way that enables the operation of a net zero global economy. The chosen combination of alternative feedstocks, renewable energy sources, and approaches to abating residual emissions represents different long-term strategic positions for the system after 2050. Selecting different pathways to net zero e.g. most economic or fastest abatement, will also impact its continued relevance and future growth prospects in a net zero global economy.

This report focuses on three scenarios. One scenario was selected to illustrate the challenges and risks of achieving net zero with unimpeded demand side growth and only supply side interventions. The other two scenarios act in tandem to create a strategic choice between the most economic and fastest abatement approaches to net zero, within which executives must chart their organization's transition strategy. These scenarios are not forecasts but use the best available data to describe what needs to happen to bring about net zero through different approaches. As such, the report aims to be a starting point for key decision makers to align around a common set of facts, challenges and potential solutions by shedding light on uncertainties around future demand and technology for net zero chemicals.

The biggest risk of all is inaction. This is true for the chemical industry, but even more so for the entirety of society which depends on its future. The perfect economic, policy and technology conditions are unlikely to present themselves imminently. Thus, while this report aims to provide the best possible quantified view of the future, leadership through uncertain times will be the deciding factor in bringing about a positive outcome for the global chemical system, for society, and for the planet. We hope that through this work we inspire leadership and action to unlock capital, drive innovation, enable policy making and build the chemical system the planet needs.

Naoko Ishii
Executive Vice President and Professor, University of Tokyo
Director, Center for Global Commons

Martin Stuchtey
SYSTEMIQ Founder & Project Director

1. The five Global Commons Domains are: Climate System, Ozone Layer, Oceans, Land Biosphere, Ice Sheets & Glaciers
2. Greenhouse gas (GHG) emissions are categorized into three groups or "Scopes" by the Greenhouse Gas Protocol. Scope 1 covers direct emissions from sources owned or controlled by the company. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating and cooling. Scope 3 covers all other indirect emissions that occur in a company's value chain.
3. Using a python coded Agent Based model
4. Pathway C1. Current global emissions are ~60Gt, meaning this will be consumed by mid-2028 at current rates.
5. Planet centric refers to operating within nine planetary boundaries: climate change, novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biochemical flows, freshwater use, land-system change, biosphere integrity.

Endorsements

I applaud the breadth and depth of this unprecedented report that quantitatively analyzed pathways for the chemical industry to reach net zero not only in scope 1 & 2, but also scope 3 upstream and downstream. While it contributes to clarifying uncertainties that have impeded the chemical industry's progress in net zero, it is also a warning that has made us renew our resolve in sustainability. We are keen to collaborate with a broad spectrum of partners on this journey toward the new roles of the chemical industry. I am sure this report will be widely acknowledged and trigger many such collaborations in the industry to accelerate the transition this report calls for - we are proud to have sponsored this groundbreaking research.

– **Nobuo Fukuda**, Representative Corporate Executive Officer,
Executive Vice President, Mitsubishi Chemical Group Corporation

Healthy and resilient biophysical systems on Earth — our Global Commons — are at the heart of our health, security, and prosperity and we must work together to manage them responsibly. Unfortunately, they are subject to excessive human pressure, threatening the stability of the entire planet. In addition to climate impact, the chemicals industry in its current state has an adverse impact on a number of the planetary boundaries that regulate the liveability on earth. The release of novel entities, including plastic pollution, has already exceeded the estimated safe boundary. Therefore, concerted steps need to be taken to rapidly mitigate the chemical industry's impacts and achieve net zero pollution. The Planet Positive Chemicals report provides an unprecedented and detailed roadmap for the industry and its value chain. It demonstrates that the necessary transformation is possible and outlines the need for stakeholders across the value chain to act now to ensure that the innovation and investments required are galvanized to tackle this existential challenge.

– **Professor Johan Rockström**, Stockholm Resilience Centre,
Potsdam Institute for Climate Impact Research

The chemicals industry is at a pivotal moment: without change it could lose its social license to operate. At the same time, the challenges are immense, and it is arguably the hardest sector to abate. The Planet Positive Chemicals sets out tangible pathways for the sector to become the enabler of a sustainable economy and develop a planet-positive system. The sector is in dire need of transformational leadership to drive the required changes and the report marks the beginning of an urgent and business-critical conversation for the industry and its value chain.

– **Paul Polman**, Co-founder and Chair IMAGINE, Member of the Board of SYSTEMIQ Ltd

The Planet Positive Chemicals report recognises clearly that the chemical industry lies at the heart of the global economy, and therefore it holds great potential to spark change across multiple sectors. By 2050, the sector can become a carbon-sink, using CO_2 from the air to produce chemicals, and can be a vehicle for growth in the global south. In order to make this a reality however, the time to act is now. Effective regulations, policies, investment and coordination are required to realize these opportunities and transform this sector into a force for good for sustainable development, climate and the environment.

– **Nick Stern**, Professor of Economics, Chair of the Grantham Research Institute on Climate Change and the Environment, London School of Economics, Chair of the Board of SYSTEMIQ Ltd

Chemicals are at the core of a successful transition to a net zero economy: and the pace of chemicals decarbonisation could make or break our ability to reach essential climate targets. The Planet Positive Chemicals report sets out the challenge and makes clear that both supply and demand side actions will be critical to ensure that the sector moves away from dependence on fossil fuels. Achieving this transition is clearly technically and economically feasible but as the report emphasises, will require collaboration across the industry value chain - from governments to financiers and companies both within and outside the industry - if fast enough progress is to be delivered.

– **Lord Adair Turner**, Chair, Energy Transitions Commission

We need realistic and immediate action from industry on the climate goals agreed at an international level. The road to a sustainable global chemicals system will not be an easy one, but the Planet Positive Chemicals report is a major contribution to begin this journey. I think it will become a global reference document for at least the next decade and the 10 recommendations will help focus action on what otherwise could be seen as an impossible task. From the creation of 29 million additional jobs, to the increased use of chemicals to drive a sustainable global economy, we want to see ambitious companies grabbing these opportunities and transforming the way we see the chemicals sector.

– **Chad Holliday**, co-Chair, Mission Possible Partnership

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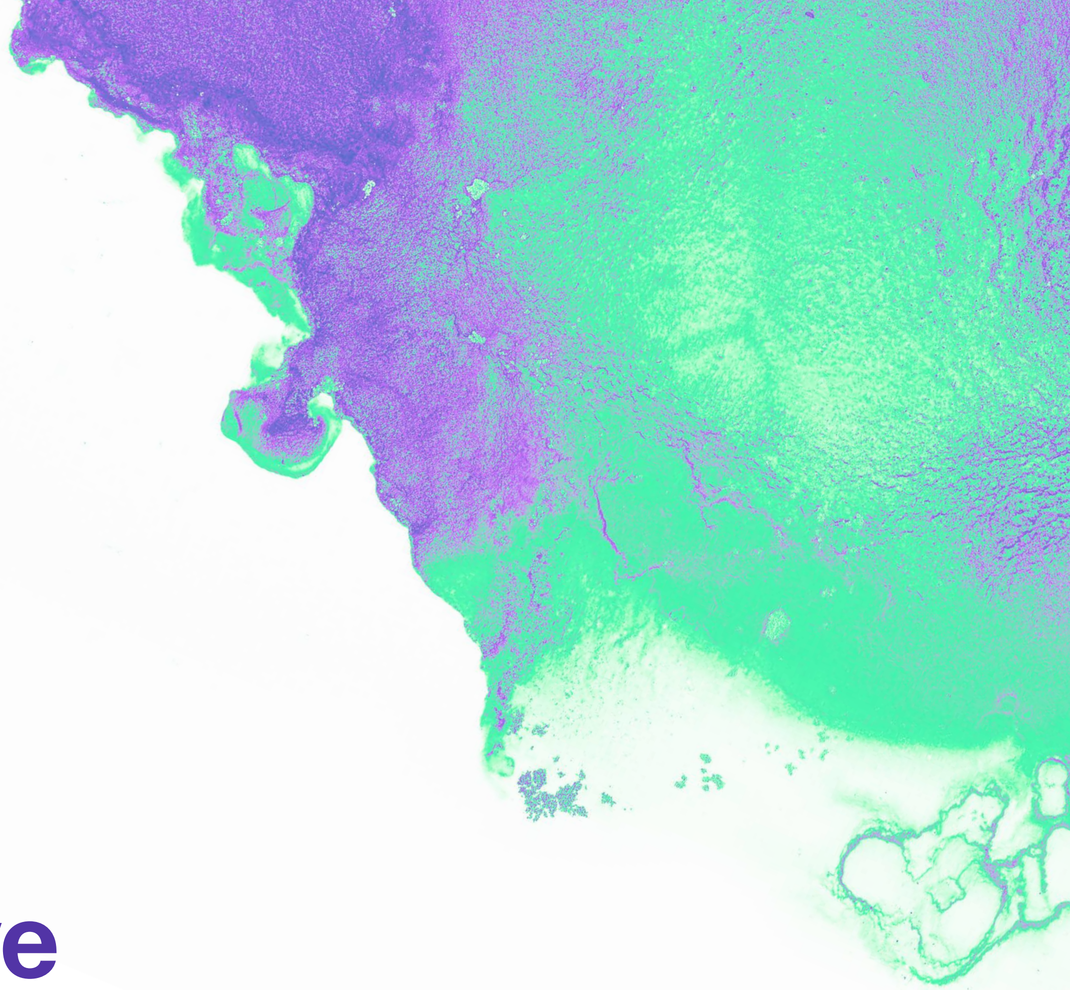


Executive summary

The chemical industry is a major building block of our global economy, providing 15 million jobs worldwide and 4% of global GDP.

The global chemical industry generates $4.7 trillion in revenues annually, representing ~4% of global GDP, and directly employs over 15 million people.[1,2] The products from the chemical industry underpin our way of life, health and prosperity and our transition to a net-zero-emissions economy. They are present in the healthcare, packaging, agriculture, textiles, automotive, construction and many other systems, with 96% of manufactured goods depending on their use.[3] As a result, the production of basic chemical intermediates, such as those in scope for this study (ammonia, methanol, ethylene, propylene, butadiene, benzene, toluene, xylene), directly impacts almost every part of the global economy. Therefore, unless the chemical system transitions to a sustainable model of operation, it makes it challenging for other parts of the global economy using chemical products to be truly sustainable.

By embracing a "planet positive" circular and net-zero-emissions transition, the chemical system could grow 2.5x by 2050 and enable transitions to net-zero-emissions in other sectors, whilst keeping its own Scope 1-3 greenhouse gas emissions in line with the Paris Climate Agreement.

This report is grounded in a detailed economic model that outlines future pathways for the chemical system from 2020-2050, along with the environmental impacts of each of these pathways. The analysis highlights three key opportunities:

1. The global transition to a circular and net-zero-emissions economy is an opportunity for the chemical system to grow annual production volumes 2.5 times annual production volume by 2050, enable transitions to net-zero-emissions in other systems such as shipping and energy storage and create 29 million new jobs globally, of which 11 million would be direct new chemical industry jobs;

2. Even with this 2.5x growth trajectory by 2050, Scope 1-3 greenhouse gas emissions from the system could realistically align with the Paris Climate Agreement; and

3. With new manufacturing approaches based on bio-based feedstock and direct air captured carbon dioxide, there is a technically feasible pathway for the non-ammonia chemical system to become a "carbon sink" that absorbs 500 million tonnes (net) of CO_2 per year by 2050.

This growth opportunity is not evenly distributed across the chemical system – it is particularly significant for ammonia and methanol-based chemical pathways. The opportunity relies on urgent and ambitious transformations in chemical manufacturing alongside aggressive demand-side circular economy approaches in the downstream value chains using chemicals in materials and products. These transformations, action plans and investment needs are outlined in detail in this report.

The chemical industry today has a significant carbon footprint and is lagging other industries in the transition to net-zero-emissions. The current trajectory of the system is aligned with 4°C of global warming.

The chemical industry is currently lagging in its commitments to science-based targets to transition to net-zero-emissions and is expected to be the last system to achieve the key tipping points needed to mainstream emission reduction technologies.[6]

The production of basic chemical intermediates in-scope for this report has a Scope 1, 2 & 3 emissions of 2.3 Gt CO_{2eq}, representing just under 4% of the 59 Gt global annual emissions and an estimated 72% of all chemical system emissions. Within the 2.3 Gt, Scope 3 represents the majority at 64% (1.5 Gt CO_{2eq}), while Scope 1&2 only represent 36% (0.8 Gt CO_{2eq}). The magnitude of Scope 3 in the chemical system is driven by its dependence on fossil, leading to high upstream scope 3 emissions from oil and gas extraction (0.5 Gt CO_{2eq}), as well as carbon-dense products such as plastics and urea resulting in high associated downstream Scope 3 emissions (1.0 Gt CO_{2eq}). It is for this reason that focusing on Scope 3 in the chemical system transition to net zero is so essential.

Based on the most recent IPCC carbon budgets and the analysis carried out for this report, the chemical system's combined production and Scope 3 emissions mean that if this one industry continues to scale up without reducing its emissions, it would be responsible for 24-38% of the total 2020-2050 global carbon emissions budget for a 1.5°C future. This "business as usual" scenario would align the system with a 4°C global warming scenario by 2050.[7]

The chemical system is already transgressing other planetary boundaries. Environmental pollution and potential unintended consequences from climate solutions (such as land use change) must be avoided.

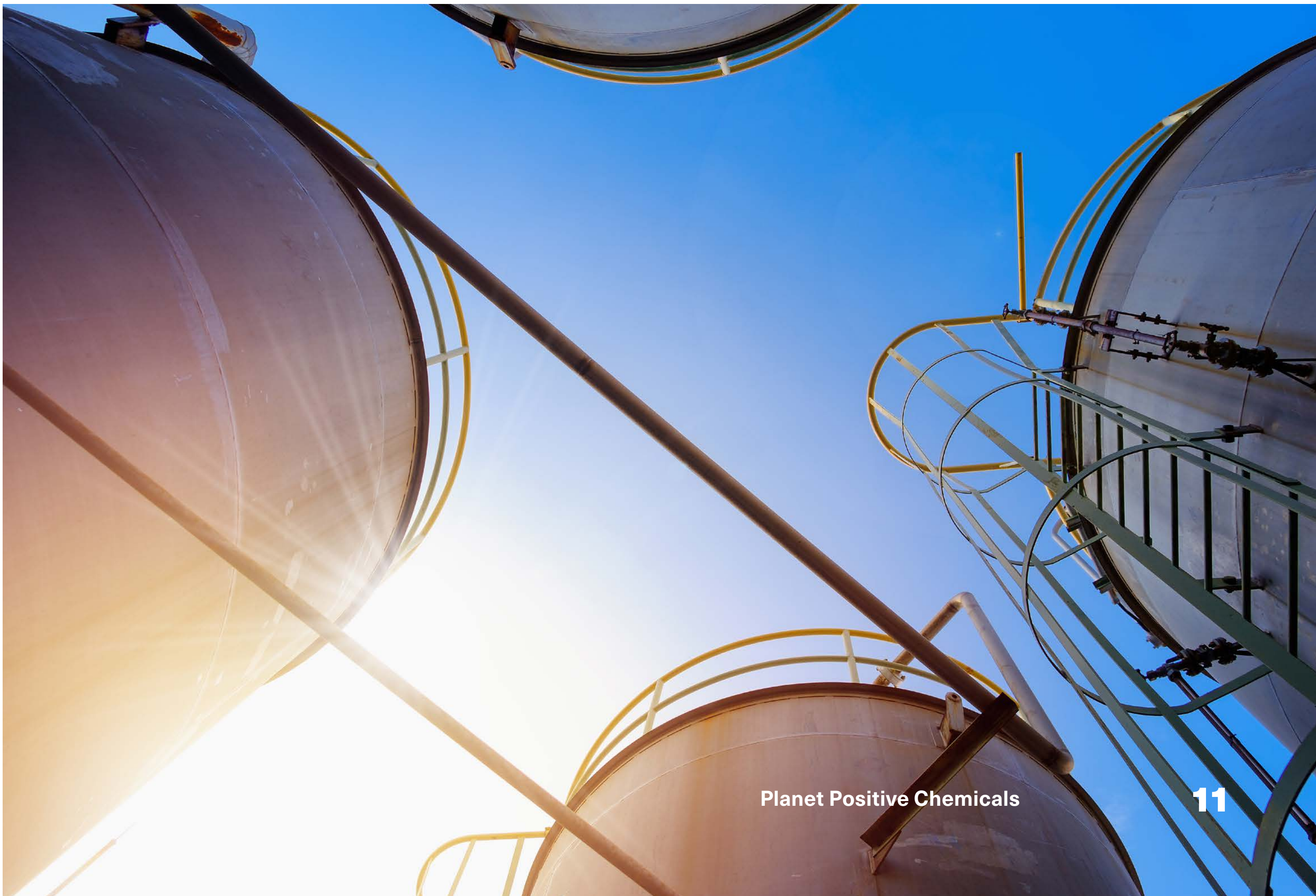
Beyond climate impacts, the leakage of chemicals and downstream products (e.g. plastics and fertilisers) into the environment has a range of other adverse impacts on the nine essential planetary processes that regulate the stability and resilience of the Earth system. The tolerable limits of human impact on these systems are referred to as "planetary boundaries",[8] and there has been increasing awareness that the chemical system is breaching many of these boundaries.

The planetary boundaries for the release of novel entities, including chemical pollution and specifically plastics, as well as biogeochemical flows (e.g. nitrogen flows contained in ammonia-based fertilizer run off), into the biosphere have both already been exceeded.[4,5] Furthermore, care must be taken to avoid an uncontrolled net zero transition, which could have severe impacts on biodiversity and land use if the use of biomass as feedstock is not regulated and sustainable, particularly in light of competition for sustainably produced feedstocks. Therefore, the current operating model of the chemical system represents a multi-pronged threat to the planet and society. Mitigating these impacts requires that the industry take a broader approach than solely abating climate impacts.

6. Analysis conducted on SBTi commitments across the sector placed chemicals commitments at 17% vs a 35% cross-sectoral average. For "The Paris Effect: COP 26 Edition" SYSTEMIQ conducted a balanced scorecard survey of all sectors to evaluate readiness to mainstream abatement technologies, among which the chemicals system was the found to be the slowest.

7. IPCC AR6 III below 4 degree is 4,220 Gt and above 4 degrees is 5,600 Gt. Based on an allocation of chemicals (2.0%), of which only 72% is in scope, and shipping (1.6%) of global emission, total emissions budgets would be 128-170 Gt respectively in a below and above 4-degree scenario. BAU-BAU scenario is expected to generate 146 Gt of CO_{2eq} emissions during the period 2020-2050.

8. The planetary boundaries are: i) chemical pollution and novel entities, ii) climate change, iii) atmospheric aerosol loading, iv) ocean acidification, v) freshwater use, vi) land system change, vii) biosphere integrity, viii) biogeochemical flows, and ix) stratospheric ozone depletion.



Demand reduction through circular economy approaches would save over $1 trillion in transition costs from 2020-2050 (~30% of total) and reduce pressure on planetary boundaries.

Demand-side circular economy approaches (reduction, reuse, substitution and recycling) can reduce the absolute amount of future chemical production and therefore the transition investment needed over the next decades by over $1 trillion (almost 30% of total incremental investment required) between 2020 and 2050. This requires coordinated and ambitious action from the chemical system and the downstream value chains using chemicals in materials, fertilisers and products.

Today, the global chemical value chain is predominantly linear,[9] with low reuse and recycling rates and significant waste generation. For example, up to 70% of nitrogen input in fertilizer is not taken up by crops and only 9-14% of plastic ever created has been recycled.[6-8]

Ambitious demand-side circular economy approaches reduce the reliance on new technology developments that are still scaling up (e.g. new bio-based or waste-derived feedstocks or carbon capture storage and utilization (CCUS)). They also reduce the growth of production, waste and pollution from the system and its associated downstream products, directly reducing planetary boundary impacts.

Applying circular economy approaches to this linear value chain can reduce total demand in the system by 23-31% (372-526 Mt) versus business-as-usual and net zero growth without sacrificing any functional benefit or utility. This is particularly relevant for non-ammonia demand resulting in 33-51% reduction. Of total system reduction, elimination represents 41% of total circularity impact, reuse 19%, substitution 14%, and recycling[10] 26%. The chemical industry must embrace this demand reduction from downstream customers, while pursuing a broad range of direct and indirect benefits circularity brings about, including; social (e.g., net job creation, thriving communities), environmental (e.g., biodiversity, soil, and natural ecosystem preservation) and climate (reduced greenhouse gas emissions).[9-12]

9. The chemical value chain today converts fossil feedstocks to chemical products which are rarely returned into the value chain via reuse or material/chemical/carbon recycling.
10. Mechanical recycling, dissolution and depolymerisation only.

The chemical system transition requires a supply-side shift away from fossil-based inputs for feedstocks and energy, towards inputs that are based on alternative forms of carbon, green hydrogen, and renewable energy. There is no silver bullet technology solution for the transition.

Decoupling from fossil: Almost the entire carbon feedstock (713 Mt carbon) used in the system is from virgin fossil sources. Fossil faces multiple uncertainties in its future, including extraction abatement challenges, potential price volatility, and unacceptable environmental impacts. Continued unilateral dependence on fossil for fuel and feedstock is a risky strategy. Furthermore, incineration and landfill are not attractive end-of-life options for non-ammonia chemicals today and carbon capture and storage (CCS) has yet to scale. Therefore, the continued extraction of virgin carbon augments the challenge of abating emissions and achieving true net zero Scope 1-3 emissions.

Switching to renewable feedstocks: There is an imperative to switch to alternative feedstocks for basic chemical intermediates production. Key alternative carbon feedstocks are biogenic and direct air captured CO_2 (atmospheric carbon), as well as point source CO_2 and solid waste (carbon as an economic by-product). By 2050, as much as 82%[11] of carbon feedstock can come from alternative sources, leaving only 77 Mt of virgin fossil carbon in the system, an 89% reduction from today. In addition, up to 234 Mt p.a. of green hydrogen may also be required, predominantly (99%) as feedstock for ammonia and methanol to enable use of alternative carbon feedstocks for chemical production.

Switching energy source: using renewable energy rather than fossil fuel to produce heat can avoid process emissions. Up to 12,000 TWh of renewable energy capacity will be required in a net zero system, although this is predominantly needed to produce green hydrogen feedstock. Of the remainder, 4% is used for electric steam crackers and other production processes, 3% is used for carbon capture, and less than 1% is used to make green hydrogen for steam cracker heat.

Carbon capture and storage: some process emissions and end-of-life disposal emissions are unavoidable and thus CCS is likely to be required as a means of abating residual emissions that cannot be addressed via switching feedstocks or energy sources. Up to 640 Mt p.a. of CCS will need by 2050 to abate the system.

11. Multiple scenarios have been modelled. The most pertinent values have been selected to illuminate the executive summary to avoid complexity. For detail around values per scenario, the main report should be consulted.

Ammonia (5x growth by 2050) and methanol (4x growth by 2050) will be central to the chemical system transition

Ammonia production is the largest contributor to Scope 1&2 emissions (0.36 Gt of CO_{2eq} – 44%) by the basic chemical intermediates industry today. Continued growth in fertilizer demand due to population growth and ammonia's use in new applications, such as power storage and fuel for net-zero shipping, mean it would experience a surge in demand from 185 Mt in 2020 to more than 1,000 Mt by 2050 (of which three-quarters is new net zero applications). This would be the largest demand growth of any basic chemical intermediate by 2050, representing as much as 32% of the 500 Mt p.a. of projected global green hydrogen demand in a net-zero economy by 2050.[13,12] This is why transforming both existing and new production capacity to renewable (non-fossil) energy and feedstocks is critical to enable a sustainable future.

Methanol also has a bright future because it can be produced from non-fossil carbon and green hydrogen feedstocks, and it can be manufactured into a wide range of downstream chemicals, including olefins and aromatics. Green methanol can therefore be used to displace fossil feedstocks (i.e., naphtha), thus avoiding upstream production Scope 3 emissions. It can also enable more efficient recycling of waste carbon within the chemical system (e.g. via capture of CO_2 from industrial point-source emissions or waste gasification). As a result, methanol is expected to experience 330% growth from 102 Mt in 2020 to ~440 Mt in 2050.

The system transformation requires capital investments of around $100 billion per year over the next three decades, but will only have an estimated ~1% impact on costs of typical products that are made from chemicals.

Achieving net zero Scope 1-3 emissions will require ~$100 billion per year in capex deployment between 2020-2050, 2.7X larger than capital requirements for business as usual growth of the system. Firstly, adequate large-scale capital must be allocated for deployment into the system transition. Secondly, a network of financial intermediaries, infrastructure, products and expertise to deploy the capital must be developed. Thirdly, a pipeline of high-quality joint venture transformation projects are needed to create a clear track record for mainstreaming circular and low-emissions technologies. Achieving this will require government policy support as well as shifting perceptions of value, business models, technology risk, rates of return, and capex profiles across the chemical value chain.

Despite the scale and holistic nature of the infrastructure transformation, the impact of the increased manufacturing cost to end user products is limited to low single digit percentages, for example soft drinks 0.7-3.2%, cars 1.0-1.1% and food items 0.6-0.9%.

12. Projections vary considerably. In this instance 500Mt global production by 2050 has been taken.

The system transformation requires coordinated action from the chemical industry and companies in its upstream and downstream value chains, the energy system, innovators and governments.

Implications for the chemical industry: Operationally delivering the transition will require the chemical industry to drive major shifts in the technologies and locations of production. Existing brownfield production capacity such as steam crackers and steam methane reformers will need to undergo retrofitting with low-emissions technologies such as green hydrogen firing, electrification or CCS. The shift will also result in the retirement of some refinery assets such as catalytic reformers for the production of aromatics.

Production infrastructure will need to shift towards low-emissions orientated technologies of electrolysis, methanol-to-olefin and aromatics, bioethanol dehydration, gasification and carbon capture and utilization. While legacy production assets are likely to remain in situ in industrial clusters to benefit from downstream integrations and synergies, greenfield capacity installation will gravitate towards regions with abundant, affordable renewable energy (for green hydrogen production) and also renewable carbon sources (for methanol production). This will result in the restructuring of global chemical value chains and trade patterns. End-of-life emissions must be abated, thus a network of carbon capture, utilization and storage (CCUS) capabilities must be applied across the global incinerator portfolio.

Looking outwards, the new operating model of a net zero chemical industry will require far deeper engagement with adjacent segments of the economy such as renewable energy providers, biogenic feedstock producers, waste managers and end-of-life disposal i.e. incinerator owners. As a result, players will require lateral and vertical integration through a framework of “build, buy or partner” with these systems, offering new synergies and revenue opportunities. Equally, looking inwards to the value chain, engagement in circular economy models (e.g., through Chemicals-as-a-Service models), may present an opportunity to decouple from the volume-based model today and derive revenue from more efficient, value-adding, service-focused applications of chemicals.

Implications for the chemical value chain: Driving rapid change will require a coordination of industries moving in parallel and new models of system governance to accelerate the transition. This may include establishing a first movers demand coalition comprising converters, brands, retailers, shipping companies and fertilizer companies to guarantee a market for low-emissions chemicals through offtake agreements. Such a coalition can also demand mandatory recycled content regulations and call for more stringent end-of-life recycling and CO_2 emission reductions as part of extended producer responsibility obligations. Brands and retailers will be instrumental in driving the implementation of circular economy approaches for plastics such as elimination and reuse models. Downstream collection and sorting of plastics must be optimized, mechanical and chemical recycling infrastructure must be expanded, and end-of-life incineration facilities must be upgraded to include carbon dioxide capture. Finally, a global charter of transition principles would help the broad range of stakeholders involved in the transition align pre-competitive approaches to shifting the system to operate within planetary boundaries.

Implications for the energy system: The energy system will need to build out renewable energy sources to produce up to 12,000 TWh for the chemical system by 2050, representing as much as 13% of global generation. This will require establishing additional generation capacity in locations with affordable, abundant renewable energy potentially presenting a major economic development opportunity in the Global South. The majority of energy will be for green hydrogen feedstock production and represent almost 50% of total global green hydrogen demand in 2050. Therefore, the chemical (and particularly the ammonia) industry will be pivotal in driving the scale-up of electrolyser production for the green hydrogen industry.

Implications for innovators: Ensuring this transformation is possible at an affordable rate and with feasible economics will require the innovation community to fast-track critical technology innovations to commercial scale, specifically methanol-to-aromatics technologies, carbon capture technologies, and electrolysers. The innovation and innovation finance community should seek to overcome the key energy intensity, material efficiency, and technical challenges in these spaces to reduce cost and scale of the infrastructure buildout needed. Breakthrough technologies capable of disrupting the industry (e.g., biotechnology, electrochemistry) should be supported generously via R&D funding and scale-up programs.

Implications for government policy makers: Policy changes are required to enable the shift to a circular and net-zero-emissions chemical system. An enabling policy framework could help to cushion economic shocks, incentivize preferred actions and disincentivize harmful actions. This could be in the form of a carbon tax[13] or incentives to put the businesses cases for low-emissions technologies on-par or better than the traditional technologies. Ultimately, either the public and/or value chain shareholders must pay the additional costs of low-emissions chemicals. National governments are the ultimate arbiter of where these costs must be borne most heavily, and each government must determine its policy based on its perspective of how society should pay the dividend back to nature and eliminate market externalities over time. Lastly, scaling adoption of circularity models upstream and downstream is essential and will likely benefit from integration with industrial decarbonization policy to ensure circularity receives due precedence.

13. Preferred over emissions trading approaches.

Urgent and coordinated action is required to change the trajectory of the industry and reduce risks for corporations, investors and society at large.

There is no time to lose. Long lifetimes for chemical industry facilities mean that investment decisions in the next few years will determine the trajectory of the industry during the critical decades out to 2050. Recent extreme weather events caused by climate change are highlighting the risks to corporations, investors and society at large, meaning that investments in fossil-fuel dependent facilities now carry well-documented stranded asset risks. “Wait and see” is no longer a viable strategy for corporations and investors in this industry.

This report illustrates viable pathways to a “planet positive” chemical system that will allow the chemical industry to thrive and grow. A number of companies are already showing the way. If industry can mainstream and accelerate this transition, it has the prospect of being every bit as central to the progressive story of the 21st century as it has been to that of the 20th century.

How to read this report: numbers and terminology

This report focuses on three scenarios. It briefly mentions the Business-As-Usual, Most Economic (BAU-ME) scenario to discuss the impacts of unmitigated scaling of the system, but thereafter, unless explicitly mentioned, figures will refer to the Low Circularity, Most Economic (LC-ME) and Low Circularity, No Fossil production capacity installed After 2030 (LC-NFAX) scenarios as a range, expressed as XX-YY million tonnes (Mt) or $XXm-$YYm in respective order. This is to provide the reader with insight into the most economic value and the fastest abatement value, identify the lower and upper boundaries of feasible pathways, and thus help the reader to chart their own pathway between these values. This report focuses predominantly on supply side abatement technologies, thus key scenarios focus on more modest levels of circularity rather than the maximum possible levels of circularity.

The time series of the analysis runs from 2020-2050, with a focus on 2050 as a post-transition end state where the system is set up for long term sustainability, but with some key values (e.g., investment costs) stated cumulatively to understand the magnitude of the transition. The analytical model is not deterministic, but rather collates a granular view of feedstocks and production technology data 2020-2050 such as costs and emissions factors, then objectively selects these year-by-year over the time series based upon the scenario priorities (e.g. most economic or fastest abatement approaches to net zero). The model optimizes based on achieving net zero Scope 1,2 & 3 upstream.

The nature of the chemicals system is highly complex, thus every effort has been made to keep the language non-technical while maintaining veracity to the subject, although a background level of knowledge about chemical production has been assumed. The reader should note the difference between the “chemical industry” (players), the “chemical value chain” (feedstock and energy production down to incineration), as well as chemical products. The term “chemical system” is used as a catch-all for the whole entity, especially given the focus on Scope 1-3 net zero. “Chemicals” refer to all in-scope chemicals, referred to as intermediates (ammonia and derivatives urea and ammonium nitrate, methanol, ethylene, propylene, butadiene, benzene, toluene, xylene). The ammonia system is split out due to its size and different approach to abatement. All other chemicals are referred to as the non-ammonia system, and chemicals other than ammonia and methanol are referred to as “olefins & aromatics”. Net zero, unless explicitly stated otherwise (e.g. Chapter 2), refers to net zero Scope 1-3 emissions.

A glossary of definitions and technical terms is available in the Appendix.

Chapter 1 focuses on the state of the chemicals system today and its impact on planetary boundaries.

Chapter 2 focuses on how the chemical industry can transition to reach Scope 1&2 net zero.

Chapter 3 focuses on how the chemicals value chain can transition to reach Scope 1-3 net zero with a focus on non-ammonia chemicals.

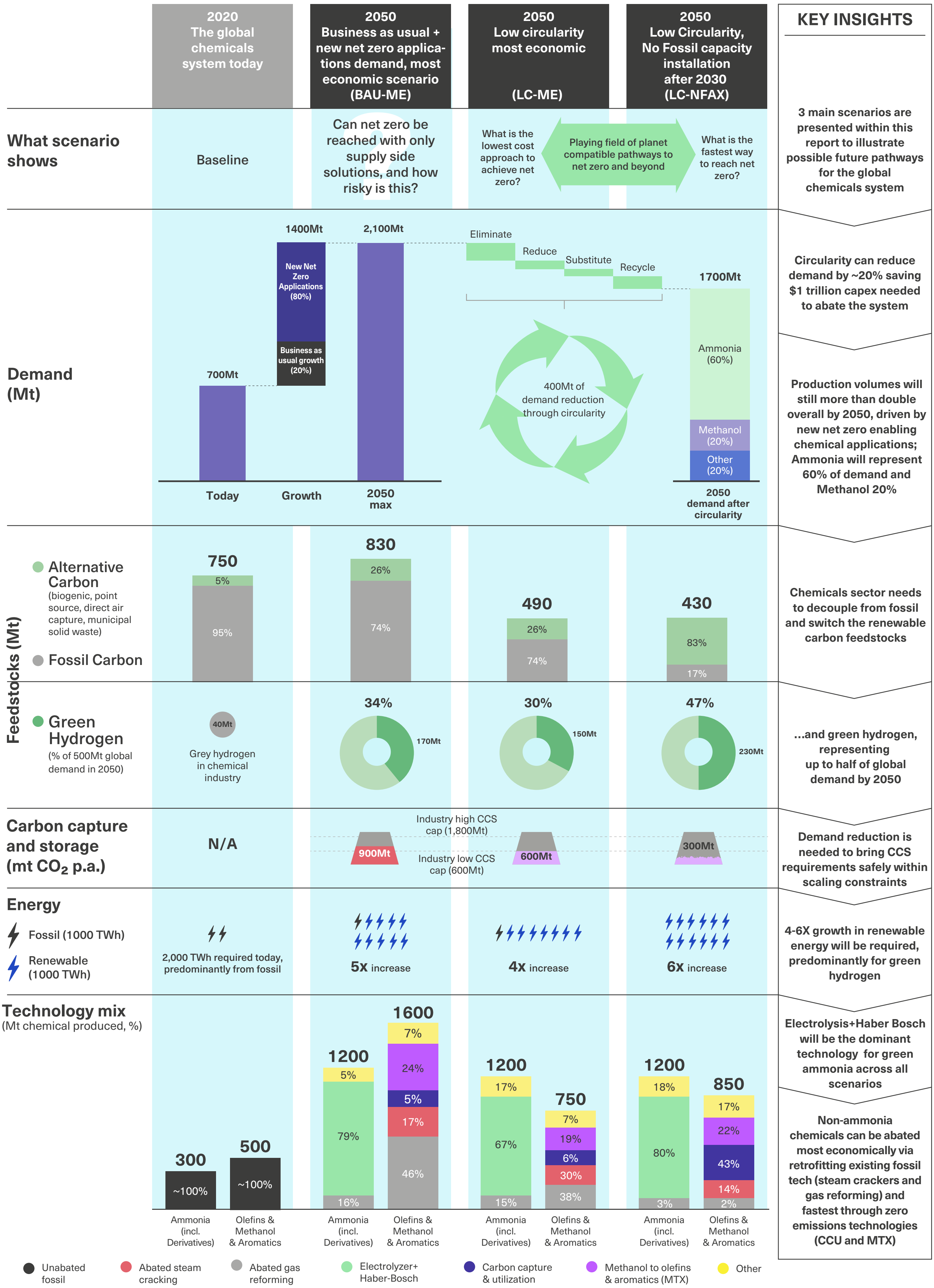
Chapter 4 focuses on the potential for the non-ammonia chemical system to achieve negative emissions

Chapter 5 discusses the implications of the transition to net zero for infrastructure operations, production geography and jobs.

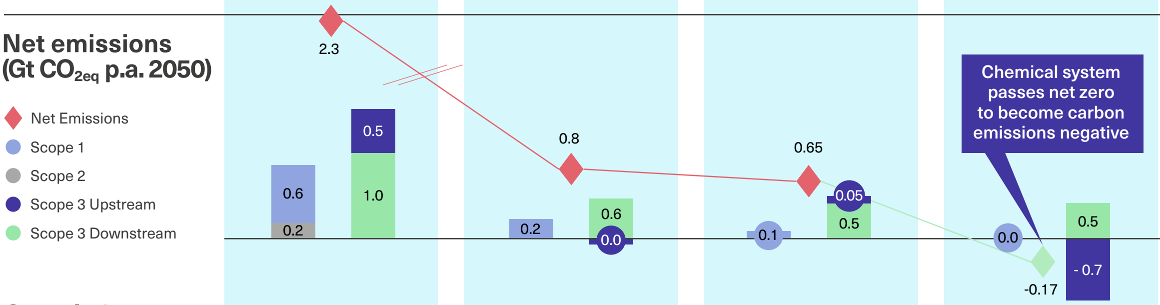
Chapter 6 discusses the economics of the transition and potential new roles for the chemical system in a sustainable 2050 global economy.

Chapter 7 presents the report recommendations of what is needed to catalyse the transition of the chemical system towards a sustainable model over the coming critical decade.

Overview of Key Scenarios



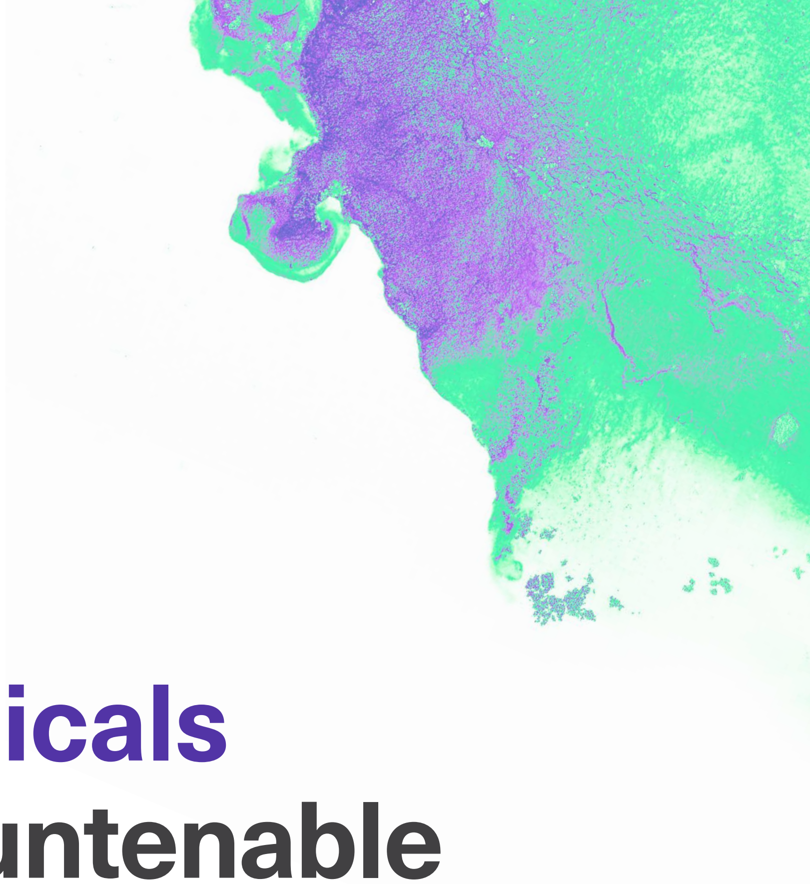
	2020	BAU-ME	LC-ME	LC-NFAX	KEY INSIGHTS
Cumulative CAPEX required (2020-2050)	$1.2 tn baseline cost	$3.7 tn	$2.7 tn	$3.2 tn	A net zero system requires ~2.7X more incremental investment than a world failing to transition
Net emissions ($Gt\ CO_{2eq}$ p.a. 2050)	2.3	0.8	0.65	-0.17	The non-ammonia chemicals system can become carbon negative from 2043 and sequester ~0.5 Gt p.a. by 2050
Cumulative scope 1-3 global emissions 2020-2050 (% of 1.5 degree carbon budget consumed)		**47Gt** 9%	**44Gt** 8%	**35Gt** 7%	Circularity and faster abatement can preserve 12Gt of the global carbon budget
Scenario summary		• Continued high fossil production thus high CCS requirements • Highest cost scenario • More emissions intensive • Net zero not achieved	• Dependence upon abated fossil production • Lowest cost scenario • Lowest cost scenario	• Decoupling from fossil • Shift to alternative feedstocks and zero emissions production technologies • Goes emissions negative by 2050 to become a carbon sink	



Recommendations

Governance	1. Establish first movers coalition(s) to seed low-emissions chemicals markets	2. Establish global charter of transition principles	3. Chemicals industry to advocate for a net zero enabling policy framework
Operations	4. Scale circularity 5. Switch production from fossil to renewable feedstock sources 6. Retrofit legacy infrastructure 7. Abate end of life chemicals		
Data	8. Digitize the value chain and disclose key environmental system data		
Innovation	9. Fast track critical innovations to commercial scale		
Finance	10. De-risk large-scale financial investment		

Note: Many numbers in the Executive Summary are rounded for simplicity. Accurate values can be found in the main body of the text.



Chapter 1:

The chemicals system – untenable growth and an imperative call for control.

Unimpeded scaling of the global chemicals system presents significant climate and planetary boundary risks, and the risks entailed in transitioning to a safe operating model need to be mitigated by increasing materials circularity as an effective tool to reduce demand and drive resource efficiency.

Chapter summary

The global chemicals system is predominantly linear, fossil-based and emissions intensive. While it has multiple compounding factors that make it arguably the hardest to abate system, action is lagging. Pressure is mounting to achieve Scope 1-3 net zero.

Continued, steady growth is projected for the system, augmented by a significant increase in demand for chemicals that enable a broader net zero global economy, namely ammonia and methanol. If the chemicals system is not abated, it aligns with a 4-degree global warming scenario.

Unmitigated growth places heavy dependence on a few untested, unscaled technologies to reach net zero, creating major climate risk if they fail to scale.

Even if net zero can be achieved, the chemicals system impacts a range of other planetary boundaries (e.g., novel entities in the form of chemical pollution, and biogeochemical nitrogen flows) due to low levels of control over the use phase of its products, meaning that there is a direct correlation between size of the system and size of leakage.

Resource efficiency through materials circularity is a highly effective strategy to increase control over the system, optimize resource use, mitigate demand growth, reduce transition costs and, most importantly, de-risk the transition to net zero in the event that some supply side technologies do not scale as anticipated.

Materials circularity can reduce total demand by 23-31% (373-527 Mt) by 2050. This involves elimination (41-47%), reuse (19-20%), substitution (14%), and recycling (19-26%) in a low and high circularity scenario.

The story of a linear system.

The global chemicals system is predominantly linear and highly emissions intensive due to its reliance on fossil sources for both feedstock and energy inputs.

The global chemicals system is predominantly linear. Only 9-14% of plastic materials, which constitute over 70% of olefins and aromatics, are recycled today. Instead, they are predominantly disposed of in waste management value chains with various level of effectiveness and leakage rates, depending on the circularity level. Similarly, about 70% of ammonia is used for food fertilizer in an inefficient linear system, with over 70% of nitrogen input not taken up by crops and potentially running off to the environment.[6–8,15]

In recent decades, the affordability of current fossil feedstocks, paired with the unequalled benefits delivered by chemical products, has fuelled more aggressive growth than experienced by any other resource sector of comparable size.[16] This growth has been largely driven by the production of plastic resins and fibres, which increased from 2 Mt in 1950 to 381 Mt in 2015, a compound annual growth rate (CAGR) of 8.4%,[6] roughly 2.5 times the CAGR of the global gross domestic product during that period.

Today's chemicals system is a by-product of the oil and gas industry. The production of petrochemicals is almost exclusively fossil-based and absorbs around 14% of oil and 8% of gas production globally.[16,17] Similarly, the vast majority of current global ammonia production uses gas reforming to produce hydrogen. By contrast, bio-based chemicals are still largely marginal, comprising less than 0.5% of plastic resins, for example.

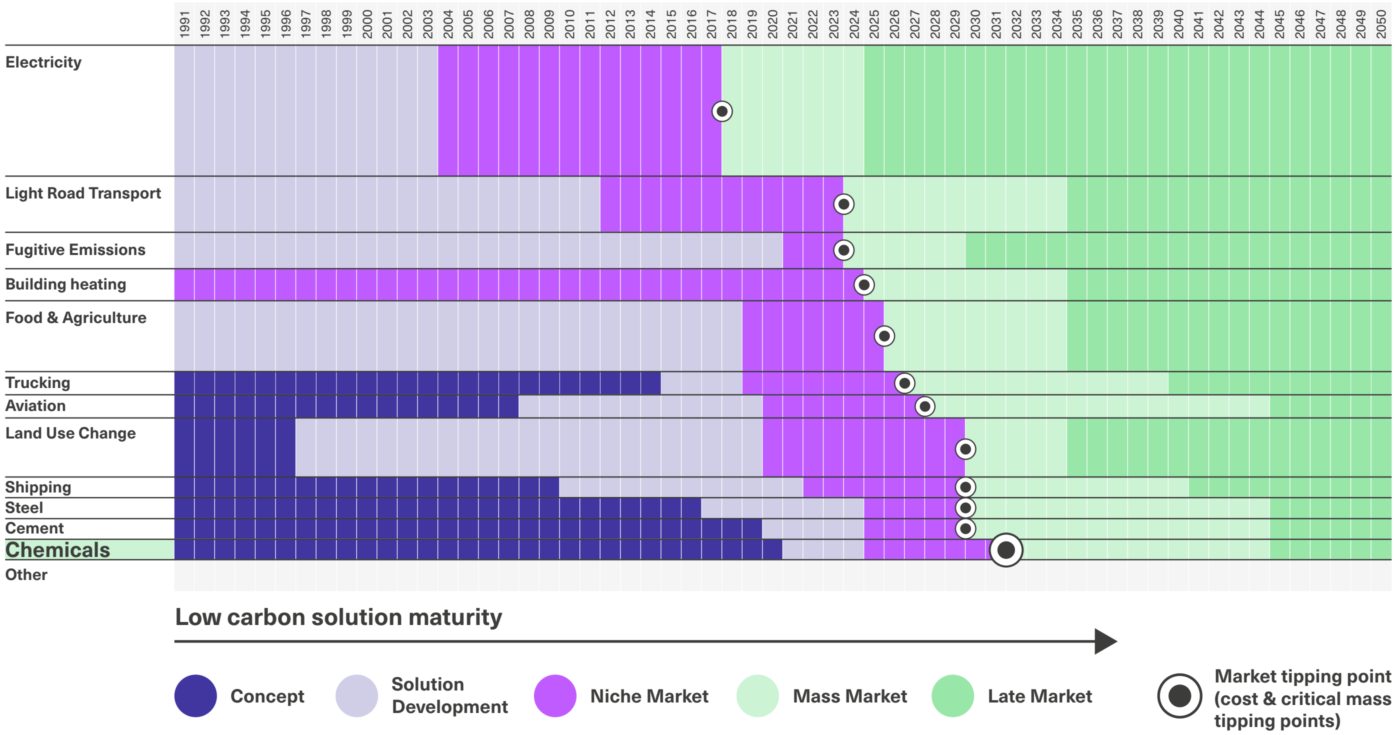
At end-of-life, 41% of plastic globally is mismanaged, meaning that it either leaks into the environment (ocean or land) or is openly burned.[8] An additional 31% is either landfilled or incinerated with or without partial energy recovery, with the latter driving massive greenhouse gas (GHG) emissions due to the carbon density of most plastic (~80%) and the low thermodynamic efficiency of electricity generation from waste combustion.

The total Scope 1&2 emissions of the chemical industry account for 2.0% of global GHG emissions today (1.16 Gt CO_{2eq}).[12,18] but Scope 3 emissions upstream (e.g., fossil extraction and fugitive emissions) and downstream (e.g., end-of-life incineration or fertilizer nitrous oxide emissions) account for 64% of the industry's total emissions – an additional 1.46-2.79 Gt of CO_{2eq}.

The chemical industry is arguably the hardest-to-abate sector. Other hard to abate industrial sectors include heavy duty road transport, aviation, iron and steel, shipping, aluminium, and cement and concrete, the Scope 1&2 emissions of which collectively account for around 30% of global GHG emissions.[19] The cement, iron and steel, and chemicals sectors, which together account for around 6.5 Gt CO_{2eq}, are considered particularly hard to abate due to processes requiring high temperature heat inputs, long asset lifetimes that create slow infrastructure turnover, and producing GHG process emissions as outputs.[20] However, the chemical industry is arguably the hardest to abate sector for the following, additional reasons: i) chemicals generate high upstream emissions due to their current fossil nature; ii) the industry has high end-of-life emissions due to the high embedded carbon content in plastics and N_2O emissions from fertilizers; and iii) a complex range of technologies is required to abate the system across an extraordinary diversity of applications across all sectors, i.e. there is no silver bullet.

Figure 1: Sectoral score card toward low-emissions market tipping point – sourced from "The Paris Effect: COP26 Edition"

The chemical industry is anticipated to be the last to tip towards low-emissions models



It is expected that the chemical industry will reach low-emissions technology market tipping points later than any other sector when evaluated with a balanced score card (Figure 1).[14] There are three immediately evident reasons why more progress may not have been made:

1. **Uncertainty around demand for low-emissions chemicals.** Basic chemical intermediates operate in commodity markets where operational margins do not currently take carbon cost into account. This makes it difficult to make a business case for the deployment of capital into more expensive forms of production if the market is not going to recognize the added value of these low emissions chemical products in the near term.

2. **Technology risk.** Large scale proof of concept is still required for key technologies (e.g., carbon capture and storage [CCS], electrification, and non-coal-based methanol-to-olefins and methanol to aromatics) and carbon circularity (e.g., carbon capture and utilization [CCU], gasification, and pyrolysis). Many of the technologies required for abatement are at the start of their learning curves and require major process adaptations, making them expensive. Equally, there is considerable uncertainty around which of the many technology options to invest in. Moreover, many of these technologies (e.g., CCS) cannot economically operate at a small scale and therefore require large capex investments to prove their concept and economic viability. This results in high barriers and economic risks to participation.

14. The Paris Effect, COP26 Edition, SYSTEMIQ (2021). Methodology contained in report Appendix.

3. **Uncertainty over Scope 1-3 upstream and downstream pathways to net zero.** To date there has been a lack of clarity over the availability of feedstock and technology at scale, the required capital allocation over time, the rate of GHG abatement required, and the parameters within which to execute a safe, planet centric transition.

There is growing recognition that the chemical industry needs to address its Scope 1&2 and, increasingly, end-of-life Scope 3 emissions. The Glasgow Financial Alliance for Net Zero (GFANZ), representing 450 institutions with $130 trillion of assets under management, have established as a "starting line criteria" that businesses and industry need to measure their Scope 3 impact where reliable and practicable.[21] So far, 73 chemical companies globally have committed to setting SBTi targets within 24 months, 11 have already set targets in line with a 1.5 degrees maximum global warming (15% of the total vs cross-sector average of 32%), and a further 2 have set targets to well-below 2 degrees Celsius.[22] In order to overcome these challenges and make the transition to net zero feasible, both supply and demand side management will be required.

The incompatibility of growth and climate change objectives.

Uncontrolled demand growth is highly risky in all scenarios for the chemical industry because any key supply side technology failures will result in unacceptable emissions.

The chemical industry is set to grow steadily by 2050. Under a business-as-usual demand scenario,[15] IEA expects the production of the eight major chemical intermediaries to increase 1.5-fold by 2050, from 693 Mt in 2020 to 972 Mt in 2050 (CAGR 1.1%).[15,23] To enable a net zero global economy, demand for chemicals will need to more than double to reach 2,078 Mt by 2050, driven overwhelmingly by low-emissions ammonia. Achieving net zero in the shipping industry and energy sector will require ammonia production to increase 4-fold to replace fuel oil as shipping fuel, accounting for an astonishing 625 Mt per year by 2050, and specific countries for which ammonia for power is relevant, such as Japan and South Korea,[16] will account for up to 161 Mt by 2050.[24,25] Methanol production will also increase by 260-400 Mt to enable net zero Scope 1&2 production of olefins and aromatics.[26, 17]

Without action, cumulative emissions from in scope chemicals could account for 29-44% of the 1.5-degree global carbon budget due to the chemical industry's deep reliance on fossil.[12] The report analysis suggests that, in a business-as-usual demand and supply scenario, Scope 1-3 emissions will increase from 2.29 Gt in 2020 to 7.75 Gt in 2050 (+338%), accounting for a cumulative 29% (146 Gt) of the 1.5-degree carbon budget over the period from 2020 to 2050 (Figure 2). However, uncertainties regarding both upstream and downstream Scope 3 emissions could lead to much higher estimates – from 4.5-4.6 Gt in 2020 to 14.6-14.8 Gt in 2050 – causing severe climate risk and potentially accounting for up to 44% of the 1.5-degree carbon budget.

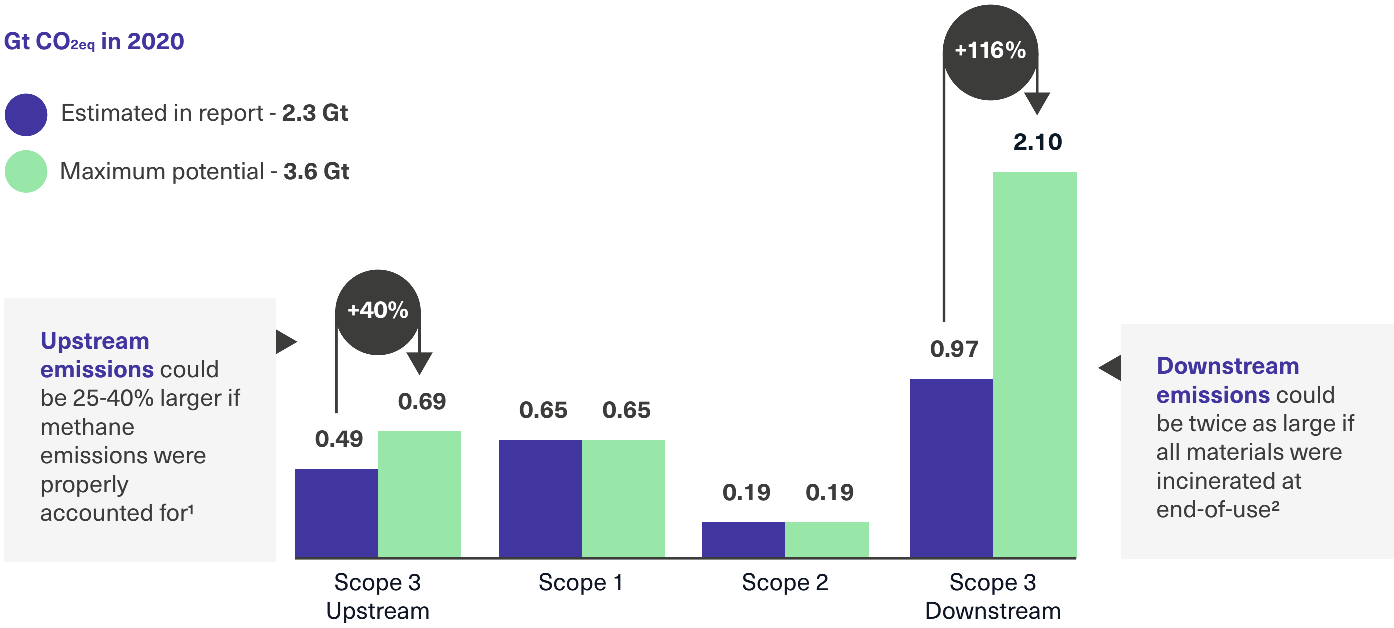
15. The business-as-usual IEA projections assume the world remains largely unequal by 2050. In a fundamentally different, more equal 2050, where the Sustainable Development Goals have been achieved, per capita consumption levels (e.g., of plastic and fertilizer) could be similar across global economies. In such a scenario, chemical production could be two-fold higher than the business-as-usual projection – up to 2,162 Mt by 2050 – further exacerbating the risk of missing the net zero target by 2050.

16. Expert interview from ETC

17. New demand for olefins, aromatics and methanol from significant renewables buildout and the shift to electric vehicles is also considered in this study but significantly lower volume compared to ammonia's growth.

Figure 2: Total system emissions by Scope 1,2, 3 upstream and 3 downstream in 2020

Methane emissions from fossil extraction upstream and uncertainty over downstream waste management mean total system emissions could be almost 60% higher than estimated in this report



Note: (1) Nature, 578, p. 409–412 (2020), (2) Assuming no benefit from energy recovery and no CCS.

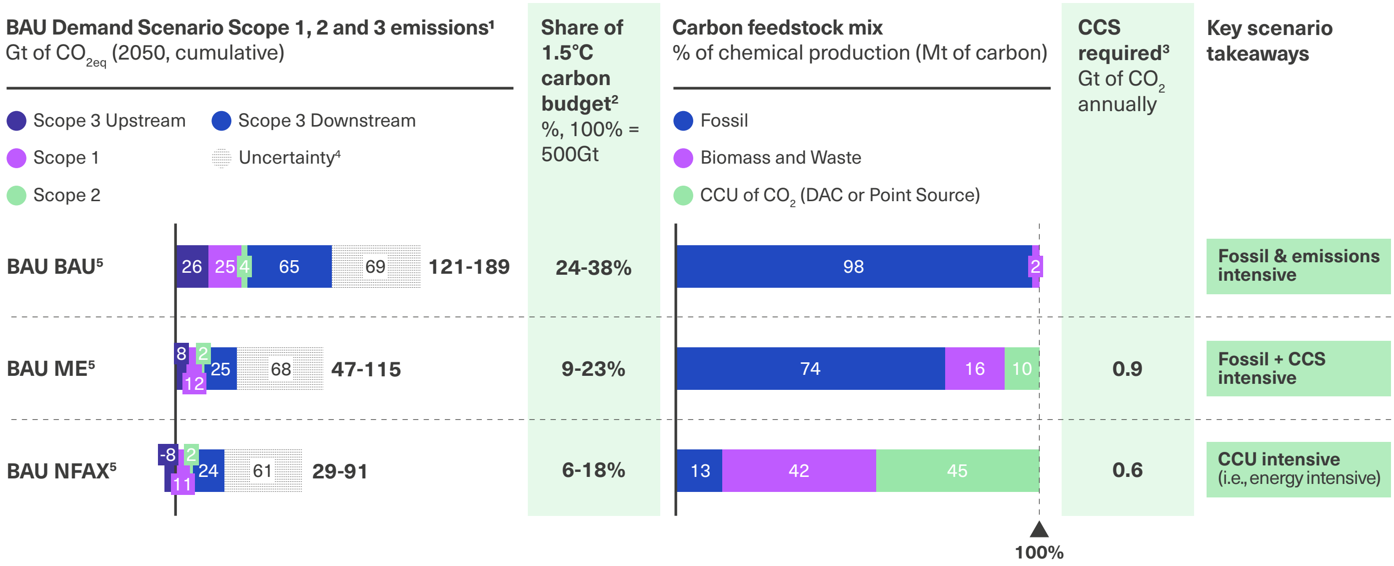
Upstream, fugitive methane emissions[18] are potentially underestimated.[28] Today, upstream emissions represent 22% of the industry's GHG emissions (0.49 Gt) but fugitive methane could contribute more than is currently estimated. According to recent studies, actual upstream emissions could be 25-40% higher (up to 0.61-0.69 Gt in 2020), presenting an even greater climate risk if unmitigated. Full abatement of these emissions is complex but achievable with enough will and investment, as highlighted at COP 26 in Glasgow with the launch of the Global Methane Pledge.[29]

Downstream, lack of transparency and control over waste management systems lead to uncertainties over resulting emissions.[8,30,31] Today, downstream emissions represent 42% (0.97 Gt) of the industry's GHG emissions but this could rise to 61% (2.10 Gt) if all waste were to be incinerated with or without energy recovery. Given current waste management practices – a mix of landfill, incineration, recycling, and leakage – only a portion of all potential end-of-life emissions actually take place and these stem predominantly from combustion (either controlled through incineration with or without energy recovery, or uncontrolled from open burning). As partial energy recovery through incineration is perceived to be a more socially acceptable end-of-life transition technology than landfill, a shift toward standardized incineration could put both the industry and society at risk if those emissions are not effectively mitigated through CCU or CCS.[32,33] Additionally, data gaps in waste management create uncertainties over the quantity of plastic remaining in stock versus that entering end-of-life, presenting a serious risk of underestimating plastic's contribution to climate change. In Europe, for example, 43% of plastic put in the market is unaccounted for in waste statistics.[30,31]

18. The IPCC defines "fugitive emissions" as intentional or unintentional releases of gases from anthropogenic activities. In particular, they may arise from the production, processing, transmission, storage and use of fuels, and include emissions from combustion only where it does not support a productive activity (e.g., flaring of natural gases at oil and gas production facilities).[27]

Figure 3: Business-As-Usual Demand Scenarios: Comparison of key characteristics (emissions, feedstock mix, CCS requirement)

Steady demand is unstainable from a climate perspective, and achieving net zero in such conditions is risky due to heavy reliance on just two technologies: CCS and CCU



Notes: (1) Refer to Appendix for Scope 1,2 and 3 definition, (2) IPCC, AR6 III, 2022 (3) includes both CCS from production processes and incineration+energy recovery (4) uncertainties account for potentially 20-40% higher fugitive methane emissions and for full release of embedded carbon at end-of-use and assuming no benefit from energy recovery (5) BAU demand refers to demand scenario according to IEA projections assuming no demand reduction or resource efficiency levers; most economic and no fossil supply refers to scenarios used to achieve net zero scope 1&2 in those conditions

Achieving net zero without any demand reduction or increased attempts at resource efficiency creates heavy reliance on affordable and effective CCS at scale. Our analysis suggests that the most economical pathway to achieve net zero Scope 1-3 emissions under business-as-usual demand projections will lead to the industry relying for the most part on a fossil feedstock plus CCS system. In such a scenario, the chemical industry could need up to about 1.7 Gt of annual CCS capacity, including additional capacity to mitigate end-of-life incineration. The associated infrastructure would be on a scale roughly equivalent to a third of the current global gas industry, raising serious questions about the feasibility of relying too heavily on this strategy over the next 30 years, (see Chapter 3 section on CCS).

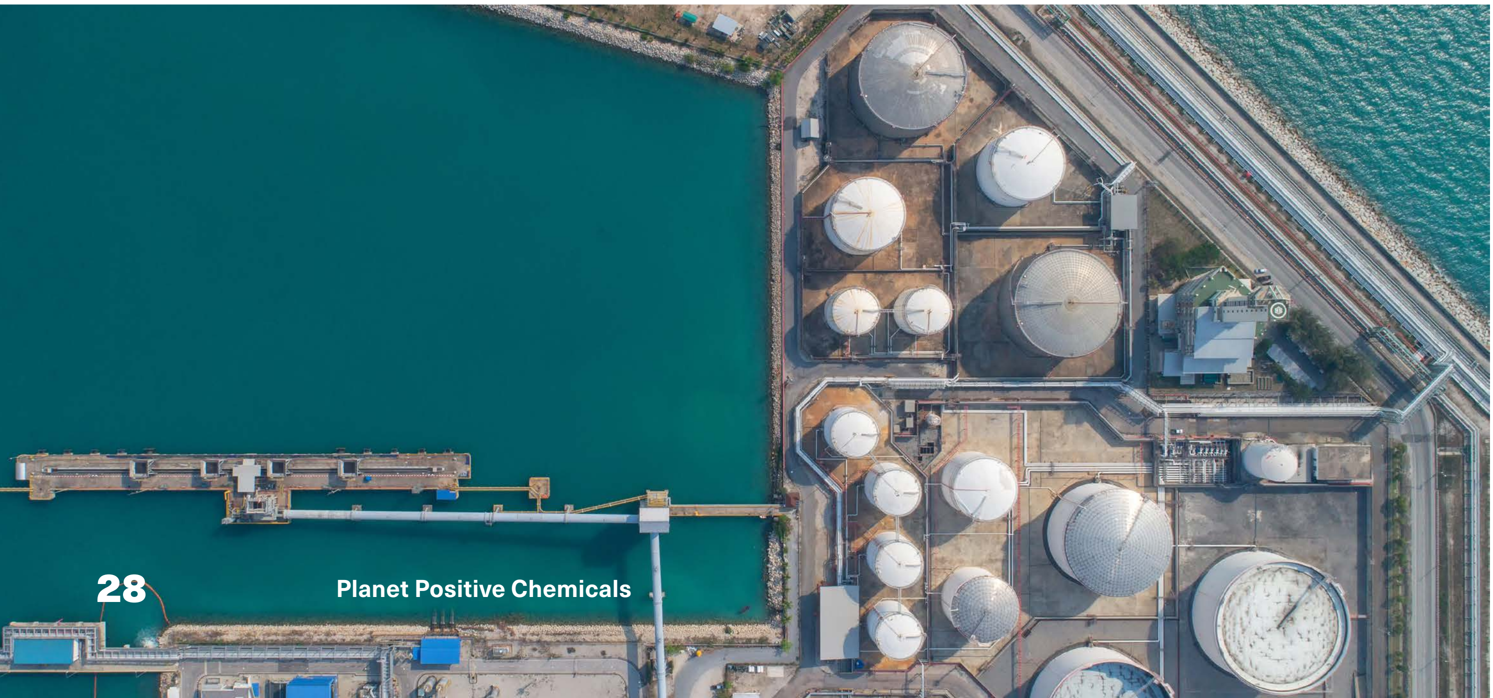
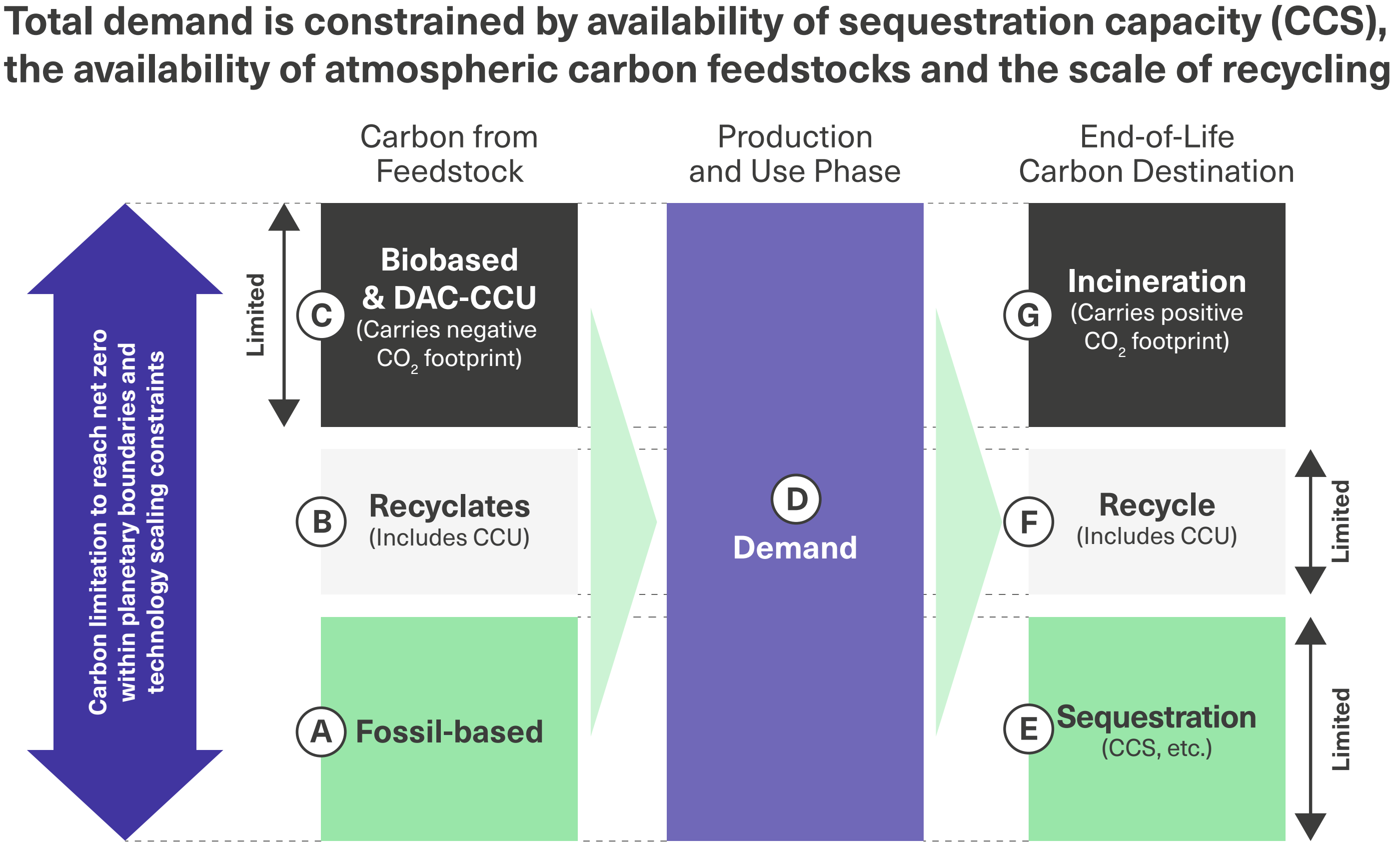


Figure 4: System-level net zero demand constraints as defined by supply side abatement capacity



Potential scaling constraints on supply side abatement technology mean demand reduction is required to safely transition to net zero Scope 1-3. The scaling of the system is constrained by the availability of technologies that either sequester carbon (i.e., CCS) or allow the use of alternative feedstocks that offset emissions with a negative emissions factor (i.e., direct air capture [DAC] or biogenic feedstocks). As Figure 4 shows, for Scope 3 category 12 (end-of-life treatment) net zero to be achieved, all residual positive emissions (G) must be cancelled out by the same amount of carbon in feedstock carrying a negative footprint (C). As the supply of biobased feedstock is limited, the amount of (C) is limited unless DAC can be deployed. Furthermore, the amount of fossil carbon entering the supply chain (A) must equal the amount of sequestered carbon (E), which again has risks and limitations. Therefore, the chemical industry's ability to support the demand (D) under Scope 3 net zero depends on the capacity of (C) and (E) while maximizing (B) and (F). See footnote for detail.[19]

If any of three key technologies (CCS, DAC and use of sustainable biogenic feedstock) fail to scale, demand will be too big for supply side interventions to achieve net zero. This is evidenced by the BAU-ME scenario, in which 55% of the global biogenic feedstock available and allocated to the chemical industry and 52% of the CCS capacity is consumed. A sensitivity has been assumed whereby only a third of this capacity is available in a downside scenario, meaning that a business-as-usual growth system (BAU-ME) would significantly exceed these capacities and fail to reach net zero, while a system reduced in size by low levels of circularity ambition (i.e., LC-ME or LC-NFAX) would still achieve net zero to within a margin of error.

19. Carbon balance requires A+B+C = D = E+F+G. By definition B = F, therefore A+C = E+G. Net zero further requires C = G, therefore A = E. Thus, the boxes with the same color must have the same amount of carbon under Scope 3 category 12 net zero for CO2. This chart assumes Scope 1 & 2 emissions to be net zero, and focuses only on CO2 emissions in Scope 3 category 12.

Unabated scaling of the chemical industry is incompatible with planetary boundaries.

To avoid "carbon tunnel vision" and safeguard the global commons, the industry needs to assess its impact across the broader set of nine planetary boundaries.

Due to the interlinkages between the planetary boundaries, an appropriate transition needs to have positive impacts across a range of broader planet-focused metrics beyond GHG emissions (Figure 4). The climate transition cannot be an isolated strategy and identifying planetary boundary trade-offs is essential. While the development of strong climate pathways will have indirect positive impacts on some planetary boundaries (e.g., ocean acidification, aerosol loading), for others a complementary, comprehensive and holistic strategy must be developed. For example, biogenic feedstock usage and renewable energy generation capacity rollout must be linked to biosphere integrity and land system change.[5] Fertilizer growth and management must be conceived of with biogeochemical flows and freshwater use in mind.[4] And the impact of novel entities on planet and human health must be assessed and monitored.

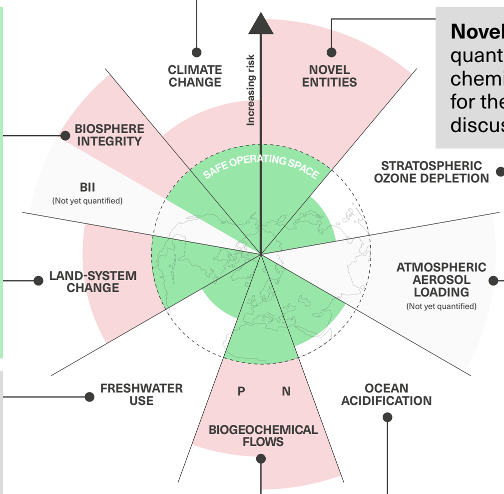
Figure 5: Planetary boundaries in relation to this analysis

The chemical industry has a direct impact on multiple planetary boundaries and ultimately a role to play in safeguarding the global commons

Climate Change: The chemical industry has an essential role in enabling society to remain on 1.5C trajectory given its emissions are embedded across all industries. Achieving net zero will be critical. However, the chemical industry is arguably the hardest to abate sector due to the combination of embedded carbon, high temperature processes and large and long assets life.

Biosphere integrity and land system change: Biomass will be a key feedstock to achieve net zero, sourcing must be capped to ensure land restoration and biodiversity is not unintentionally sacrificed at the expense of climate strategies.

Freshwater use Anticipated impacts are not significant given future chemical production processes are not expected to consume more fresh water and desalination could be an affordable risk mitigation strategy.



Novel Entities: A recent study has quantified the irreversible state of chemical pollution which is critical for the industry to address yet not discussed in this study.

Stratospheric ozone depletion: Not examined.

Atmospheric Aerosol: Achieving net zero will have an indirect positive impact from reduction of combustion (directly via carbon capture or indirectly via deployment of renewable electricity).

Biogeochemical flows: The chemical industry has a role to play in proactively encouraging fertilizer demand reduction levers (e.g., food waste, diet change) and higher nitrogen use efficiency levers (e.g., precision agriculture, nitrogen inhibitors) as well as best agriculture practices (e.g., crop rotation).

Ocean acidification: Achieving net zero will have an indirect positive impact due to limitation of carbon dioxide in the atmosphere and fertilizer run-off.

Global Commons Domains

Climate system
Aerosols, atmospheric circulation and composition, carbon cycle, monsoons

Ozone layer
Stratospheric ozone layer

Land biosphere
Amazon & boreal forests, freshwater, grassland/tundra, permafrost, soil carbon sink

Oceans
Acidity, AMOC, biodiversity, coral reefs, ENSO, methane hydrates, oxygen content

Ice sheets & glaciers
Arctic sea ice, EAIS, Greenland ice sheet, inland glaciers, WAIS

- Main focus of the study
- Boundaries for which levers are directly accounted in the study
- Boundaries for which indirect positive impact is expected
- Boundaries not impacted by the results in this study

Notes: Picture credit: Stockholm Resilience Centre

Leakage is inherent to any system but must be kept under control to ensure safeguarding of the global commons. Leakage from the chemical industry's supply chain exists in the form of GHG emissions in the air (e.g., CO_2, N_2O), and large scale chemical runoffs and localized pollution in the environment (e.g., microplastics, fertilizer run-off, CFCs).[3,8,12,34,35] Leakage has an adverse effect on climate, biodiversity and ecosystems more broadly, and on human health more directly. Optimizing the size of the chemicals system to design out waste inevitably minimizes mass leakage and thus reduces potential impacts on planetary boundaries.

In a regenerative world, where land is restored and biodiversity maintained, biomass will be limited. The demand for biomass has surged, but not all forms of biomass production are sustainable. Truly sustainable biomass supply is complex to estimate, but the latest biomass availability research estimates the global supply at 40-60 exajoules (EJ), equal to about 2,900-4,300 Mt.[5] Taking the needs of other industries (e.g., wood industry, pulp and paper, sustainable aviation fuel requirements) into account , this analysis caps the share the chemical industry can use as biomass feedstock at only 10 EJ (about 720 Mt of dry biomass).[5] Scaling technologies that can process biomass streams (especially currently hard-to-valorise ones) will be relevant to any climate roadmap, but either over reliance on those technologies or promoting the development of an unsustainable biomass supply will have adverse effects on land use and biodiversity, and ultimately add to the existing climate risk.

Synthetic fertilizers are essential for human development, but misuse or overuse disrupts biochemical flows and creates environmental externalities such as eutrophication and ocean acidification. Feeding the growing world population will require 50% more synthetic fertilizer by 2050 at current rates, but with weak nitrogen use efficiency and considerable runoff, the environmental impacts are also set to increase irreversibly.[36] The chemical industry should seek to ensure that the fertilizer its produces is used appropriately downstream and that best agricultural practices are rolled out, although ownership of this will reside with regulators, agri-tech companies, and food producers. Fertilizer production can be reduced if food waste is mitigated, diets shift from animal protein to vegetal protein, and if precision agriculture enables more effective use.[36] Altogether, fertilizer production could be reduced by 11-29%, leading to a direct reduction of run-off. The chemical industry may also be able to develop new business models to support this sustainable transition while compensating for the financial loss, with fertilizers-as-a-service one obvious example.

Ubiquitous plastic usage has led to increasing amounts of leakage into the environment – currently estimated at 11 Mt entering the ocean per year, threatening biodiversity and ecosystems worldwide.[8] Plastic has been the fastest growing material of the last century, but the lack of adequate waste management systems has created a gap.[8] Macro- and micro-plastic are both prevalent and under increasing scrutiny. Recent public awareness has raised the issue to the top of the sustainability agenda and created momentum for a Paris-like binding UN treaty, which governments have committed to negotiate by 2024.[35] Alongside mitigating emissions from production processes, the Breaking the Plastic Wave (2020) report examines the fate of plastic materials and associated demand reduction and resource efficiency levers, including waste management systems and the resulting effects on leakage. The analysis suggests that, if these levers are ambitiously developed, by 2040 environmental leakage both on land and in the ocean can be effectively reduced by more than 80%, and microplastic pollution can be reduced by 78%. Developing the appropriate circular economy for plastic – including elimination, reuse and waste management systems – will have multiple co-benefits for society beyond reducing GHG emissions from virgin production or offering carbon feedstock pools.

The safe operating space for the introduction of novel entities[20] (e.g., entities which are geologically new) has already been exceeded, according to recent research, and this is almost exclusively due to chemical pollution.[3] "Outside the safe operating space of the Planetary Boundary for Novel Entities" was published in early 2022 in the journal *Environment, Science & Technology* by a team of leading scientists, arguing (quantitatively for the first time) that novel entities are being released in the environment at a rate outpacing humanity's ability to conduct safety related assessment and monitoring. Entities of concern include plastics, as well as additives (e.g., plasticizers), pesticides, and down-the-drain consumer products. While this report does not further discuss the impact chemicals have on human health as it is a separate and dedicated area of research, it is vital that the chemical industry conduct further studies to address these concerns. More specifically, additional research is necessary to determine whether climate mitigation strategies could cause unintended adverse or beneficial impacts on flows of novel entities, (e.g., the role of material substitution).

Anticipated impacts on freshwater use by the chemical industry are not significant on a global level, and desalination and purification of brackish water will provide an affordable mitigation strategy in certain local circumstance. Therefore, water is not discussed further in this report. While the chemical industry is a significant consumer of water, the production of primary chemicals accounts for only around 1% of global freshwater usage.[15] Additionally, the technologies recommended in this report are not expected to consume significantly more water compared to existing processes as they typically require lower temperatures or rely on electrification, removing some cooling needs. The production of green hydrogen will also require less water than fossil fuel extraction and processing today.[14] However, groundwater depletion constitutes a major risk for localized chemical clusters of concern in some regions (e.g., China's coastline, southern U.S.). Since desalination has drastically decreased in terms of both costs and energy consumption in recent years (ca. 0.7 $\$/m^3$, 3-4 kWh/m^3), it might provide an interesting risk mitigation strategy for the industry at large.[37] With needs ranging from approximately 2-20 m^3 of water per tonne of ammonia and steam cracker products respectively, the additional cost for chemical production is marginal (approximately 0.5-1.5% per tonne chemical).[38,39]

Atmospheric aerosol loading and ocean acidification will be indirectly but positively impacted by climate mitigation strategies. While ocean acidification will be positively affected by halting the increase in CO_2 concentration in the atmosphere and minimizing fertilizer runoff, atmospheric aerosol will benefit from the reduction of combustion and associated emissions due to carbon capture and the decarbonization of the energy sector. On the other hand, the stratospheric ozone layer depletion requires different set of levers to the ones discussed in this report and therefore is not examined here.[4]

Optimizing demand for chemicals offers a unique opportunity for the industry to contribute to the stewardship of the global commons and justify the renewal of its licence to operate. Bringing the size of the chemical industry system to a sustainable scale means that GHG reduction technologies, which are bound by technology scaling and feedstock/energy constraints, can more safely transition to net zero and withstand shocks if one or two technologies fail. In addition, a resource efficient economy will allow the industry to focus on essential demand with the greatest value added for society, while reducing or substituting some non-essential utility. This new demand model could be the basis for a new social contract that aligns the industry's economic requirements with society's demand for environmental and social justice.

20. New entities are defined as "new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects" (Steffen et al, 2015). This includes chemical and plastic pollution.

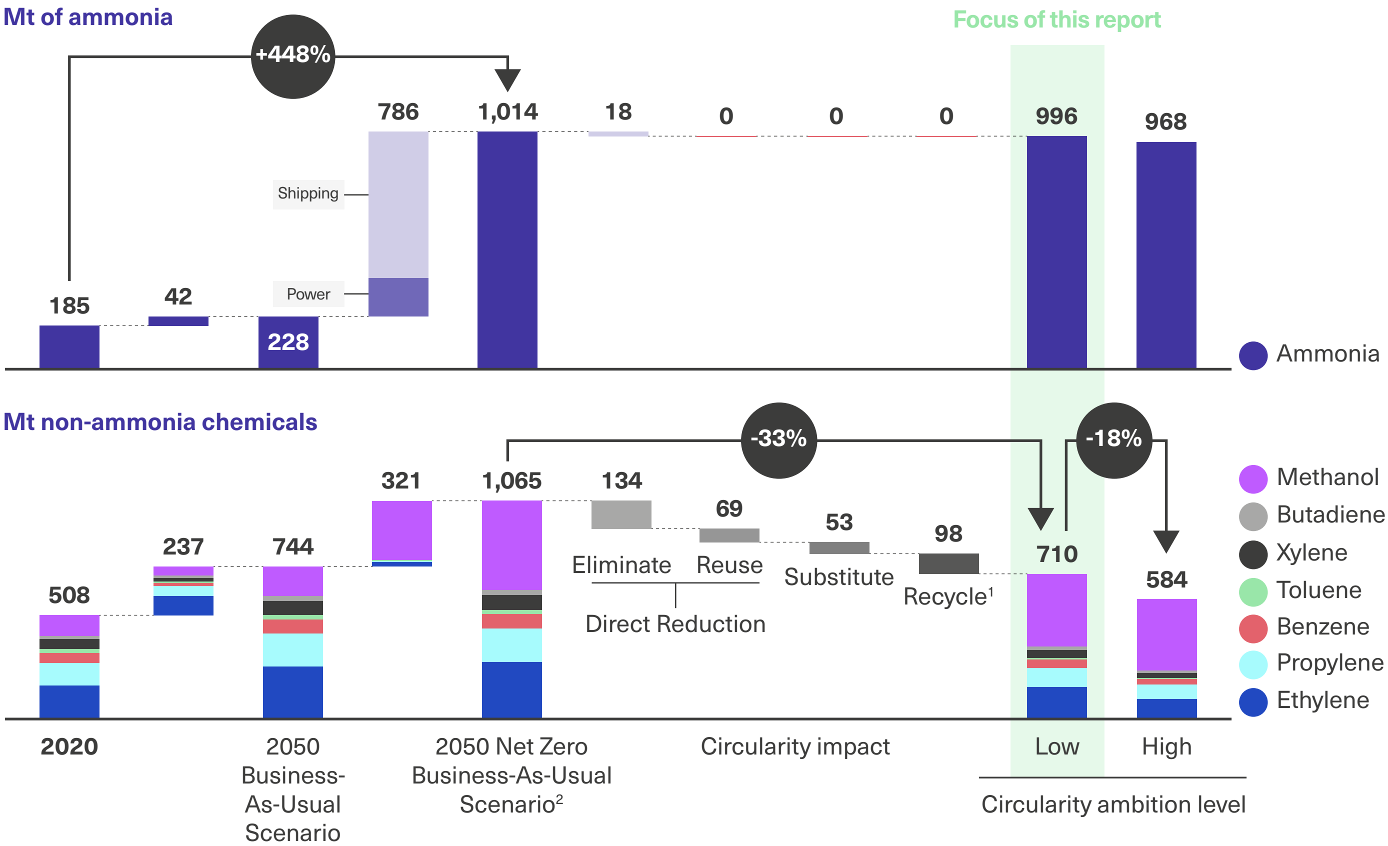
The imperative call for circularity.

Circularity driven by material demand reduction and resource efficiency is a pre-requisite for the chemical industry to safely transition to operation within planetary boundaries.

This analysis suggests that ambitious deployment of circular levers can reduce 2050 business-as-usual demand for the eight chemical intermediaries studied by up to 23-31% (in this section, range refers to low and high circularity ambition levels respectively). This is particularly relevant for non-ammonia primary chemicals, where it can lead to up to 33-51% demand reduction without removing any utility benefits (Figure 6). These circular levers include business models that lead to a net demand reduction for end products and, by extension, basic chemical intermediates (see Appendix). Most, if not all, levers will be driven by resource efficiency strategies from downstream consumer facing or product manufacturing industries. Reducing the need for a material (or a portion of it, e.g., through reuse) in the first place, abates emissions from its entire value chain by removing the need to extract fossil resources, manufacture goods and the associated energy, and manage the related waste generated during and at end-of-life. It also eliminates the risk of leakage. And all this at little to no cost for the system. This report groups the circular levers into four relevant categories – elimination, reuse, substitution and recycling – and analyses them across five key industries: agriculture, packaging and fast-moving goods, building and construction, transportation, and textiles.

Figure 6: Basic chemical demand analysis between 2020 and 2050

While ammonia will grow significantly to fulfil new net zero applications such as shipping and power, non-ammonia chemicals will experience the greatest impacts of circularity



Notes: (1) Recycling includes mechanical recycling, depolymerization and dissolution technologies; other chemical recycling technologies such as pyrolysis and gasification were considered in the supply model as they produce basic chemicals

(2) Refers to business as usual demand with new net zero enabling applications added

MTX demand for LC-ME illustrated. Additional demand growth or reduction for BAU and HC demand not captured.

Direct reduction – including elimination and reuse – is by far the most important lever, accounting for 59-67% (221-351 Mt) of total demand reduction of basic chemical intermediates by 2050. All industries are expected to embrace resource efficient strategies (Figure 6). Demand reduction can take two forms:

- Strict utility elimination accounts for 41-47% (152-246 Mt) of demand reduction. It is defined as where an entire product, or a share of it, is no longer required to deliver the same service to society. Elimination is relevant to all industries where economical and technical solutions exist and are socially acceptable. Transportation fuel related demand (e.g., methanol as fuel, fuel additives) represents the largest elimination potential in a net zero world where transportation is decarbonized, accounting for 70 Mt by 2050 compared to 2020 consumption patterns. Sustainable transition toward more efficient building and use of space will require fewer overall resources and can deliver another 24-59 Mt reduction.[40] Changes in diet, precision agriculture, and reduction in food waste together have the potential to remove the need for 18-46 Mt of fertilizer by 2050.[36] Eliminating unnecessary packaging could lead to 19-26 Mt reduction.[8] Waste reduction in textile supply chains can reduce the need for 3-6 Mt of synthetic fibres.[41]

- Service or reuse models (19-20% of total reduction) is where a product's utility is still valued but its delivery through a new business model requires less material for the same output. A traditional reuse model is milk delivery in glass bottles that are returned and refilled, which has in modern times been replaced by linear plastics. Today, service or reuse business models is an expanding, rejuvenated concept and is likely to be applied to more and more industries as the bottlenecks associated with new supply chains and value proposition are overcome.[42] As of today, reuse is especially relevant for the packaging industry, reducing the need for 52-70 Mt of basic chemical intermediates by 2050, and for transportation through mobility-as-a-service, which can potentially reduce an additional 13-27Mt. New business models in the fashion industry might lead to an additional 4-8 Mt reduction.[8,41,43]

Substitution is the smallest lever, accounting for 14% of total demand reduction for basic chemical intermediates, and is mostly relevant for the packaging and textile industries. It includes all levers where utility is being substituted with a material not produced by the chemical industry in scope of this analysis. Material substitution requires clear GHG benefits to be implemented and a thorough life cycle assessment to ensure no unintended consequences are generated on other impact categories (e.g., deforestation, biodiversity loss). It can be an especially relevant lever to consider for chemicals with high leakage potential. Substitution will be a key lever in the packaging industry, with the rising use of paper and compostable materials expected to displace 38-44 Mt of demand by 2050. The construction industry might also see a small shift toward bio-based materials, estimated at 8-16 Mt. Finally, the fashion industry might be the most impacted by material substitution due to the return of man-made cellulosic fibres (e.g., lyocell, viscose) and compostable synthetic fibres (e.g., PHAs), which could displace up to 3-5 Mt.

Recycling is a relevant lever, but it is unlikely to account for more than 19-26% of demand reduction for basic chemical intermediates due to feedstock and scaling limitations. Two forms of recycling are considered:[21]

- **Mechanical recycling[22] is expected to scale to its maximum potential, given that it has the lowest energy requirements, but will still only meet 23-32% of total polymer demand.** Driven by favourable policies, the report analysis suggests that mechanical recycling alone will reach a 33-39% recycling rate[23] globally by 2050 (in contrast the EU has targeted 55% of plastic packaging by 2030) and therefore will remain the primary recycling technology for polymers.[8,44] Achieving more ambitious recycling rates will be constrained by inherent limitations to the technology, including: (1) losses along the collection, sorting and recycling value chain; (2) limits to producing high quality recycled grades (e.g., food grades) due to the complexity in recovery of pure material and the presence of different polymer grades, additives, or specific contaminants (e.g., oil); and (3) lack of waste management (especially collection and sorting) infrastructure development in the Global South.[8] While innovation across the value chain is expected to increase high quality closed loop recycling, this analysis suggests that open loop recycling, defined as the recycling of material into applications with lower requirements and used by other industries (e.g., food grade bottles into textiles), will still account for over 25% of recycling volumes globally. Policies set to achieve higher recycling targets will necessarily require significant decreases in sorting losses (via technological advances) or will rely on alternative chemical recycling technologies (e.g., pyrolysis and gasification), or a combination of both.

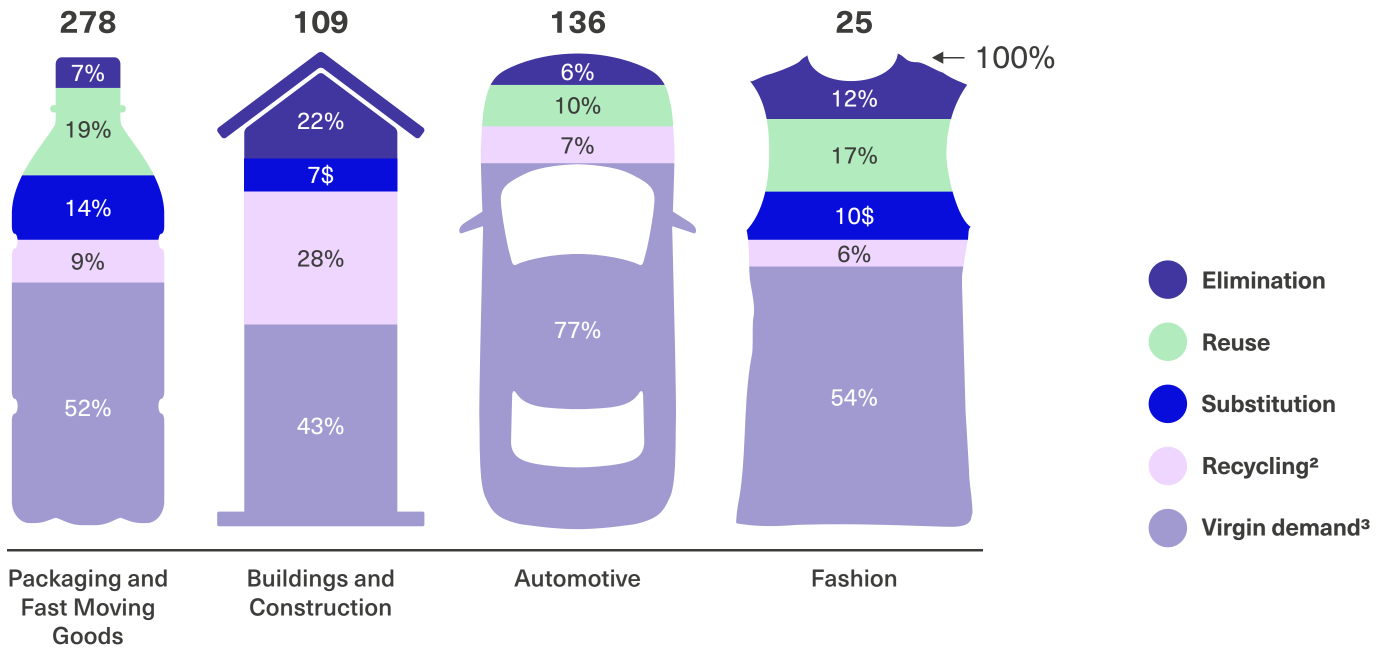
- **Downstream chemical recycling technologies (e.g., depolymerization and solvent-based recycling) are expected to continue to play a smaller role compared to mechanical technologies, and to be dedicated to specific product applications, leading to the production of 5-10 Mt of monomers and polymers by 2050.** Downstream chemical recycling refers to a wide array of technologies that recycle polymers into molecules and typically involve either a molecular reaction (e.g., depolymerization) or the use of a chemical (e.g., solvent). These technologies could be game changing for certain sectors (e.g., polyethylene terephthalate in textiles and bottles, rigid food grade polypropylene, and polystyrene) by complementing mechanical recycling. In the case of depolymerization, it can fill gaps by accepting grades rejected by the mechanical recycling industry (due to contamination or certain materials – like fibres – being hard to mechanically recycle). Solvent-based technologies could also be increasingly used as a complementary step after (not instead of) mechanical recycling, to further purify material and potentially achieve virgin or even food-grade quality outputs (an effect not quantified in this study). However, despite their high relevance, these technologies are unlikely to be silver bullet solutions as a combination of technological constraints, current cost, emissions profile, and competition with mechanical recycling for feedstock make them unlikely to become mainstream technologies for all sectors and all polymer resins by 2050.[31,45]

21. Feedstock recycling technologies (i.e., pyrolysis and gasification) are not covered in this section of the report but are discussed later as they enable the production of basic chemical intermediates (e.g., olefins, syngas).
22. Mechanical recycling constitutes the recycling of polymers without altering their chemical structure and without the use of subsequent chemical intermediaries. Quality of the output is typically lower than virgin due to the mixing of polymer grades and their related additives.
23. Note that recycling rates differ from use of recycled content. Each metric was calculated using the same numerator – amount of plastic recycled – yet the denominator for recycling rates is the total amount of plastic waste generated, while for recycled content it is total amount of virgin plastic produced.

Figure 7: Change in basic chemical demand through circularity across key downstream industries

All major downstream industries will be impacted by demand reduction levers and resource efficiencies leading to major shifts for the non-ammonia chemical industry

% of change by weight, 100% = 2050 business as usual demand[1]



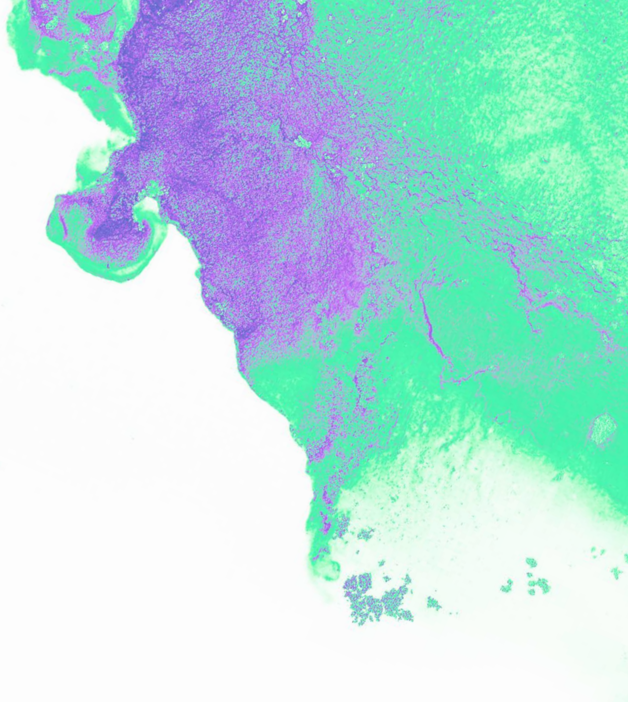
Note: (1) volumes considered are for the low ambition scenario and only include demand derived from the 8 chemical in scope for this project: ethylene, propylene, methanol, ammonia, benzene, toluene, xylene, butadiene (2) Recycling includes mechanical recycling, depolymerization and dissolution technologies; (3) virgin demand includes all supply production processes yielding virgin products regardless of the feedstock source and therefore include fertilizer synthesis from wastewater nutrient recovery, waste gasification and pyrolysis.

Implementing circularity will fundamentally alter the shape of the system by 2050, transitioning it from a predominantly linear operation. It is therefore prudent that circularity is enacted under two key principles:

- **Upstream prioritization** – in an optimal circular system, the lowest energy, most material efficient processes is maximized before waste descends to less efficient technologies (i.e., maximizing mechanical recycling before passing waste to chemical recycling).[46] This broadly means maximizing upstream technologies as far as possible due to their downstream value chain ripple effect. For example, one tonne of elimination results in 100% reduction in material use, direct removal of collection and sorting costs as well as removal of any recycling or disposal costs, emissions and resource losses, vs one tonne of chemical recycling which sustains a larger system.

- **Complementarity of technologies** – similarly, to ensure recirculation of material with the greatest energy and resource efficiency, technologies would ideally not compete e.g. for feedstock sources at a market level; chemical recycling technologies would not cannibalize the best feedstocks before mechanical recycling.[46] In practice, long-term feedstock agreements, feedstock tracking, appropriate pricing mechanisms, and infrastructure synergies will be key enablers.

Implementing circularity will reduce incremental capex requirements to reach net zero by around $0.20 tn for circularity and $0.77 tn for supply side abatement cumulatively 2020-2050 in the most economic scenarios, so a total saving of almost one trillion dollars, (see Figure 37 for relative costs of ammonia vs non-ammonia and circularity impacts). Circularity offers to opportunity to create greater resource efficiency, reduce leakage and pollution, reduce GHGs, create new business models and therefore revenue streams, and simultaneously reduce overall systems transition cost. While this analysis has assumed a modest level of circularity, higher levels make attaining net zero and operating within planetary boundaries quicker, easier and more affordable.



Chapter 2:

Getting the house in order – achieving net zero production of basic chemical intermediates (Scope 1&2)

Achieving net zero Scope 1&2 is feasible by implementing three complementary strategies: shifting feedstocks, switching energy source, and applying CCS. This requires an almost complete shift to new low-emissions technologies.

Chapter summary

The operation of a net zero Scope 1&2 chemicals system can be characterized by three strategies: a shift from fossil to alternative feedstocks (e.g., point source, waste, biomass, direct air capture and green hydrogen), a shift in energy source from fossil to renewable (mostly green hydrogen), and applying CCS.

These three strategies can be applied to seven technology processes that will form the basis of the future net zero chemicals system: (1) electrolysis (to produce H_2) will rapidly scale, especially for ammonia, and will compete with existing **(2) gas reforming** (to produce H_2), the future of which depends on its ability to connect to CCS; **(3) gasification** (to produce syngas from waste and biomass) will develop but likely remain expensive in many regions; **(4) carbon capture and utilization (CCU)** to produce syngas from CO_2 will emerge as an alternative source of carbon, while catalytic reforming (to produce aromatics in refineries) will be phased out as the fuel industry declines; **(5) steam cracking** can continue to operate with retrofitting technologies[24] while **(6) methanol-to-olefins and methanol-to-aromatics (MTX)**, as well as **(7) ethanol dehydration** (to produce ethylene), will provide new routes to produce much needed olefins and aromatics.

Ammonia production is the largest single contributor to the chemical industry's Scope 1&2 emissions today (0.37 Gt of CO_{2eq} or 45% of the Scope 1 and 2 emissions produced by the basic chemical intermediates industry today) and is by far the largest growing chemical by 2050. Abating its emissions is critical to enable a sustainable future. Ammonia demand will surge from 185 Mt in 2020 to 996 Mt by 2050, predominantly as a low-emissions fuel and thus abating greenfield production is imperative to achieve net zero. Abating ammonia Scope 1&2 emissions is driven by two technological pathways: gas reforming plus CCS, and electrolysis.

Methanol will play a central role within the system both as a means of recycling carbon at end-of-life and in the production of olefins and aromatics from renewable sources of carbon and green hydrogen. Production of olefins, aromatics and methanol accounts for 0.46 Gt of CO_{2eq} today, amounting to 55% of the Scope 1&2 emissions of the basic chemical intermediates industry today, and represents the next challenge for the industry to solve. Production of methanol from biomass, waste, or CO_2 in combination with green hydrogen is the most relevant net zero pathway (i.e., fossil-free and net zero Scope 1-3) and can then be used to produce olefins and aromatics via MTX. The production of these chemical intermediates will increase from 508 Mt in 2020 to 710-859 Mt in 2050.

24. Retrofitting technologies include, for example, using green hydrogen as a heat source, requiring replacing burners on the steam cracker, or applying carbon capture and storage. For more information please refer to the technical appendix.

Scope 1&2 production emissions abatement options for the chemical industry can be delivered through three main approaches:

Switching feedstock from fossil, switching to renewable energy sources, and using carbon capture to avoid residual emissions.

The chemical industry can achieve net zero Scope 1&2 by deploying just three strategies (Figure 8):

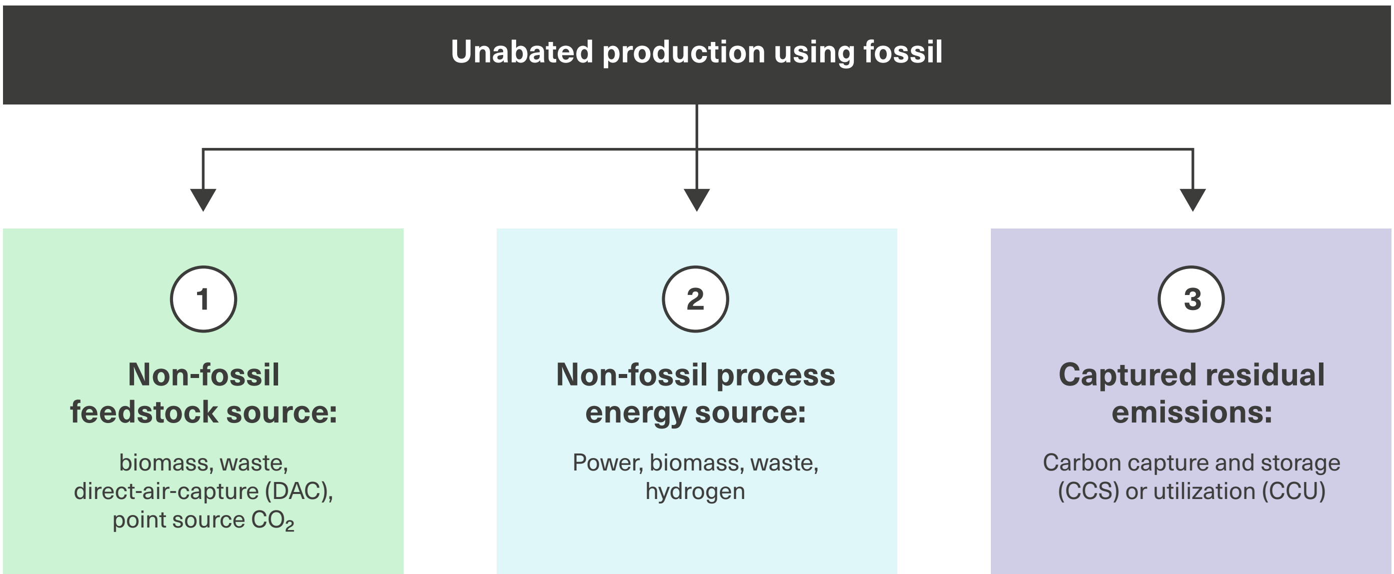
- **Switching the feedstock so that over 59-93% comes from sustainable sources by 2050,** up from <0.5% in 2020. Sustainable feedstock sources will be required to abate Scope 1&2 emissions from feedstock used as energy (e.g., crackers off-gases subsequently used as fuel for energy production on-site) and from carbon dioxide released as by a product of a reaction (e.g., gas reforming to produce hydrogen and subsequently ammonia). The new mix of feedstock will be balanced across new available pools comprising wastewater (17-20%) for fertilizer production, biomass (31-35%), waste (1-2%), hydrogen (9-12%), point source (9-15%), and direct-air-capture (0-15%).[25]

- **Switching the energy source so that 89-98% of production processes are powered by renewable energy sources by 2050,**[26] up from 2% in 2020. Energy substitution will be direct through renewable electricity (89-97%), although a large fraction of this share is used to produce green hydrogen. Biomass and waste will play a minor role in providing energy in both LC-ME and LC-NFAX scenarios (~1%).

- **Capturing emissions so that up to 60-400 Mt (LC-NFAX and LC-ME respectively) of carbon is captured annually from chemical production processes by 2050**[27] (Scope 1&2 only), such that CO_2 from chemical synthesis processes and/or the energy provision step is captured and permanently stored underground. Even after system efficiencies driven by demand reduction, the most economic scenario still relies heavily on CCS to achieve net zero.

Figure 8: Strategies to abate Scope 1 & 2 GHG emissions in the chemical industry

Abating GHG emissions will require three fundamental and complementary approaches to be leveraged



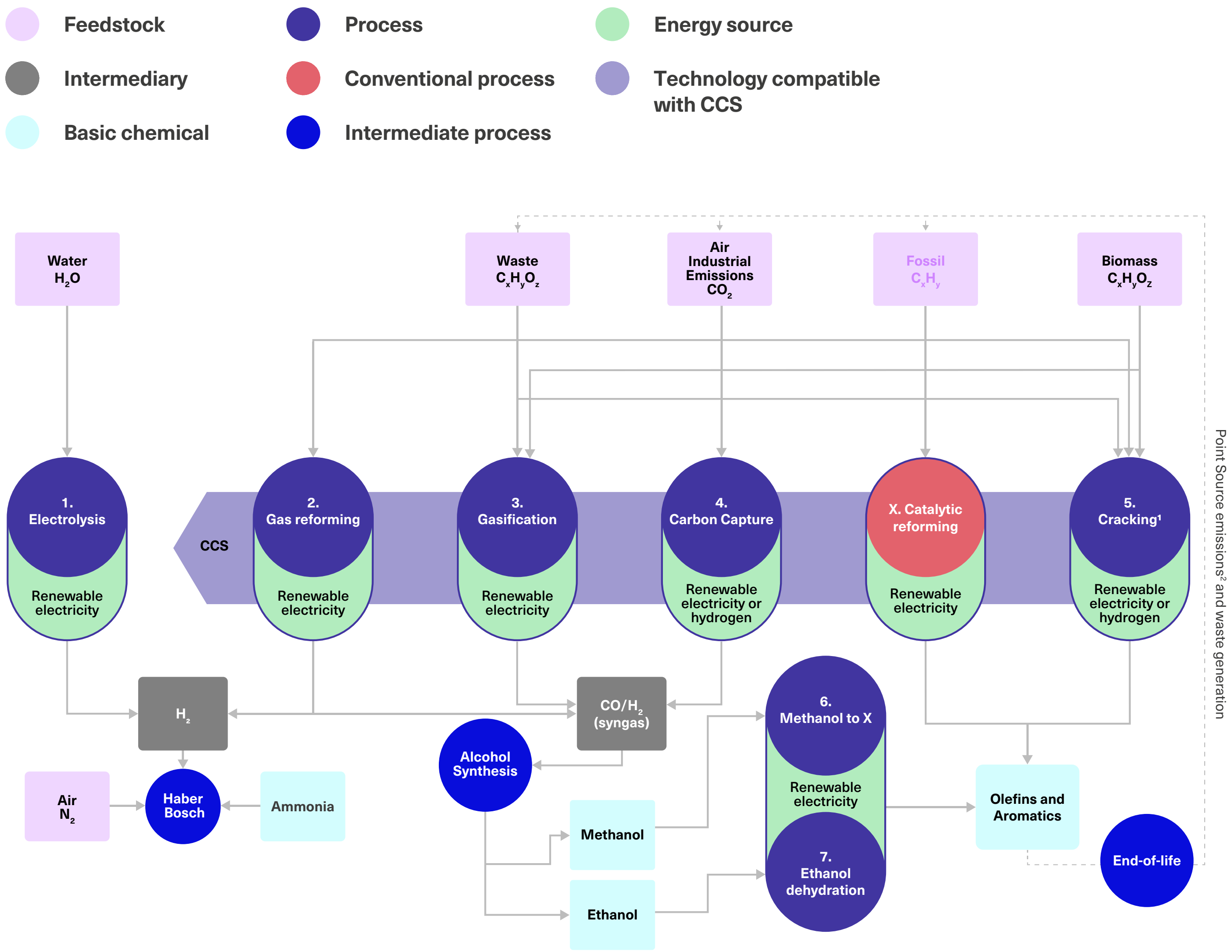
25. Weight percent in tonnes of raw feedstock required.
26. The energy from non-fossil sources is legacy capacity abated retrofitted with CCS and long term will be phased out after 2050.
27. Only includes CCS from chemical production processes; Scope 1 and 2 emissions for the chemical sector. Excludes CCS from incineration.

Seven processes form the basis of the new chemical industry.

The chemical industry will rely on seven key processes to achieve net zero Scope 1&2 and enable the application of feedstock shift, energy switch, and CCS (Figure 10).

Figure 9: Production process map of basic chemical intermediates

Five feedstock sources and eight processes form the basis of primary chemicals production, seven of which will be used to abate the system



Note: this figure exclude transition technologies (e.g. blue ammonia, blue hydrogen) (1) pyrolysis is considered as a sub-technology of the cracking system (2) point source encompass potential emissions from production processes, incineration but also other industries.

1 **Electrolysis is one of the technologies with the largest growth potential, representing 67-80% (LC-ME and LC-NFAX respectively) of ammonia production by 2050 as the most promising technology for the synthesis of green ammonia via the production of green hydrogen.** It is the only relevant alternative in a no fossil scenario, but requires significant investment to reach commercial scale.[45] The electrocatalytic conversion of water into oxygen and hydrogen is appealing from a feedstock point of view as it does not rely on carbon sources, unlike existing gas reforming technologies, and can be powered 100% by renewable electricity. Hydrogen can then be combined with nitrogen to produce ammonia (Haber-Bosch process), which is the conventional process today for creating ammonia. Electrolysis relies on metal-based electrocatalysis and faces significant material demand constraints, for example over rare metals such as platinum, as well as requiring major renewable power generation capacity expansion.

2 **Gas reforming capacity accounts for 2-15% of ammonia production and 2-38% of methanol, olefins and aromatic production by 2050, but will be highly dependent on the future of fossil feedstock and CCS.** The historically important thermal conversion pathway of methane into either carbon dioxide and grey hydrogen or methanol might be completely phased out by the respective growth of electrolysis and CCU. However, the technology is still highly relevant in a "most economic" scenario given its scale to date and opportunities to be retrofitted with CCS at lower cost. In the case of ammonia production, hydrogen is then combined with nitrogen (Haber-Bosch process). This route would require two upgrades to be retrofitted to reach a climate viable solution: the energy provision must be electrified, and the carbon emissions produced must be stored or utilized.

3 **Gasification of biomass or (plastic) waste will represent 1-2% of ammonia production and 3-8% of methanol, olefins and aromatics. It remains a versatile route towards both hydrogen and methanol and subsequently ammonia, olefins and aromatics in a net zero world, but is still in the early commercialization phase.** Thermal conversion of solid carbon-containing products (e.g., biomass, waste) into syngas can be followed by catalysis-driven conversion of the latter to produce chemical intermediates (e.g., methanol, ethanol). While biomass and waste gasification exist at scale for energy production, with almost no exceptions methanol has been produced at commercial scale via coal and petroleum coke gasification plants to date.[47,48] Gasification can also be combined with either electrolysis or CCS to appropriately rebalance (decrease) the C:H ratio to allow for Scope 1&2 abated methanol synthesis.[47] The scale of gasification will be limited by the inherent cost of the process, which is likely to make it uncompetitive in regions where hydrogen and renewable energy sources (RES) are expensive.

4 **Carbon capture and utilization (CCU) is expected to emerge as an alternative source of carbon for methanol production, representing 6-44% of methanol, olefins, and aromatics production by 2050.** The catalytic conversion of CO_2 (from direct-air-capture or point source industrial emissions) with green hydrogen can be directly transformed into methanol.[28] As a result, the future of CCU in the chemicals system is bound to the low-cost access to H_2 and CO_2. In a world where fossil is socially unacceptable, and waste and biomass gasification expensive or availability limited, CCU is emerging as a leading alternative to provide carbon on the provision that is it recycled.

28. CO_2 does not need to be converted to CO in this case.

5 **Steam crackers will remain essential assets as a route to produce olefins, representing 14-31% of olefins and aromatics production by 2050, and the process will be retrofitted in various ways depending on the regional opportunities.** Thermal conversion of distilled petroleum products (e.g., naphtha) or gas (e.g., ethane) are the most common routes to olefins today. Aromatics are also produced as by-products, but to a lesser degree. Crackers can be abated in various ways to deliver climate neutrality. To achieve this, the energy provision must be electrified or shift towards hydrogen or ammonia, and the feedstock sources must shift to incorporate biomass or waste (via pyrolysis or similar conversion technologies). Otherwise, any remaining Scope 1 carbon emissions must be captured and stored. Another abatement option is to upgrade the methane off-gas from the cracking process to methanol via syngas and then convert the methanol to olefins and aromatics via MTX processes, thereby avoiding emissions as well as increasing the high value chemical yield from the cracker.

6 **Methanol to X (X=olefins and aromatics, thus MTX) is likely to become the new technological platform for the synthesis of olefins and aromatics via non-fossil pathways. It represents 19-22% of the production mix by 2050, potentially reaching the scale of cracking today, especially as conventional technologies are decommissioned.** This offers the possibility that methanol will become the primary system feedstock, displacing naphtha. The catalytic conversion of methanol to olefins, based on coal as a source of carbon, is at commercial scale today but exclusively used in China.[49] MTX is emerging as the most preferred route to produce olefins from non-fossil feedstock such as biomass, waste and captured carbon. The process of converting methanol into aromatics is at an earlier stage in terms of development, but is the key pathway for the production of aromatics and is essential to fill the gap caused by decreasing production due to the decline in catalytic reforming.

7 **Ethanol dehydration will continue to grow modestly to remain among the most relevant technologies by 2050, representing 0-8% of olefins production.** The production of ethanol from crops through fermentation is already a well-established market, producing >120 Mt.[50] By 2050, the production of ethanol from the conversion of syngas (e.g., via CCU or gasification), which has been proven at scale, is expected to be more competitive than conventional technologies (e.g., via dedicated crops and fermentation).[47] Different syngas to X technologies are expected to compete on the market (e.g., leveraging synthetic routes or biotechnologies) creating opportunities for the alternative ethanol route. Consequently, ethanol dehydration will be competitive with methanol to olefins (MTO) where relevant.

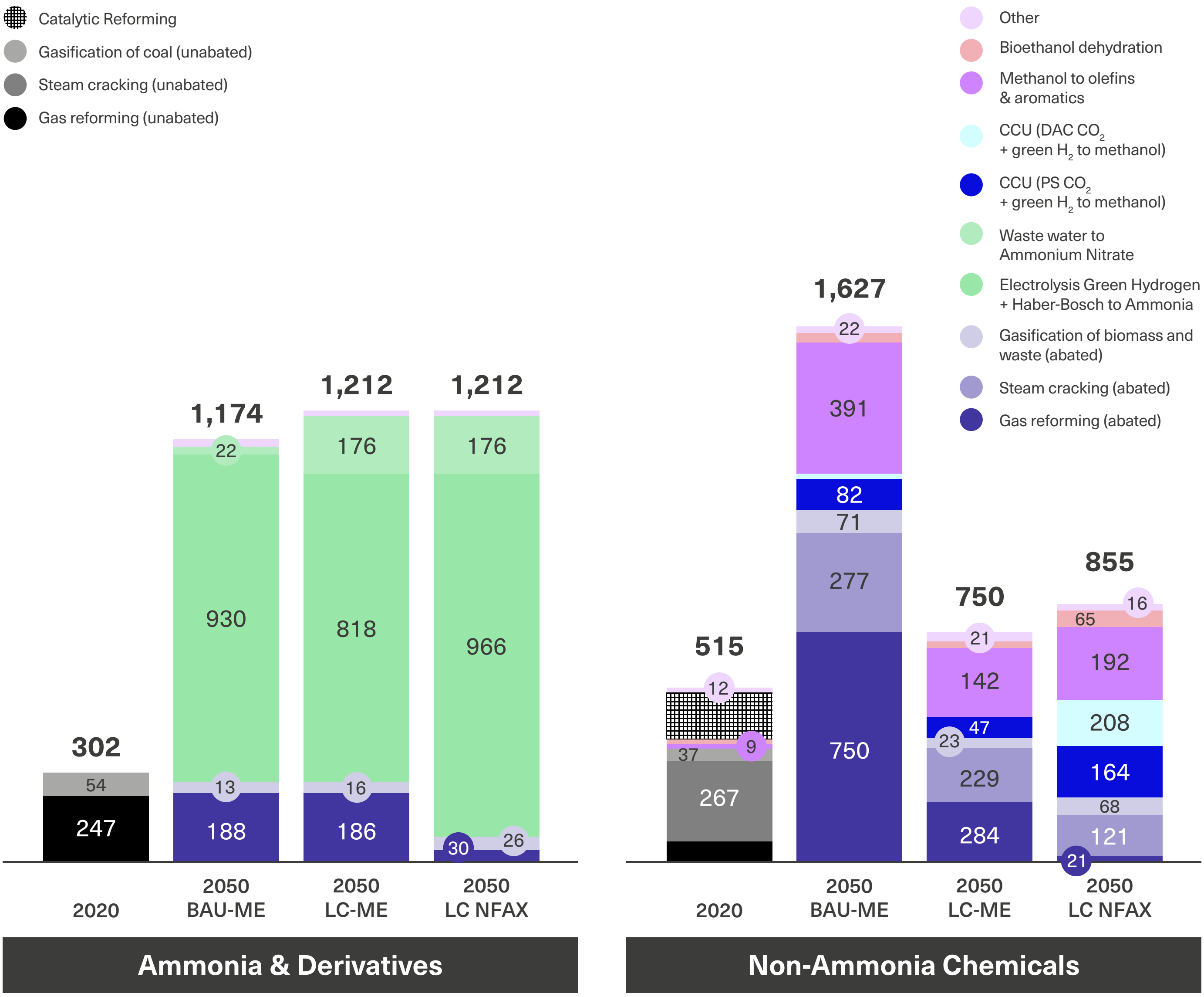
X **Catalytic naphtha reforming will decline and ultimately disappear from the technology mix by 2050, having been a significant source of basic chemical intermediates, as a result of the decline in fuel refining demand.** Today, by-products from the catalytic reforming of distilled petroleum products (e.g., naphtha) deliver the majority of aromatics production, and catalytic reforming's prime function is to provide octane for the gasoline pool. As gasoline demand declines towards zero, catalytic reformers will likely cease to operate, and their aromatic by-products will no longer be available.

The mix of these technologies across scenarios can be seen below (Figure 10) in which it is evident that ammonia production is dominated by electrolysis to produce green hydrogen for Haber-Bosch. However, olefin and aromatic production varies between dependence on abated fossil technologies such as steam cracking and gas reforming in LC-ME vs LC-NFAX which depends more heavily on CCU and MTX for faster abatement. More detail on this will be discussed in the coming chemical deep-dive sections.

Figure 10: Chemicals production split by technology grouping

In 2050, Ammonia is consistently dominated across scenarios by a single technology, electrolysis to produce green hydrogen for Haber-Bosch, while the future of olefins and aromatics production depends on a choice between abated fossil and non-fossil production technologies

Chemicals Production split by technology grouping
Mt Chemicals produced



Note: 1) Both the methanol production as well as chemicals produced from methanol are included. 2) Electrolysis includes the production of urea, which requires CO_2 and could also be included under CCU. 3) 2050 LC-ME corresponds to the low circularity demand scenario presented in section 1, ammonia differs due to the use of different units: Mt of ammonia in demand scenario vs Mt of urea and ammonium nitrate in production scenarios. Total non-ammonia chemicals may vary vs other demand charts due tp use of methanol as a feedstock for olefins & aromatics meaning proportions will vary by use of the MTX pathway.

By 2050, the new mix of production processes will require greater flexibility in output balances compared to what has been proven at scale to date in order to respond cost-effectively to varying balances of demands within olefins and aromatics. With new technologies emerging, the mix of chemical outputs (products and by-products) will change to a degree. Specifically, the model suggests that the shift from crackers to MTO technologies will lead to an oversupply of propylene to meet ethylene demand,[29] while the shift from catalytic reforming to methanol to aromatics (MTA) may lead to either an oversupply of benzene or xylene, depending on the technology used. This tension between production technologies and demand requires improvements in MTX catalysis, but novel processes will allow more flexibility and enable producers to tune process outputs to market demand.

The technology roadmap to achieve net zero Scope 1&2 for the industry laid out in this report leads to the conclusion that:

- Conventional technologies[30] employing fossil as fuel and feedstock are fundamentally unsuited to a net zero world in their current state and will require a complete shift (decommissioning, retrofit, upgrade) to achieve Scope 1-2 net-zero, regardless of the time horizon.

- Shifting towards new energy sources without switching feedstock (e.g., remaining predominantly fossil) will require CCS to be implemented at scale across the industry and at chemical end-of-life. As most processes have efficiency losses, and despite greater utilization of heat between processes within a co-located cluster, emissions would occur as soon as the fossil carbon used as feedstock is consumed. If the chemical industry perpetuates the fossil feedstock paradigm, the successful scaling of CCS will be a pre-requisite for net zero, which is strategically risky and will still result in some residual emissions.

Shifting toward new feedstock and away from the fossil plus CCS system will require a more radical change in infrastructure and significant investments into new plants, but is more likely to be a successful climate mitigation strategy. The switch in feedstock will be necessary but require deep transformation to ensure proper supply to the industry and sufficient handling of feedstock consistency. However, the alternative of wide-spread CCS application is inherently riskier and still does not lead to net zero due to upstream Scope 3 emissions and incomplete CO_2 capture in CCS (see Chapter 6 of the report for implications of infrastructure costs).

The following section examines four chemical sub-systems in detail, starting with ammonia, followed by methanol, then olefins (ethylene, propylene and butadiene) and finally aromatics (BTX – Benzene, Toluene, Xylene), whose future are interlinked from a chemical, feedstock and technology process perspective. The need to apply the three abatement strategies and seven processes described in this chapter in very different ways to achieve net zero Scope 1&2.

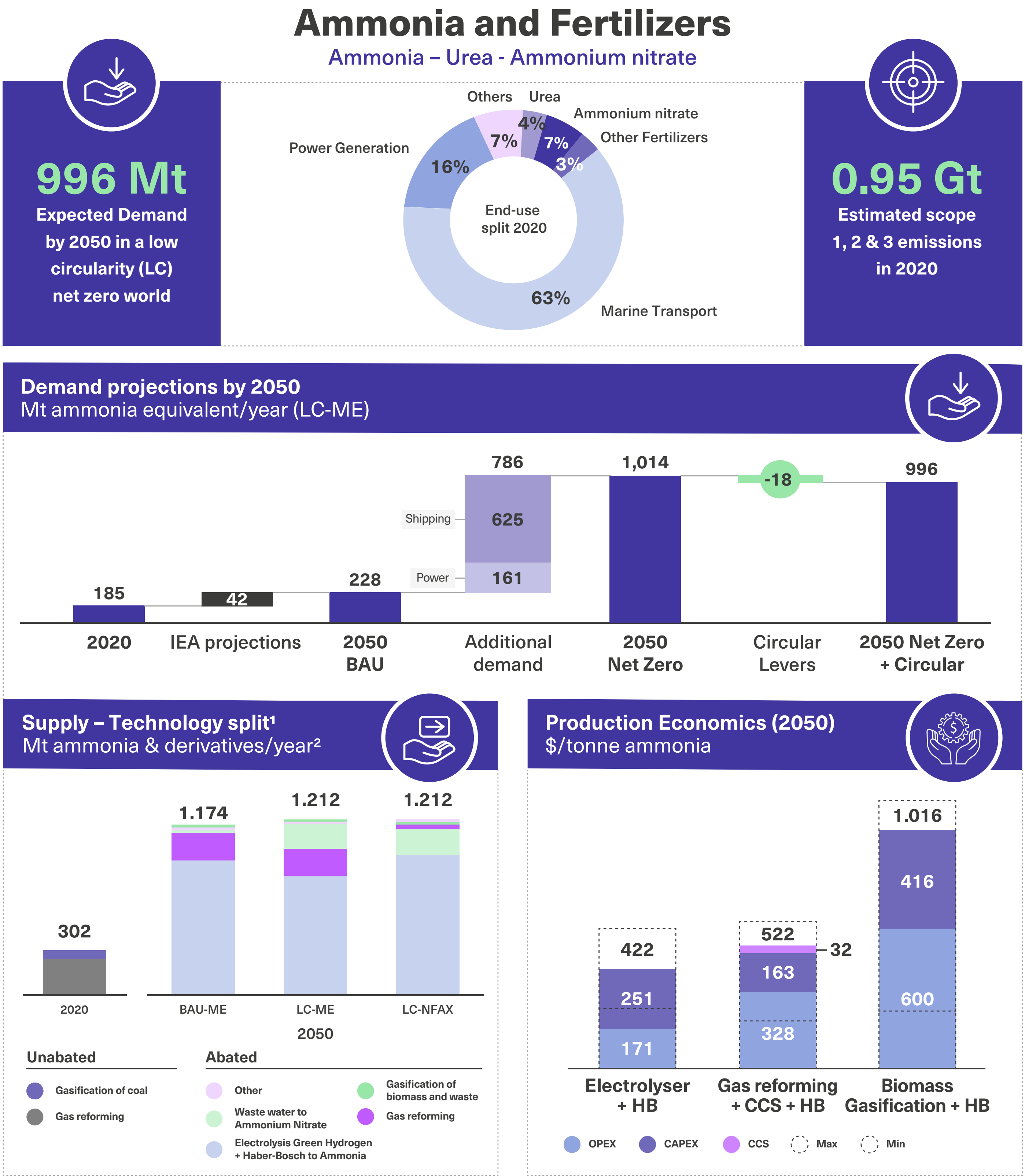
29. Our research shows that, on average, crackers tend to produce more ethylene than propylene, while MTO processes tends to produce more propylene than ethylene. The 1-1 subsitution of crackers by MTO processes for the production of olefins will therefore not be straightforward.

30. Defined as technologies fed with fossil feedstock and without CCS used for the production of chemicals today , for example catalytic reforming, steam reforming, and steam cracking.

Ammonia as fertilizer and low-emissions fuel.

Abating ammonia production Scope 1&2 is different to abating other basic chemical intermediates as it is achieved by switching from high emissions hydrogen feedstock production (grey) to two low emissions upstream technology pathways: gas reforming plus CCS (i.e., blue hydrogen), and electrolysis (i.e., green hydrogen).

Figure 11: Ammonia demand and supply overview by 2050



Notes: (1) The model is designed to reach higher production capacities than required by demand. The precise oversupply margin is defined by asset retirement in the case of oversupply and differs by scenario. (2) Values are calculated as sum of Mt ammonia/ammonium nitrate/urea and not ammonia equivalent.

Ammonia contains nitrogen, it does not contain embedded carbon and therefore is fundamentally different from other basic chemical intermediates in scope (Figure 11). It is one of the highest volume chemicals manufactured today, with 185 Mt produced, ~70% of which is exclusively used for producing nitrogen fertilisers.[23] As ammonia production is the largest contributor to Scope 1&2 emissions by the chemical industry, abating its emissions is critical to enable a sustainable future, especially as ammonia is considered the most promising pathway toward decarbonizing shipping and power in specific countries.[31, 6–8,23,51] In addition, despite greater efficiency in use, fertilizer production will continue to grow to feed a growing population.

The synthesis of ammonia is straightforward but expensive, with hydrogen production the main emissions factor requiring attention. As of today, ammonia is synthesized via the Haber-Bosch process, which is a high temperature and high-pressure process. This fundamental technology has not changed significantly for a century and is not expected to in the near future. The Haber-Bosch process itself has no mid-high technology readiness level (TRL) contender, although alternative catalysis and processes to reduce the temperature and pressure are being researched.[32] Additionally, the process is electrifiable at large scale (pumps, compressors, heating) , making the transition if not easy at least reasonably achievable.[23,52] However, upstream, the production of hydrogen feedstock requires attention as almost all emissions occur at this stage.[53] Hydrogen can come from three sources: (1) the conventional route: gas reforming; (2) electrolysis, which is expected to be available at large scale by 2025; and (3) coal, biomass or waste gasification.[33]

Green hydrogen will dominate the production of low carbon hydrogen compared to blue hydrogen (fossil + CCS) due to lower production costs in almost all regions. The falling costs of electrolysers and renewables make green hydrogen from dedicated renewables sites very favourable in cost compared to greenfield blue ammonia plants. Beyond economics, the lack of CCS requirement for green hydrogen is easing the infrastructure transition requirements. While some of the existing gas reforming and coal gasification infrastructure may be economically retrofitted with CCS units, the analysis suggests blue ammonia will represent a small overall share of total ammonia production (<15%, largely dependent on gas price assumed). Uncertainties around upstream methane emissions and residual CCS emissions make electrolysis also more desirable from a climate perspective. Given the significant majority of low carbon hydrogen will be green hydrogen derived via electrolysis, this report focusses predominately on green rather than blue hydrogen.[45] Deploying green hydrogen for zero-carbon ammonia production is crucial, as completely abating the emissions from the significant ammonia production growth will be imperative to get the global climate transition right, probably more so than for any other chemical.

31. Non-CO_2 emissions from ammonia combustion (i.e., N_2O and NOx) can be abated with high efficiency in selective catalytic reduction (SCR) systems.

32. Energy efficiency of the process has been optimized significantly over the last decades getting increasingly close to theoretical minimum energy required for the reaction.

33. Other technologies not mentioned here are considered below TRL 7 and excluded from the analysis (e.g., ammonia electrocatalysis).

By 2050, the future of ammonia production will decouple from gas reforming. In both BAU-ME and LC-ME scenarios, the technology only accounts for 16% and 15% respectively, falling to just 2% in the LC-NFAX scenario. Instead, electrolysis will emerge as the dominant alternative technology pathway, accounting for 67-80% of ammonia production by 2050. Electrolysis will develop fastest in regions where abundant, low-cost renewable energy is available to produce cheap green hydrogen. In a world where regulatory pressure increases on fossil feedstock, or where a sufficiently high carbon pricing mechanism is put in place, the larger abatement potential from electrolysis will create incentives to shift faster, despite operating challenges around energy intermittency.[34] It is worth noting that the relative competitiveness of each technology – determining which comes out as a front runner in all pathways – is dependent on the price of natural gas and the price of power: a gas price increase to above $10/MMBTu or a RES power price below $45/MWh would be enough to make electrolysers equal to the gas reforming plus CCS system.[35] In all scenarios, gasification remains small due to higher costs in most regions.

Ammonium nitrate production is expected to increase as it is less Scope 3 emissions intensive than the alternative (i.e.,urea), and because it is the only intermediate where a climate efficient process allows direct synthesis, by-passing ammonia production.[34] Ammonium nitrate is one of the largest nitrogen-based fertilizers (after urea), with 48 Mt of production in 2020.[23] Filtration of wastewater can yield ammonium nitrate. Given its affordable cost and feedstock availability,[36] wastewater is overwhelmingly available and an externality in most countries; therefore it needs to be valorised. Wastewater is likely to be recovered instead of synthesized via ammonia, but it often requires significant scale to justify the initial capital investment. Additionally, ammonium nitrate is 28-41% less Scope 3 emissions intensive than urea, making the substitution an attractive option for limiting N_2O emissions.[56] As a result of its lower Scope 1&2 production and Scope 3 emissions, ammonium nitrate production is expected to benefit from a shift away from urea and reach 157-236 Mt by 2050 for fertilizer applications only.

34. Haber-Bosch requires a constant hydrogen stream given its scale and temperatures, therefore, if using electrolysis, it requires mitigating intermittency of renewable energy. This can be either in the form of back-up connection to the grid or an on-site hydrogen storage solutions to act as buffer.

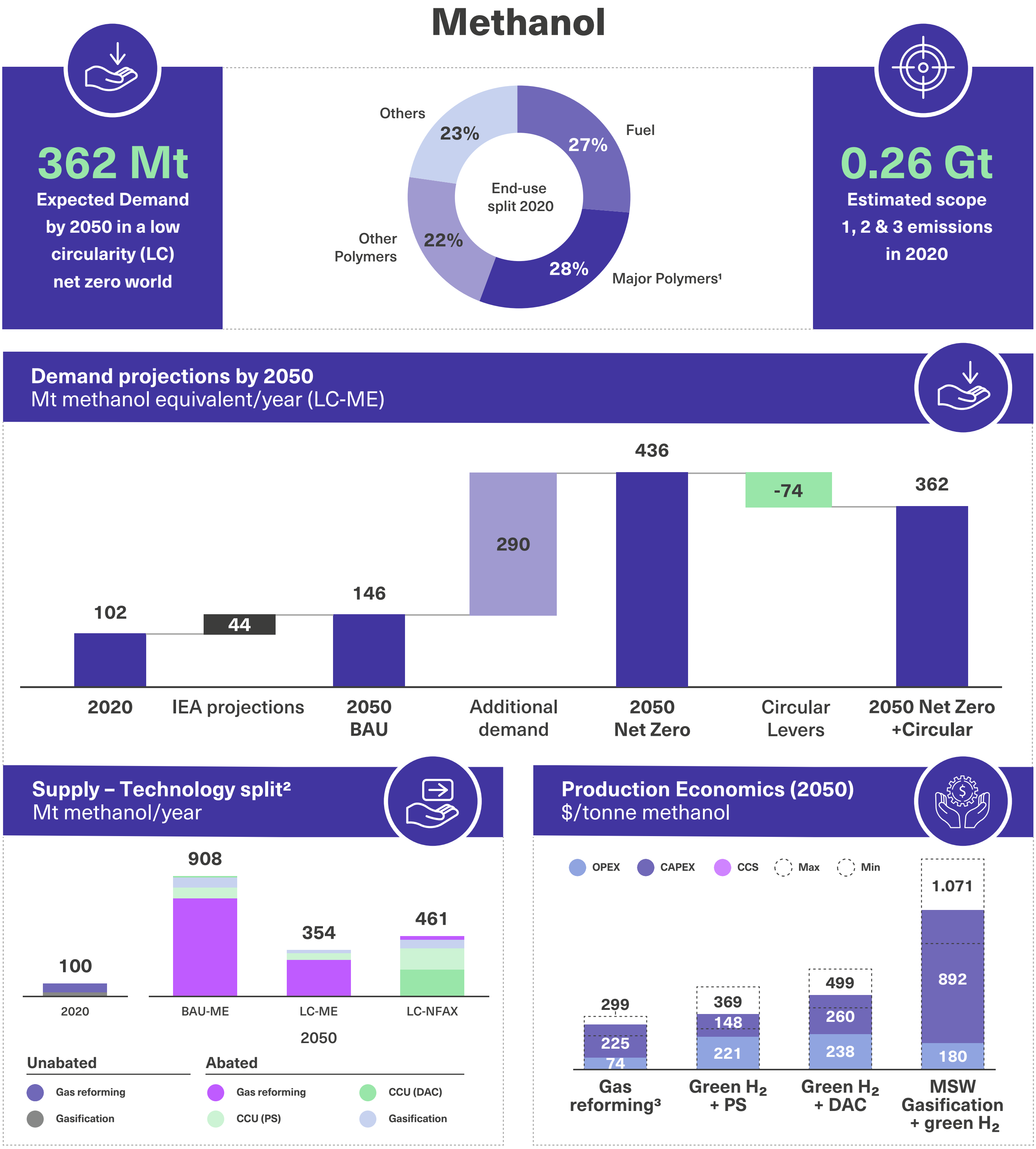
35. All of these price moves are within the realms of probability, as demonstrated by market price history (54,55).

36. Expert interview.

Methanol, the new platform chemical for alternative carbon.

Methanol will become the cornerstone of carbon management in a net zero world via production routes from all carbon sources to key carbon outputs.

Figure 12: Methanol demand and supply overview by 2050



Notes: (1) Includes PE, PP, PS, PET, PUR, PVC (2) The model is designed to reach higher production capacities than required by demand. The precise oversupply margin is defined by asset retirement in the case of oversupply and differs by scenario. (3) Combined reforming, fully abated scope 1&2 (4) CAPEX and OPEX from lowest and average cost RES regions presented.

In this analysis, methanol emerges as a key new system input by 2050, allowing carbon to be recycled back into the chemicals system and displacing naphtha, thus enabling the net zero transition (Figure 11). Methanol can be produced from biomass, municipal waste, or CO_2 in combination with green hydrogen and therefore enables a fully circular CO_2 life cycle. The critical switch of carbon source from fossil to waste, biomass and atmospheric CO_2 requires a fundamental shift in the infrastructure of the chemical industry, away from steam crackers and towards MTX (see Chapter 5).

With 102 Mt in 2020 and growing to 362-511 Mt in 2050,[37] methanol will become a central building block for many chemicals in the industry. Methanol is already the primary chemical with the highest diversification of its end-product portfolio, with 28% being used for the major polymers,[38] 22% used for lower volume polymer applications,[39] 27% used for fuel, and the rest used in a wide range of other chemical products. Methanol's future is intrinsically linked to the other carbon-based primary chemicals, as it can be converted to olefins via MTO and MTP (methanol to propylene) and aromatics via MTA. Methanol will also be the feedstock for all critical derivatives for polymer production: ethylene, propylene, benzene, xylene and formaldehyde. Other methanol demand remains flat as its use as gasoline's blend component is abandoned and circular consumption and mechanical recycling levers are implemented. Moreover, methanol is not expected to become a key energy carrier for shipping fuel, energy storage, or road transportation in a net zero scenario because it emits carbon dioxide on combustion. It can therefore at best be carbon neutral in these applications, whereas the use of methanol as a chemical feedstock may lead to overall negative life-cycle emissions (see Chapter 4).

In contrast to ammonia, the abatement challenge for methanol is two-fold: realizing a simultaneous 4-5 times growth in demand while abating production emissions, ideally via a feedstock switch towards sustainable carbon sources. Today, around 37% of all methanol production is based on unabated coal gasification and the overall methanol emissions intensity globally is on average about 3 tonnes of CO_2 per tonne of methanol. Therefore, abating the emissions from methanol production is essential for the abatement of the entire chemicals system. As discussed in Chapter 3, non-fossil feedstocks are also preferred from a Scope 3 downstream perspective.

37. The demand for MTX means that LC-ME and LC-NFAX have different demand profiles for methanol.
38. PE and PP via MTO, minor contributions to PVC, PET and PU.
39. Predominately resins produced via formaldehyde derivatives.

However, non-fossil production methods are more expensive than those based on fossil feedstocks, in particular natural gas. This is in part driven by the high capex and energy intensity of gasification. Moreover, large amounts of green hydrogen (10 Mt in LC-ME and 73 Mt in LC-NFAX) are required for the synthesis of methanol from waste, biomass and CO_2.[40] While costs for green hydrogen are declining, they need to drop below 1 $/kg for it to become cost competitive with fossil production technologies, which is unlikely to happen in locations where fossil is available. The formation of a green methanol commodity market is therefore essential to overcome the production cost premium.

By 2050, methanol production is dominated by abated gas reforming (80%) in the LC-ME scenario and by CO_2 + green hydrogen conversion (81%) in the LC-NFAX scenario. Gasification of coal (+CCS), biomass and waste contribute smaller shares of total production (6-15%). The mix of different gas reforming technologies, complemented with CO_2 point source and DAC, will play a major role in future production.[41] The up-scaling of methanol production relies on CCS (53 Mt in LC-ME) for blue hydrogen production, and the availability of CO_2 as a feedstock (513 Mt in LC-NFAX).

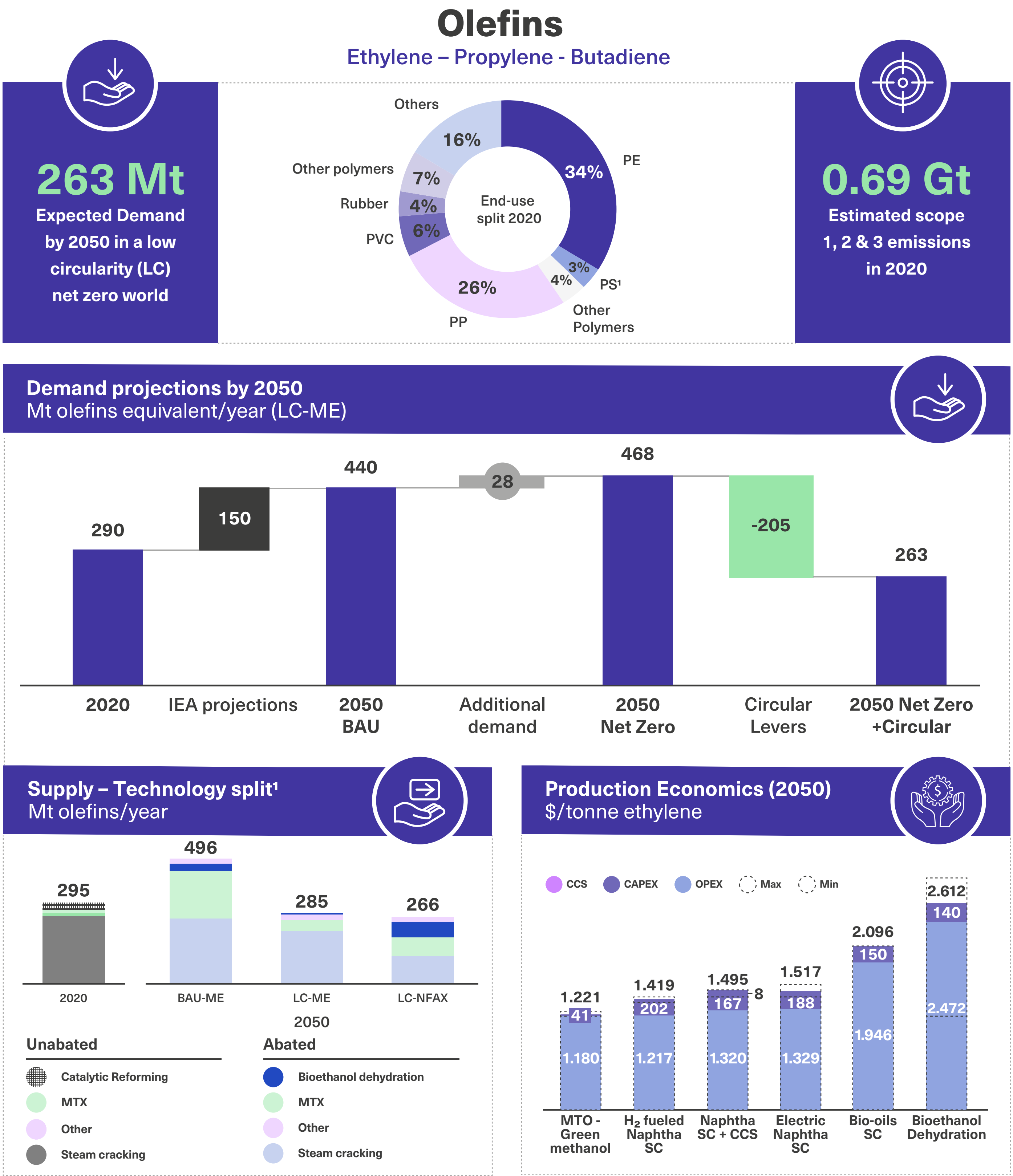
40. Green hydrogen would be co-fed to fully utilize all carbon in the waste and bio feedstocks before entering the methanol synthesis reactor.

41. Gas reforming can be abated via CCS of process and flue gas emissions, electrification of heat provision, or via adjusting the reforming process to avoid any additional heat input and the full conversion of process carbon.

Olefins: challenges and opportunities.

Olefins will continue to be a predominantly cracker-based industry in a net zero world and the rise of MTO will heavily depend on the future of fossil as a feedstock.

Figure 13: Olefins demand and supply overview by 2050



Note: (1) The model is designed to reach higher production capacities than required by demand. The precise oversupply margin is defined by asset retirement in the case of oversupply and differs by scenario. (2) SC = steam cracking (3) All SC business cases include a off-gas upgrade unit via methanol synthesis and MTO to fully abate scope 1&2 emissions

With the three major olefins representing 290 Mt in 2020 (ethylene 56%, propylene 39%, and butadiene 5%), olefins have incontestably become the cornerstone of the chemical industry's ability to produce a wide diversity of products, especially polymers, which represent 84% of their use (Figure 13). While hundreds of different polymers exist, five of them – poly(ethylene), poly(propylene), poly(ethylene terephthalate), poly(vinyl chloride) and poly(styrene) – represent 73% and are used across almost all sectors. The continuous cost reduction in olefins production has partially fuelled the growth for low-cost plastic over the last century and is the basis of the non-ammonia chemical industry known today.

Combined demand for olefins would reduce by 28-50% from 2020 to 2050 in a world where elimination, substitution, and upstream recycling[42] are leveraged across just four industries – transportation, construction, fast moving goods, and textiles. Reduction is the most important lever and will mostly come from packaging and construction, followed by transportation, assuming the scaling of new consumption patterns (e.g., packaging reuse, compact living, mobility-as-a-service). Mechanical recycling and other recycling technologies will play an important role in reducing demand for basic olefins, but will not come close to displacing demand for virgin plastic. This analysis suggests that recycling capacity will scale aggressively by 4-fold, from 23 Mt in 2020 to 95 Mt in 2050,[43] but still represent only 40% of combined virgin and recycled plastic demand by 2050.

Demand for olefins related to the net zero transition, especially ethylene, will require an additional 28 Mt. Most notably, with the surging demand for wind and solar, demand for olefins as a basic component will increase. Solar panels will require a range of specialty chemicals such as ethyl vinyl acetate (EVA) and fluoropolymers (e.g., PVF, PTFE), creating significant demand for additional ethylene. Wind farms will require blades, whose core structure might be made of PET among other materials and require a range of more technical composite materials (e.g., epoxy, PVC, PUR).[25]

42. Includes mechanical recycling, depolymerization and solvent-based recycling. It excludes pyrolysis and gasification which ultimately produce olefins and therefore do not reduce demand.
43. Calculated on an olefin-basis not on polymer basis. Therefore, mass excludes all non-olefinic polymer functions.

Olefin demand can be met by methanol to olefins production (15-26%) as well as hydrogen and ammonia fired, electrified and CCS-fitted crackers (43-75%). The rest will be met by other smaller-size technologies including bioethanol dehydration. Regulation may ultimately be required to force retrofitting and/or decommissioning of existing crackers in a world where demand growth is flat and the need to build new capacity is not pressing. MTO is the most relevant pathway to produce sustainable olefins, especially in a no-fossil future, as there is limited supply of waste and biomass feedstock and MTO will be complemented by equally relevant bioethanol dehydration (24% of olefin production in LC-NFAX). On-site upgrade of crackers with small MTO units to valorise off-gases while abating Scope 1 emissions will be competitive from 2035, due the decreasing cost of zero carbon methanol. In addition, electric crackers are only found to be economical on a new-built basis, so most existing cracker retrofits will use cheaper available options (e.g., hydrogen-powered crackers or CCS) in a world with stalling demand. The future of electric crackers therefore also depends on the future of olefins demand, and whether new-build will be needed or not.[44] Finally, in a no-fossil scenario, ethane crackers have been found more complex to retrofit given their lack of flexibility in switching feedstock sources.[45] As a result, ethane crackers will need to be phased out.[46] By contrast, naphtha crackers, while benefitting from a wide range of feedstock substitutes (e.g., pyrolysis oil from plastic waste or bio-oils), might also benefit from the deployment of technologies in other industries, especially the aviation industry as naphtha-like grades are co-produced with sustainable aviation fuel. Overall, the analysis suggests that most existing crackers will be retrofitted rather than decommissioned, if not because it makes economic sense, at least to safeguard existing onsite synergies with downstream processes.

The ability to flex product output ratios among olefins is needed as up to ~75% of olefins are co-produced and certain products (e.g., propylene) might become oversupplied. In the chemical space, supply has an important role in structuring demand given the physical constraints of chemical processes. For example, today, around 95% of butadiene is produced as a by-product of the steam cracking process, the main purpose of which is to produce ethylene and propylene. This by-product oversupply resulting from process output ratios is also true for MTO processes. Oversupply of base chemicals presents a significant risk to the re-structuring of demand based on new market prices and availability, but an even greater risk is the slower adoption of reduction, substitution, and recycling levers – especially in an ambitious circular scenario.[47] This must be resolved by developing processes with better capabilities for fine-tuning chemical outputs to justify investments in MTX processes. Additionally, some plants might need to be shut prematurely if circular objectives from downstream industries are met, as today's capacity would in some scenarios already meet projected 2050 demand.

44. Note that the analysis considers existing commitments for new-built fossil run crackers (e.g., in China).

45. Biogas technologies have been considered unable to produce volumes require to substitute ethane cracker feedstock.

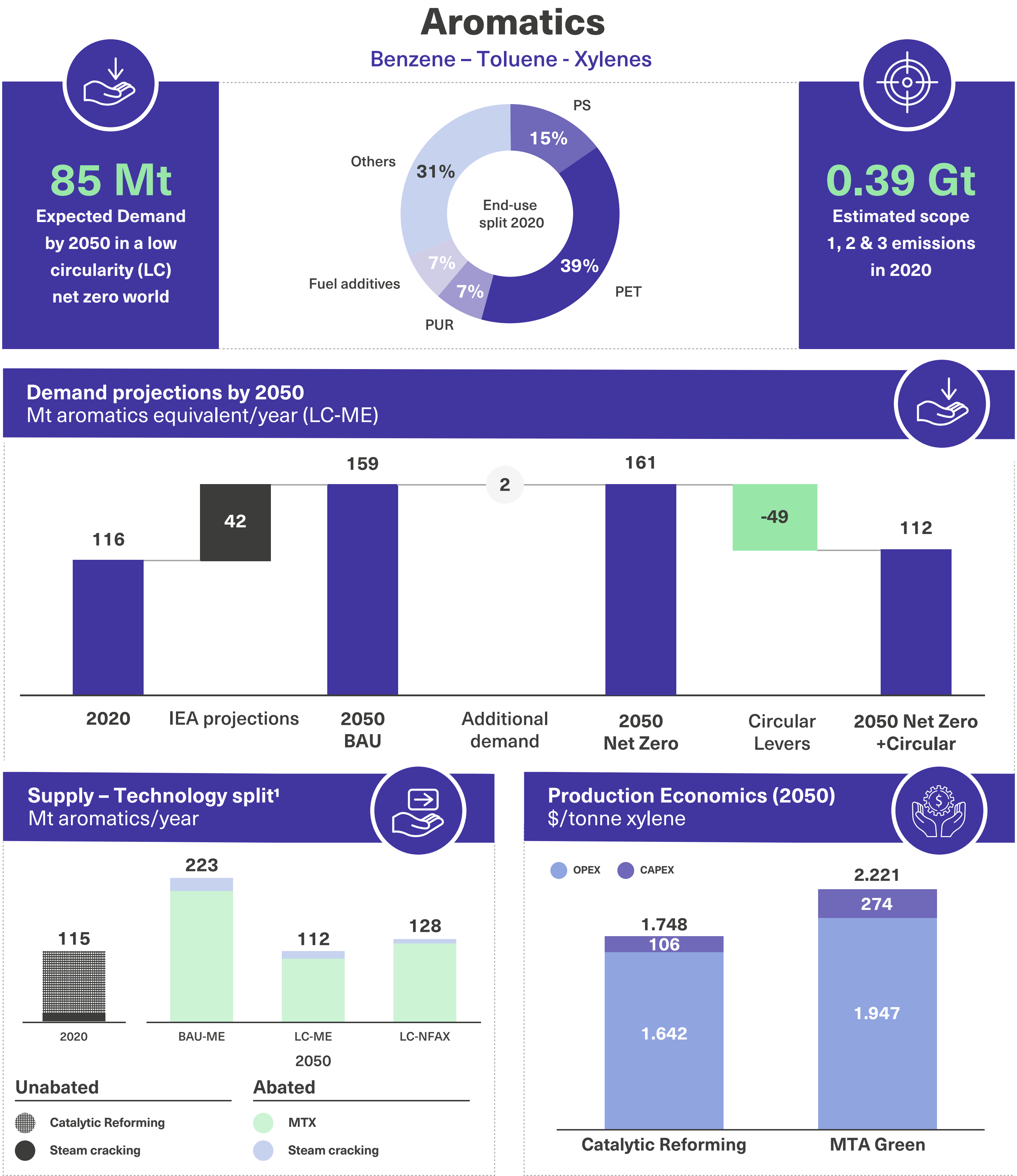
46. It highlights the difficulty some regions dominated by ethane cracker infrastructure will have to move away from fossil feedstock (e.g., North America), which might create localized lock-in effects.

47. Given the long asset lives of the chemical plants, the risk of market distortion through oversupply is real. In such a world, an opposite effect on demand may arise e.g., (a) polymer prices may drop significantly and may potentially lead to increased demand, or (b) entire plants may shut down potentially leading to demand across several olefins as co-products would also be lost.

Aromatics: the need for a fundamental shift in production.

Aromatics are likely to be the chemicals most profoundly affected by the transition to net zero due to the demise of catalytic reforming as a main source of production.

Figure 14: Aromatics demand and supply overview by 2050



Notes: (1) The model is designed to reach higher production capacities than required by demand. The precise oversupply margin is defined by asset retirement in the case of oversupply and differs by scenario. Larger discrepancies are observed for aromatics due to poor fit between MTA production mix profile and demand ratio of benzene:toluene:xylene.

At 116 Mt in 2020, demand for aromatics – benzene (36%), toluene (23%), xylenes (40%), referred to collectively as BTX[48] – is significantly smaller in volume compared to olefins, ammonia, and methanol (Figure 13). Like olefins, aromatics are mainly used as building blocks for polymer applications, of which just three – PET, polystyrene and poly(urethane) – represent 61% of total consumption. Toluene is the least valuable of the aromatics, its main uses stem from blending into the gasoline pool, producing isocyanate for polyurethanes, and the onward production of benzene and xylene.

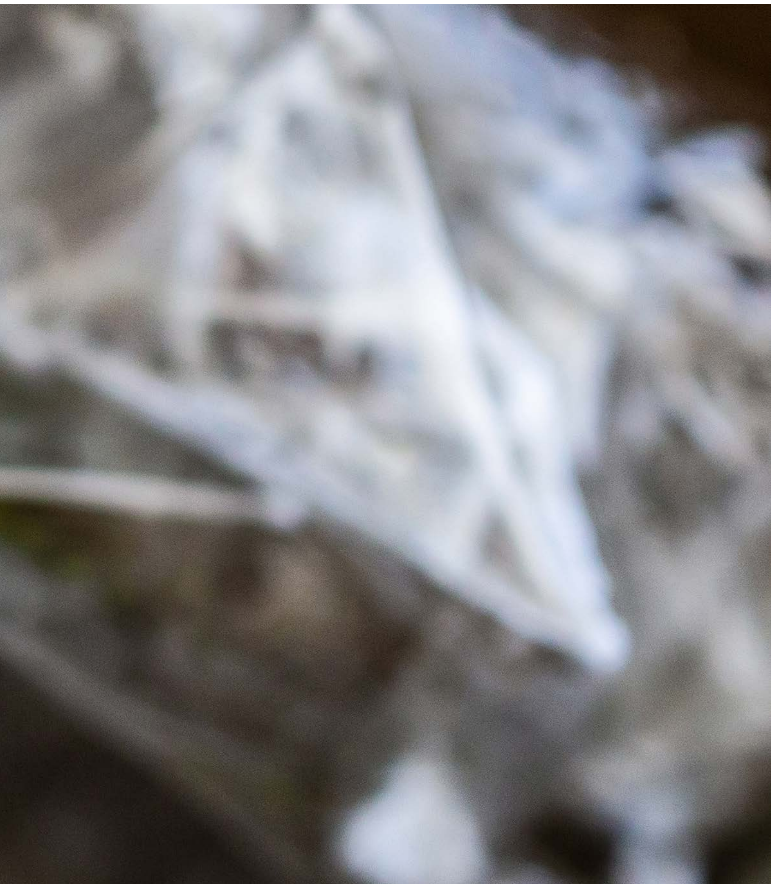
Demand for aromatics is set to remain mostly flat by 2050 as growth is levelled off by the expansion of downstream circular strategies. Projected demand growth is cancelled by the combination of the three levers over the next 30 years: (1) elimination and recycling of PET bottles and films will considerably impact the PET market that represents over 80% of the xylenes outlet; (2) the reduced need for fuel will eliminate over 25% of demand for toluene, for which value is likely to decrease even further; and (3) the potential reduction in the use of polystyrene across industries, for various economic and social (rather than technical) reasons, may considerably affect benzene demand as it represents over 30% of polystyrene demand.

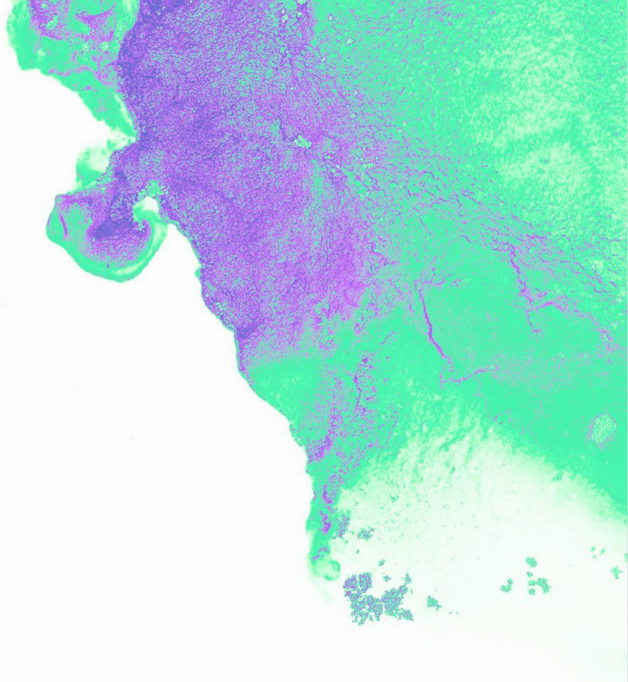
Today, most aromatics are produced as a by-product in fuel or olefins production; in the future, fuel production will undergo a necessary decline and olefin production will produce less aromatics. The expected decline in fuel use, and therefore reduced need for refineries across the world, means less aromatics will be available from that source. In parallel, the shift in olefin production processes will also reduce aromatics availability. Cracker retrofitting (e.g., change to feedstocks containing less aromatics and naphthenes) will also mean less aromatics in the output ratio, and alternative olefin production processes (e.g., MTO and ethanol dehydration) will not produce any aromatics.

48. These percentages are pre-toluene conversion. Toluene is, in some regions, considered a by-product and commonly converted into benzene and xylenes which are higher value chemicals. Xylenes in this report include the 3 isomers para-, ortho-, meta-xylene.

To date, MTA constitutes the only existing route to a sustainable supply of aromatics decoupled from that of olefins in a net zero world. In a world shifting away from fossil, MTA is therefore the only alternative, which constitutes a technology risk for the industry. Given the outlook on fuel and olefins discussed above, getting MTA technologies to a higher TRL, so that it can be demonstrated commercially at scale, is absolutely key to the net zero transition.

Similarly to olefins, there is a chronic risk of oversupply of one of the aromatics (benzene, toluene or xylene) unless production technologies (e.g., crackers, MTA) develop more flexible product slates. As explained for olefins in the previous section, given the physical constraints of chemical processes, supply plays an important role in structuring demand in the chemical space. The analysis performed for this report suggests that aromatics processes are the least flexible over changes in demand. The production ratio for the main aromatics will not exactly match the change in demand, that affects each one differently (e.g., different sectors, timelines, materials), therefore creating some oversupply. As for olefins, oversupply may not occur as demand may adjust to supply, but it will lead to reduced incentives for downstream industries to implement circular levers to their full extent. The future of xylenes and PET is especially critical, but it would require further analysis to understand whether PET demand can influence xylenes production (and therefore all aromatics production), or whether xylene production will be stronger, thereby slowing the incremental use of recycled content or de-incentivizing it for PET elimination.





Chapter 3:

The elephant in the room – how to address feedstock and end of life emissions (Scope 3)

~64% of in-scope emissions of the chemicals system lie in Scope 3. Reaching full net zero therefore requires changing the feedstock carbon source, decoupling from fossil, and changing the end-of-life carbon destination from GHG emissions to recycling and sequestration.

Chapter summary

The vast bulk of total in-scope system emissions stem from Scope 3 (~64% today). Therefore, abating Scope 3 is the biggest driver for system emissions reduction and the driver of the bulk of the technology shifts needed to abate the system.

Decoupling from fossil feedstock increasingly mitigates system transition risk. Fossil faces multiple, compounded risks in its future and the unilateral dependence upon it for feedstock and energy sources is a highly risky strategy towards 2050.

Therefore, there is an imperative to shift to renewable carbon feedstocks such as waste, point source, direct-air-capture (DAC), and biomass as they offer an alternative means of low emission production that leaves more fossil carbon in the ground.

There is no silver bullet alternative feedstock: each of these renewable feedstocks entail multiple trade-offs around cost, energy density, mobility, ubiquity, abundance, and impact on planetary boundaries, so securing access to a diversified range of feedstocks is advisable to de-risk production.

Alongside carbon, hydrogen feedstock will also need to be secured, amounting to 20-50% of global green hydrogen production by 2050, predominantly for feedstock to enable the use of these alternative carbon sources but also to power some hard-to-abate processes.[13]

Circularity can extend beyond material boundaries into a broader concept of carbon circularity via use of pyrolysis, gasification, and incineration +CCU to drive higher levels of molecular circularity withing the system.

The carbon density of olefins and aromatics means that downstream Scope 3 emissions are large (35% of emissions), but there is no attractive end-of-life solution today; traditional landfill is socially unacceptable, has capacity limitations, and risks potent methane emissions, while unabated incineration is highly emissions intensive.

Therefore, a better end-of-life solution must be developed. Either incineration must be abated as soon as possible through a framework of either CCU or CCS, or measures must be taken to establish a new form of solid state controlled disposal of plastic, mitigating any pollution, leakage or methane emissions risk.

However, given the risk of these nascent technologies failing to scale, every effort must be made to drive maximum circularity and resource efficiency in order to reduce materials reaching end of life in the first instance.

Scope 3 emissions represent 64% (1.46 Gt of CO_{2eq}) of the combined ammonia and non-ammonia chemical industry's total emissions today and thus should receive equal – if not more – focus when discussing abatement as Scope 1&2 emissions. This section focuses largely on approaches to abating Scope 3 for the non-ammonia system, given that the bulk of ammonia abatement comes from switching to green hydrogen for the Haber-Bosch process, as discussed in Chapter 2. However, it cannot go without mention that ammonia represents around 50% of total scope three downstream emissions today and 80-90% of total system residual emissions in LC-ME and LC-NFAX scenarios in 2050 (339 Mt CO_{2eq}). Despite efforts to optimize deployment of less emissive fertilizers, increase nitrogen efficiency and improve land management, some N_20 emissions are considered inevitable from the agricultural sector. These emissions are considered justifiable based upon food system services rendered to society, and natural solution offsets or compensations are warranted to balance these positive emissions.[49] The downstream impacts of urea and the switch to ammonium nitrate have already been discussed in the ammonia section of Chapter 2.

In the non-ammonia system (58% of total system emissions today, 1.3Gt scope 1-3), 66% of emissions reside in Scope 3[50] (upstream accounting for 31% and downstream accounting for 35%, a total of 0.9 Gt). For this reason, abating feedstock production and end-of-life disposal in effect determines many of the technology choices required in Scope 1&2 abatement of the non-ammonia system, particularly for greenfield production. Therefore, while Scope 1&2 abatement is an imperative for the chemical industry to maintain its license to operate, abatement of Scope 3 emissions offers the largest opportunity for system abatement.

Achieving Scope 3 net zero in the non-ammonia system can be accomplished by: 1) switching from fossil feedstock sources to alternative, renewable carbon feedstocks and green hydrogen; and 2) abating end-of-life emissions through CCUS on incinerators.

Fossil Feedstock: time to switch.

The attraction of fossil feedstock and fuel is understandable given its energy density, mobility and abundance, but emissions intensity and strategic risk mean the system must aim to shift away from this paradigm towards alternative, renewable forms of feedstock to abate Scope 3 emissions.

The development of the chemical industry is deeply rooted in the history of fossil carbon sources and fossil feedstocks, which are economically and chemically attractive compared to alternatives given their abundance, mobility, energy and carbon densities. While some of the processes that will be used to abate the system are not new (e.g. steam cracking or gas reforming), innovations are required to power them with new energy sources, feed them with new (and arguably more challenging) feedstocks, or connect them with CCS. Therefore, all legacy fossil technology that remains in the system will require some form of retrofitting.

As can be seen in Figure 15, the current non-ammonia system is highly linear, removing carbon from the ground as fossil and using it to make olefins or aromatics, which then accumulate either in the economy, the atmosphere, or the environment via leakage and landfill. This is not a sustainable operating model for the system. Continued upstream fossil production emissions and end-of-life incineration emissions or traditional landfill with associated methane emissions are not acceptable in a net zero world.

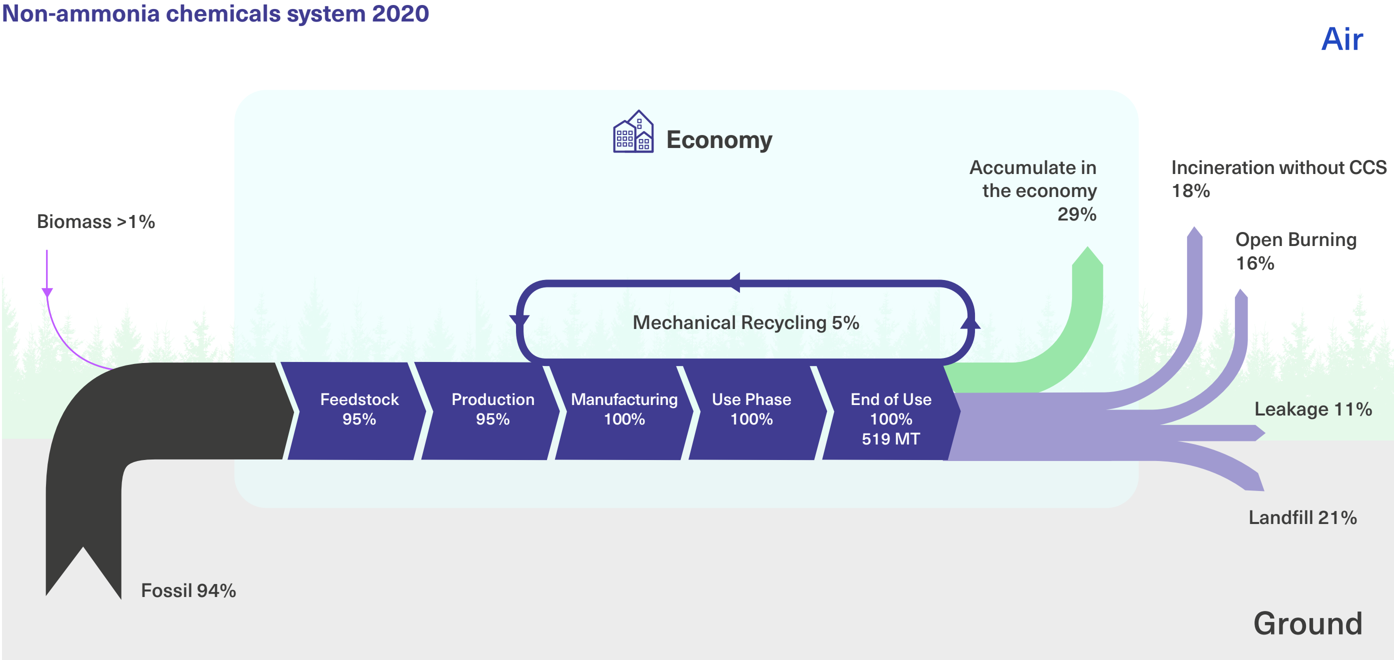
49. It is for this reason that the LC-ME scenario does not reach net zero, and in LC-NFAX, the impact of carbon negativity is reduced at a system level due to the need to offset these residual emissions. Whether the non-ammonia system should use used as a means of offsetting the ammonia system is a question of principle outside the scope of this study.

50. 38% of the total in scope system emissions (412Mt and 466Mt Scope 3 up and downstream olefins & aromatics respectively, over total system emissions of 2,295Mt).

Figure 15: Chemical production flows 2020 non-ammonia chemicals system

The current non-ammonia chemicals system is highly linear and fossil-based

Non-ammonia chemicals system 2020



Note: % of chemical production from sources and to end of use destinations
Mechanical Recycling includes solvent-based recycling technologies
Over a long term horizon chemicals stored in the economy (eg. construction plastics averaging 35 year lifespans) will begin to churn out

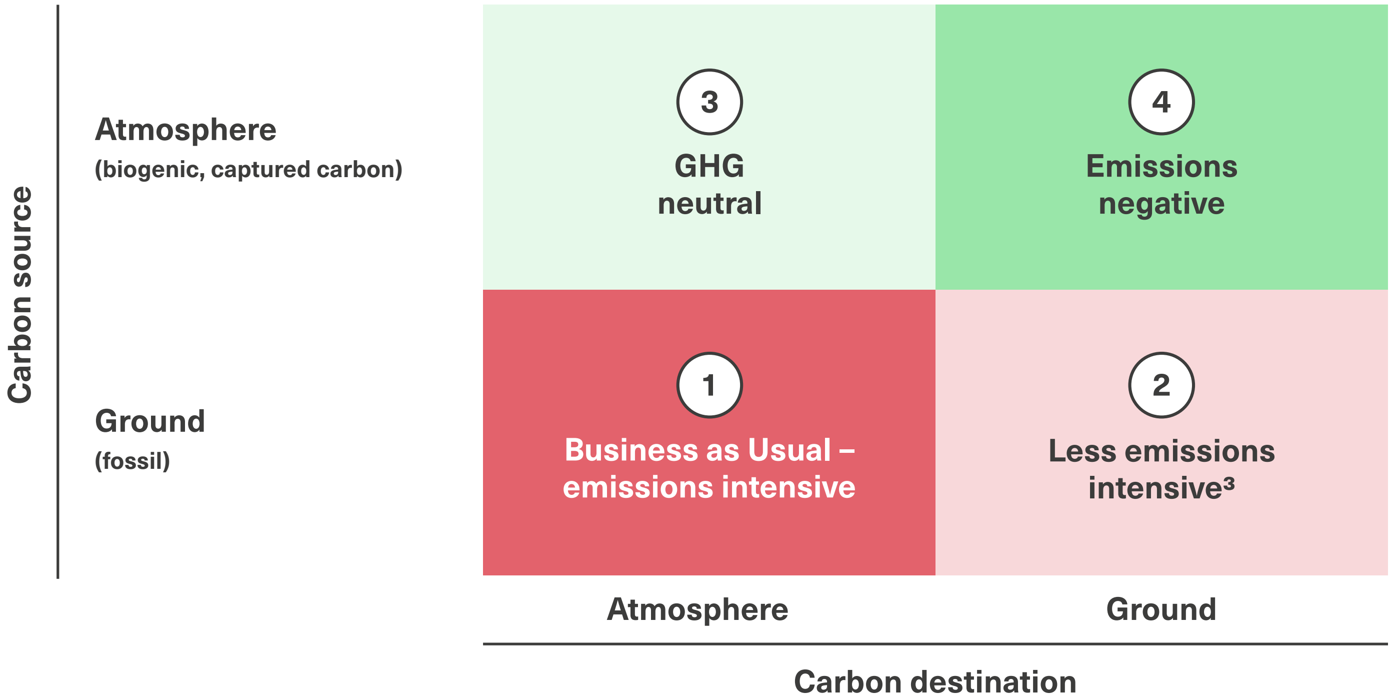
Figure 15 is a Sankey diagram that shows, relative to tonnes of chemical produced, where feedstocks originate proportionately, how much material is circular and where chemicals produce end up at end of life.[51] From the figure, it is evident that the in scope non-ammonia chemicals system operates on a linear model that largely functions by extracting fossil carbon from the ground and uses it to make plastics that – often after a single use – are either landfilled,[52] openly burnt in an uncontrolled fashion or increasingly incinerated and emitted as CO_2. Due to the challenges fossil fuel and feedstock face, as described in the previous section, the system must shift from its current fossil "ground to air" carbon emissions vector in order to de-risk the system's transition to net zero. Notably, a large proportion of plastics enter stock in the economy; these are typically durable plastics i.e. construction plastics with lifespans of 35 years or more. These will ultimately churn out of the economy but are predominantly landfilled without organic contamination thus their embedded carbon is considered to have a neutral GHG impact on system GHG emissions. In addition to the business-as-usual pathway of sourcing carbon from the ground and emitting it into the air, three alternative carbon pathways emerge (Figure 15).

51. Numbers are indexed to production volumes, therefore do not represent either tonnes of carbon or tonnes of feedstock/waste, thus will not correspond with values in feedstock, waste or CCS charts.

52. Plastic in landfills does not directly cause GHG emissions, but organic contamination of e.g. food contact or hygiene waste plastics result in methane emissions generation. The UK Department of Food & Rural Affairs estimates that 22% of all UK methane emissions stem from landfilling. The methane emissions intensity of landfilling has led to the EU implementing the Landfill Directive, requiring member states to send no more than 10% of municipal solid waste to landfills by 2035, resulting in the majority of European waste being incinerated with energy recovery, which is of lower emissions intensity but still emitting >2 tCO_2 /t of waste.

Figure 16: Long term carbon pathways possible in the chemicals system

Can the carbon vector of the chemicals system be inverted to sequester carbon in a new climate positive operating model?



Note: (1) Neutrality in the context of CCS technologies should be read as 'quasi-neutral' as residual emissions will occur, (2) As these are long term carbon pathways, the temporary presence of carbon in the economy is not represented, (3) Still may result in some emissions due to upstream fossil production but significantly reduced due to end of life sequestration

The system must shift from fossil to alternative sources of carbon feedstock, of which there are four principal categories to choose between within this analysis: biogenic, municipal solid waste, point source, and direct air capture (DAC). Similarly, the system must shift from traditional landfill, open burning and unabated incineration to a non-emitting technology such as incineration + CCS. As a result, four carbon vectors exist around which to build the future system operating model:

1. **Business-as-Usual – emissions intensive:** today's "ground to air" pathway as the current predominant model whereby fossil carbon is used to make plastic, which is incinerated at end of life.

2. **Less emissions intensive:** sourcing fossil carbon to make plastic then sequestering emissions at end-of-life via e.g. incineration + CCS, thus "ground to ground". Emissions still occur due to unabated upstream fossil feedstock production i.e. methane leakage, thus this route will require emissions offsetting.

3. **GHG neutral or negative:** using atmospherically sourced feedstocks such as biogenic sources, and then burning them at end-of-life. An "air to air" model which has neutral emissions – the carbon in the feedstock is returned to the air.

4. **Emissions negative:** sourcing carbon from the atmosphere in biogenic feedstock and sequestering it in the ground at end-of-life via e.g. CCS thus "air to ground".

The below framework illustrates the key similarities and differences in feedstock properties based on their physical state and geophysical source (Figure 16).

Figure 17: Relationship and trade-offs between alternative feedstocks

Four key alternative carbon feedstocks are linked by their geophysical source and their physical state, impacting how they are processed and how they drive the system towards a new paradigm: carbon negativity or carbon circularity

	Gaseous Carbon	Solid Carbon	
Economic by-product	Point Source	Municipal Solid Waste	Drives carbon circularity
Atmospheric Stock	Direct Air Capture	Biogenic	Drives potential carbon emissions negativity
	Carbon Capture & Utilization is key technology	Gasification is key technology	

The different properties of these feedstock sources have complex impacts on their usage in the future system, for example:

- **Abundance** – i.e. atmospheric carbon is over-abundant, while sustainable biomass is scarce.
- **Affordability** – i.e. point source is considered free, while DAC is expensive.
- **Production efficiency** – i.e. gasification of municipal solid waste via syngas to methanol then olefins & aromatics is lengthy and expensive.
- **Ubiquity/mobility** – i.e. solid feedstocks face logistical challenges and thus need densifying, while point source can only be accessed from other industrial clusters, and atmospheric carbon is ubiquitous.

Each alternative carbon feedstock faces multiple, complex trade-offs: there is no silver bullet alternative. While fossil feedstocks have excellent abundance, affordability, production efficiency and mobility, their extraction, use and disposal have multiple negative impacts on the climate and environment. Alternative sources of feedstock, however, have far more significant variance across these dimensions, meaning that there are multiple trade-offs associated with accessing each of them, as shown in Figure 18.

Figure 18: Feedstock tradeoff table

Despite its negative planetary impacts, fossil demonstrates excellent characteristics as both a feedstock and energy source, while for alternative sources of carbon there is no silver bullet

	Feedstock	Energy	Planet Positive	Abundance	Affordability	Production Efficiency	Ubiquity / Mobility	Key trade-offs
Fossil	Highly suited	Highly suited	Very Poor	Good	Excellent	Excellent	Excellent	Fossil is understandably the feedstock and energy source of choice given climate and environmental impacts have been historically disregarded
Municipal solid waste	Highly suited	Possible use	Good	Good	Good	Average	Average	Using waste as feedstock avoids disposal impacts, displaces fossil, but quality feedstocks are scarce and distributed thus require densifying at point of generation
Biogenic	Highly suited	Possible use	Excellent	Average	Good	Average	Average	Potentially carbon negative and affordable but scarce, competed for, exposed to a deteriorating climate, distributed and thus require densifying
Point source CO_2	Highly suited		Average	Excellent	Excellent	Good	Good	Abundant, free and their use acquires responsibility from other sectors for their abatement. May shrink as other sectors approach net zero
Direct Air Capture CO_2	Highly suited		Excellent	Good	Poor	Poor	Good	Ubiquitous, potentially carbon negative but highly energy intensive and therefore expensive and limited to areas with abundant renewable energy
Green Hydrogen	Highly suited	Highly suited	Good	Good	Average	Average	Good	Fuel and feedstock that is zero carbon, but highly energy-intensive thus expensive and need to be produced in regions with abundant, affordable renewables

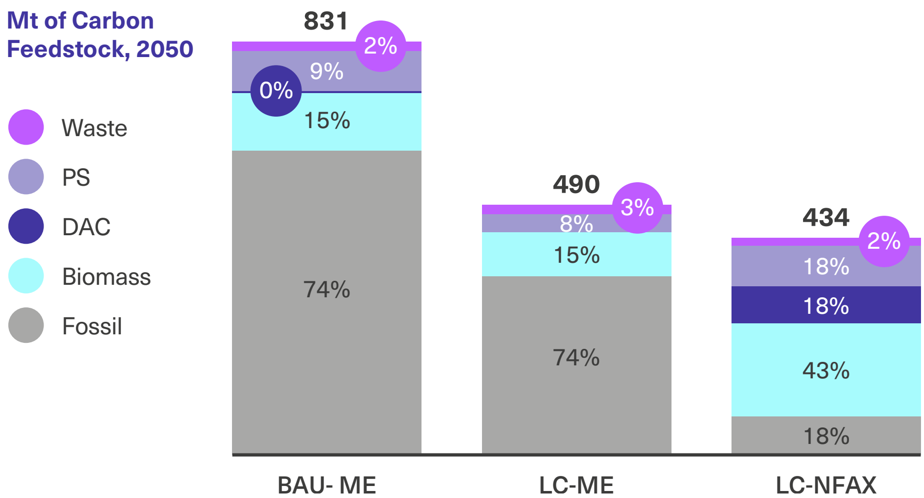
Key: Highly suited; Possible use; Very Poor; Poor; Average; Good; Excellent

Note: This chart is qualitative but informed by unit values for each feedstock aligned around the balanced score card of criteria. It takes a levelized view of the feedstock over the 2020-2050 timeframe of the analysis

As there is no silver bullet feedstock, to de-risk the transition to net zero it is prudent for chemical industry players to establish a diversified framework of feedstock sources. A key value added in this analysis is that the selection of feedstocks is not deterministic and is therefore less at risk of human bias. Instead, the analytical model used places parameters on the selection of each feedstock based on: i) feedstock availability caps (for biogenic and waste); ii) technology scaling rates; and iii) costs evolving over the 2020-2050 timeseries (see Appendix). As such, the feedstock mix, volume and region per scenario is derived for each year using computational algorithms driving off a broad range of granular data points, making it as objective as possible. The subsequent mix of feedstocks per scenario are represented below (Figure 19) and notably demonstrate, particularly in the LC-NFAX scenario, that a diversified range of feedstocks is recommended by the model to satisfy scenario parameters.

Figure 19: Carbon feedstock sources (Mt, 2050)

Shifting away from fossil carbon will be possible only if a diverse feedstock portfolio is developed

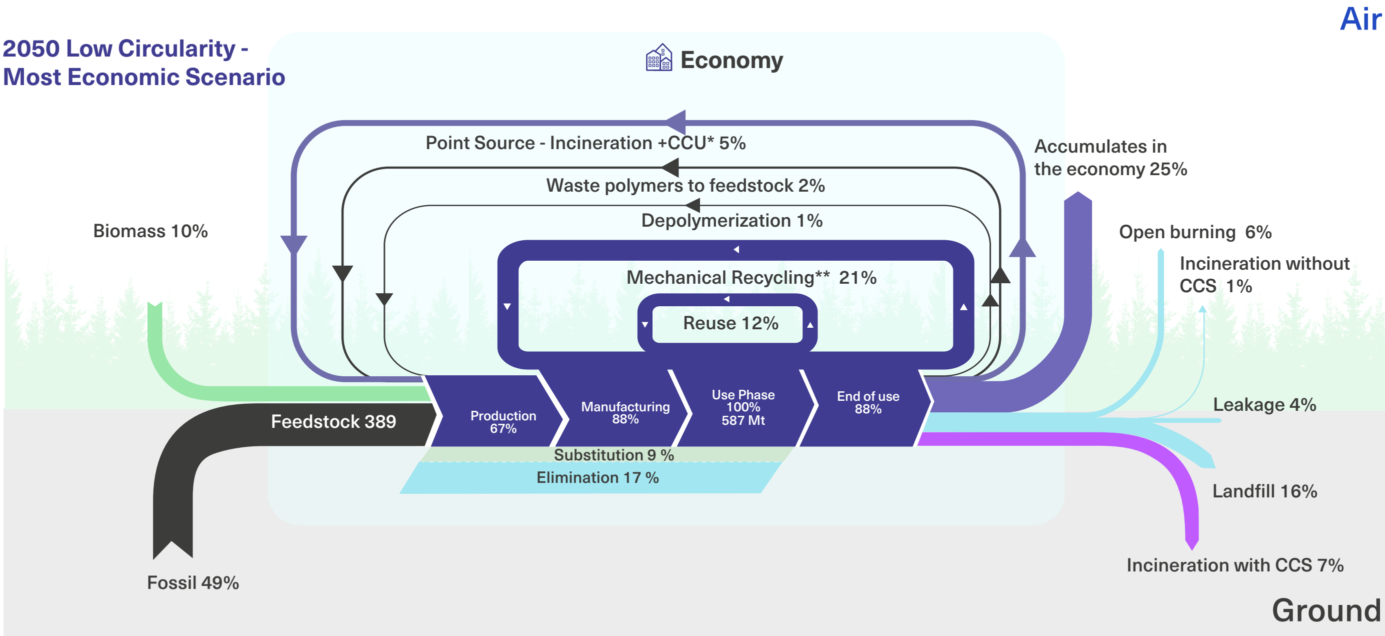


As can be seen in Figure 19, between BAU-ME and LC-ME demand side circularity is applied, reducing total carbon feedstock demand from 998 Mt to 562 Mt and shrinking most feedstock sources proportionately. Notably, fossil carbon is still the dominant feedstock in LC-ME. Then, between LC-ME and LC-NFAX, supply side abatement levers are prioritized to abate the system's emissions faster, meaning fossil dependence is reduced from 74% of total feedstock in LC-ME down to only 18% in LC-NFAX. Correspondingly, there is a lower dependence on CCS in LC-NFAX, with a third of the capacity required compared to BAU-ME and half of that in LC-ME.

LC-NFAX contains little fossil and thus contains highly diversified sources of carbon feedstocks (82%), which lowers transition risk should one or more technologies fail to scale. Biogenic sources of carbon play a consistent role but are more prominent in LC-NFAX, where they are the largest source of carbon (43%). Point source carbon and DAC are balanced (18% each).[53] Notably, over 60% of carbon feedstock in LC-NFAX is from atmospheric sources. Gasification of municipal solid waste does not feature because of the relative cost of the methanol and then MTX routes.

Figure 20: Flow of chemicals from feedstock to end-of-life – LC-ME Scenario 2050

The LC-ME scenario demonstrates increased circularity but a continued dependence upon fossil sources



Note: Substiution and Elimination represent the % chemicals that will be reduced through LC levers.
*Point Source - Incineration + CCU assumes all chemical related energy recovery emissions are circulated back
**Mechanical recycling includes solvent-based recycling technologies. Over long term time horizon chemicals stored in the economy (e.g. construction plastics averaging 35 year life spans) will begin to churn out.

From material to carbon circularity.

The scale of the linear system can be further reduced by extending the concept of circularity beyond traditional material boundaries to include "carbon circularity" through the use of by-product "waste" carbon in the economy (point source and municipal solid waste) to mitigate climate and environmental impacts.

Beyond the more traditional materials circularity, the chemicals system has the potential to derive further value from economic "waste" by-products by reusing the embedded carbon (Figure 20).[57] This carbon circularity can be achieved via four approaches; i) use of point source captured gaseous carbon from other sectors' Scope 1 process emissions, ii) pyrolysis, iii) gasification, and iv) incineration +CCU.

53. The LC-NFAX scenario builds new technologies based on maximum Scope 1-3 abatement, therefore DAC is preferred over other potentially more expensive technologies. See Appendix for further modelling details.

As can be seen in the above Sankey diagram of the LC-ME scenario, the scale of the linear system has been reduced. Elimination and substitution have shrunk the size of the total use phase while maintaining utility. The material circularity levers of reuse, mechanical recycling, and depolymerisation couple with the carbon circularity levers of gasification, pyrolysis, incineration + CCU and point source carbon from other industries to circulate carbon in the economy. This in turn reduces the scale of virgin biogenic and fossil feedstocks. While non-trivial volumes of chemicals end up accumulating in stock in the global economy, end-of-life emissions are abated by CCS or end up in landfill.

Using point source and waste carbon has a positive effect in multiple ways, including: i) the need for both biogenic and fossil virgin feedstock is reduced ii) the need for safe and controlled disposal with associated costs is removed; and iii) an abundant, low-cost source of alternative feedstock is available to the system. However, the application of all these technologies have trade-offs between themselves in terms of energy efficiency (input and recovery), feedstock tolerance/yield, cost, and production technology route.

Use of point-source CO_2 emissions are captured from industrial processes across the chemicals value chain and other sectors. As they are obtained from other sectors currently employing fossil feedstocks (e.g., steel, cement, etc.), these emissions are anthropogenic in nature for the foreseeable future. It is currently an abundant source of carbon, but it may dwindle as other sectors approach net zero and optimize their process emissions. Point source CO_2 capture is significantly less energy intensive than direct air capture, at about 0.35 MWh/t CO_2 (compared to ca. 2 MWh/t for DAC), due to higher CO_2 concentrations in industrial emissions streams;[54] it is thus also more affordable. However, the need for capture and processing infrastructure co-location has technical and cost implications. Utilizing point sourced carbon could also be considered a system service to other sectors, by acting as a destination for their carbon emissions that would otherwise require abatement/sequestration. This places the responsibility for controlled disposal of this carbon at the ultimate end-of-life after recycling (e.g., incineration + CCS or responsible landfilling) on the chemicals system.

Pyrolysis of waste: Given other post circularity efforts (including mechanical recycling, dissolution and depolymerisation), only 30-60 Mt of remaining polyolefins (or ~5-15% of total plastic waste generated) will be available, suitable and used for pyrolysis. This limited availability not only stems from competition with mechanical recycling and the availability of waste management infrastructure, but also from the inherent limitations caused by the waste quality that the pyrolysis technology requires. Only clean mixtures of PE, PP and polystyrene can be used, and this ultimately leads to subsequent sorting and losses. Investment focus is currently geared towards pyrolysis as it leverages existing steam cracker assets.[55]

Gasification of waste: Gasification of waste is far more feedstock tolerant and can deal with waste fractions not suited to pyrolysis. According to the model, 3-4 Mt will be treated this way in 2050. However, gasification follows a different, longer production pathway – through syngas to methanol then, possibly, to olefins or aromatics (MTX) – which is inherently more expensive than pyrolysis from a process opex perspective, as well as from a capex perspective given the need for greenfield production assets as this waste-to-plastic route is not built out.[56]

54. Cost/energy demand of capture will highly depend on the level of purity.

55. The levels of leakage within the existing plastic system and waste feedstock intolerance of pyrolysis mean that unless vast improvements are made in circularity, only a very small proportion of the original naphtha mass entering the cracker is returned through the system as p-oil into the cracker to displace virgin naphtha. Furthermore, some of the naphtha product slate does not go into polymers and is generally hard or impossible to recycle. For this reason, pyrolysis as a route requires on-going fossil exploitation to sustain the cracker operation.

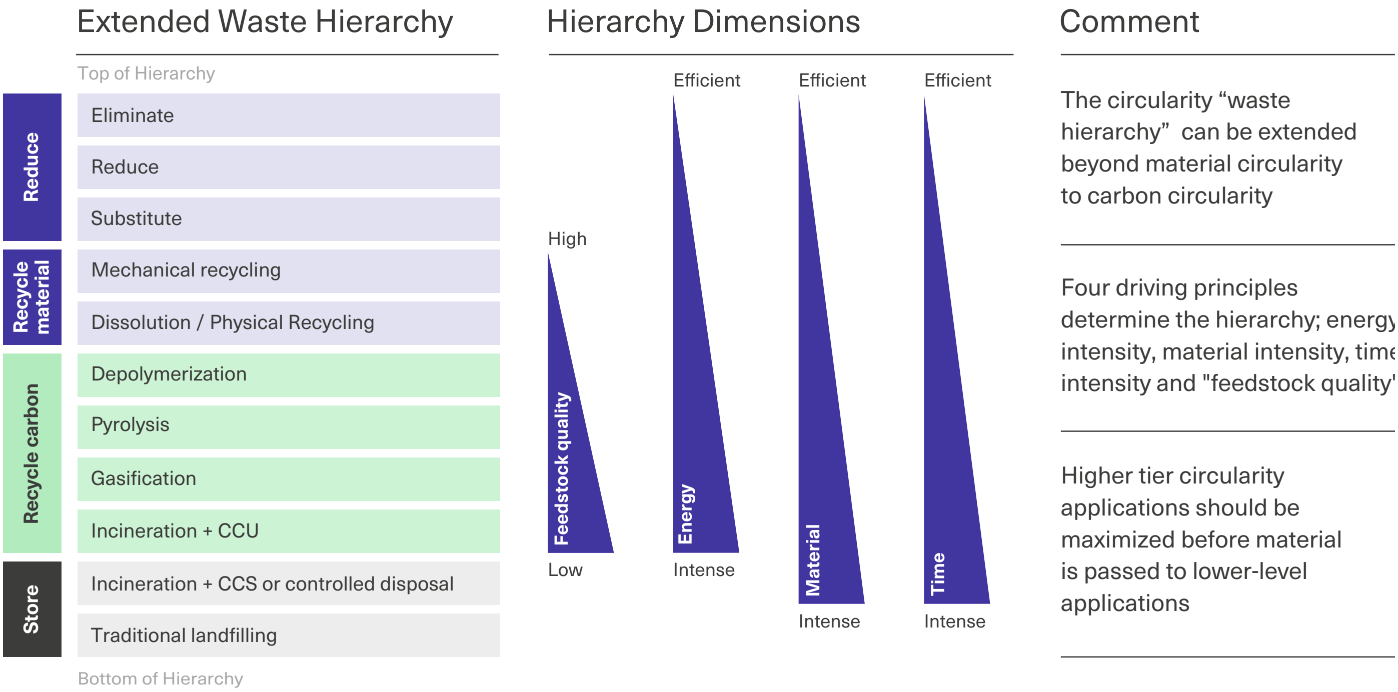
56. There are no plastic-to-plastic dedicated gasification plants operational at scale today globally at the time of writing this report, even if the component parts of the value chain exist at massive scale in different locations.

Incineration + CCU is not a widely used technology today but may become more significant in the future, particularly as policy makers intensify their focus on emissions abatement. Given that end-of-life emissions represent such a large proportion of total emissions, abatement of incinerators is essential. Where circularity has failed to keep material out of incinerators, this must be abated via carbon capture and potentially utilization as an in-system point source of carbon.

These last three forms of downstream thermal treatment (pyrolysis, gasification and incineration + CC) all face trade-offs and should be established within a complementary framework to circulate non-mechanically recyclable waste carbon. The differences in energy efficiency, material resource efficiency (process losses/yield), and feedstock tolerance mean that the "waste hierarchy" of circularity prioritization can be extended to optimize both each technology's application and the system's carbon and energy efficiency, as shown in Figure 21.[44]

Figure 21: Extension of the "waste hierarchy" beyond materials circularity to carbon circularity

Circularity growth needs to be optimized for efficiency and complementarity



Atmospheric carbon feedstocks: locking up GHGs.

The direct (DAC) or indirect (biogenic) extraction of atmospheric carbon for feedstock has technical and environmental limitations.

Biogenic feedstocks and DAC are attractive feedstocks from a GHG perspective. They are considered to have a negative carbon footprint because their carbon is sourced from the atmosphere and thus reduces atmospheric GHG concentration. As a result, even if the chemical products they make emit Scope 1 GHG, or are burned at end-of-life, their net GHG impact is zero, and if they are landfilled or sequestered through CCS, they can make total system emissions negative on a life cycle basis. However, both feedstocks have limitations.

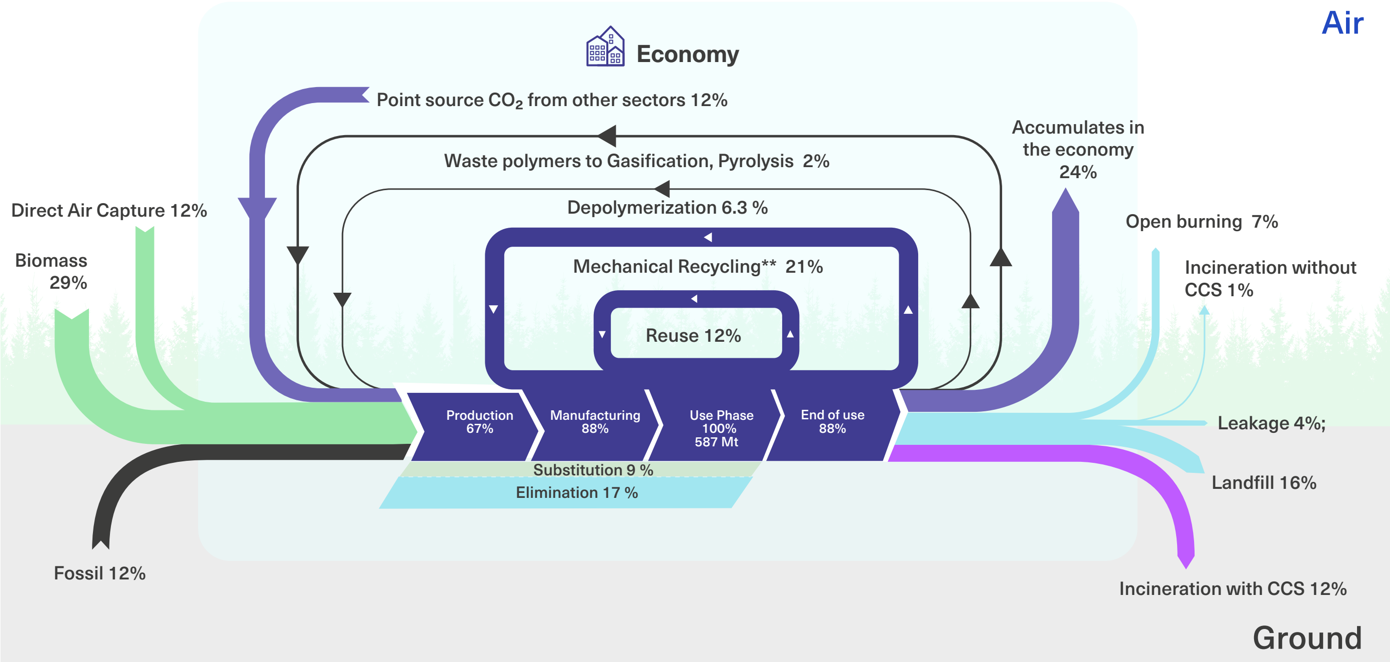
Sustainable and non-food competitive biogenic feedstocks are hard to rely on as they are scarce, intensely competed for by other sectors seeking to reach net zero (e.g., aviation), and vulnerable to a warming climate. Various analyses indicate a likely range of only 12-23 EJ of biomass earmarked for the chemical industry.[5,58] Bio-oils are limited in their use and therefore present themselves in only small quantities (44 Mt/year). In addition, there are fundamental environmental questions around the appropriateness of deliberately growing biomass for the manufacture of plastics in 2050.[59] Large increases in sustainable biomass are not anticipated, meaning any growth in its use in the chemicals sector will require re-allocation and prioritization above other sectors, for which the chemical industry is considered an appropriate use given the abatement challenges it faces.

Direct air capture of CO_2 is an appealing carbon source but very energy intensive to harness – and thus very expensive – so it will only make sense in specific geographical or local instances. However, the CO_2 price for DAC is assumed to drop from about $300 in the 2020s to below $100 per tCO_2 by 2050, with an accompanying drop in energy consumption[57] from 2 to 1.3 MWh/t CO_2. As long as it is powered by renewable energy sources, DAC is considered to have a negative Scope 3 carbon footprint upstream as it directly lowers the levels of CO_2 in the atmosphere.

Figure 22: Flow of chemical industry carbon from feedstock to end-of-life – LC-NFAX Scenario 2050

Increasingly, sourcing carbon feedstocks from the atmosphere can charge the chemicals system and has potential for generating negative emissions

2050 Low Circularity – NFAX Scenario



Note: Substiution and Elimination represent the % chemicals that will be reduced through LC levers.
*Point Source - Incineration + CCU assumes all chemical related energy recovery emissions are circulated back
**Mechanical recycling includes solvent-based recycling technologiesover a long term time horizon chemicals stored in the economy (e.g. construction plastics averaging 35 year life spans) will begin to churn out. All circulated carbon in Mt and as % of total use phase utility (I.e. Including sub and elimination).

Figure 22 represents the best case scenario for the non-ammonia chemicals system by 2050 after it has been reshaped by materials circularity, carbon circularity, feedstocks have been switched, and carbon emissions have been abated downstream at end-of-life via CCS. In this optimal state, ~60% of carbon mass feedstock (239 Mt) input into the system is sourced from the atmosphere, and only ~20% from the ground. 790 Mt of utility are still provided by the system, and only 236 Mt of carbon are released from the system into the environment or atmosphere, providing a far higher plastic use efficiency. Notably, 144 Mt of carbon accumulate in the economy and consideration must be given to the long-term churn of plastics in durable products as they reach end-of-life, for which further analysis is needed.

57. Mixture of thermal energy and electrical energy, depending on negative emissions technology.

Green hydrogen is the key ingredient in the shift to non-fossil sources of carbon.

The switch to alternative sources of carbon will require a major increase in green hydrogen feedstock production to make methanol, potentially making the chemicals system the largest user of green hydrogen globally.

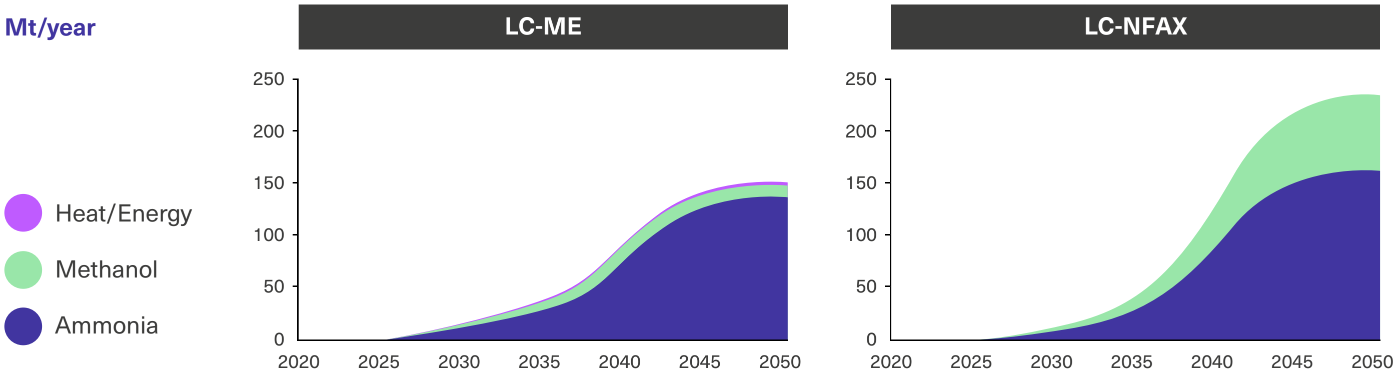
Green hydrogen will have a major role to play in the future of the non-ammonia system, allowing alternative sources of carbon to be converted to methanol and then on to olefins and aromatics. Already today, about 43 Mt of fossil hydrogen (derived from natural gas and coal) is used in the chemical industry.[60] While the large majority of green hydrogen will be used as feedstock for ammonia (68–92%) a significant proportion (7-31%) will be used to make green methanol. Coupled with ammonia usage, this totals around 147-234 Mt of green hydrogen in the LC-ME and LC-NFAX scenarios respectively (Figure 23). This equals about 20-50% of total expected green hydrogen demand in a net zero world in 2050.[45] Co-feeding green hydrogen as feedstock will also play an essential role in maximizing the carbon utilization of gasification processes by adjusting the ratio of hydrogen and carbon in a process gas stream.[58]

Green hydrogen production will become economically competitive with grey hydrogen production in average and high natural gas cost regions within this decade, meaning the chemical industry should begin seeking production sources immediately. Multiple players in the green hydrogen sphere suggest production costs below 2 $/kg by 2030.[61,62] In the long term, green hydrogen is commonly considered the lowest cost hydrogen production method in almost all geographies due to significant cost declines in renewable power and electrolysers. While smaller in volume, green hydrogen will be essential for other uses beyond ammonia and methanol production, such as high temperature heat (>800°C) typically achieved today via natural gas firing. In fact, our analysis anticipates that green hydrogen will provide most high temperature heat production for steam crackers in the chemical industry of the future.[59]

Beyond the chemical industry, other adjacent industrial sectors will also require significant amounts of green hydrogen (e.g., steel, synthetic aviation fuel), thereby presenting opportunities for cooperation synergies on production, storage, and transport infrastructure investments. Coordination across industrial clusters and with policy actors will be essential to share investment risks and coordinated infrastructure build-out, including RES production, hydrogen production, and hydrogen transport and storage.

Figure 23: Green hydrogen production by 2050

Achieving net zero in the chemicals system will require large volumes of green hydrogen, which is driven by the production of ammonia and methanol for direct usage (not for energy)



58. Gasification of carbon-rich feedstocks (e.g., coal, biomass, municipal waste) produce too much carbon vs. hydrogen for methanol production. Today, surplus carbon is released into the atmosphere in the form of CO_2. Instead, green hydrogen can be co-fed into the processes to precisely adjust the molecular ratios and eliminate any CO_2 process emissions.

59. H_2-based retrofitting is lower cost than building new electric crackers.

The role of CCS in carbon management.

CCS economy will be needed at scale to reach net zero in an orderly fashion, requiring significant infrastructure development efforts for CO_2 capture, transport and storage.

Due to constraints on alternative feedstocks and energy sources, it is likely that CCS will still be required to enable the chemical industry to reach net zero by 2050. The chemicals system today uses >99% fossil feedstock, but that radically declines to 41% and 7% towards 2050 in the LC-ME and LC-NFAX scenarios, respectively. Naphtha (82% in LC-ME and 95% in LC-NFAX) and coal (78% in LC-ME and 99% LC-NFAX) consumption drop most steeply, largely driven by the complete retirement of catalytic reforming and coal gasification, which are generally more emissions intense and often higher cost. The scenarios developed in this report do not capture national infrastructure, trade or energy security considerations and it is therefore difficult to translate these developments into national strategies (e.g., China's coal dependence). Nevertheless, it is possible to anticipate that the limited availability of alternative feedstocks might mean that fossil consumption will still be required by mid-century.

CCS is therefore necessary to abate the emissions from residual fossil usage. Beyond simply capturing Scope 1 process emissions of chemical production, CCS will be critical to abate end-of-life emissions, for example from the incineration of waste. In a net zero world, any sequestered fossil carbon extracted from the ground for feedstock must ultimately be abated by re-sequestering by the same mass of carbon. The geographic dispersion and proximity of incinerators compared to CO_2 storage sites necessitates the development of CO_2 transport infrastructure. CCS is economically attractive for Scope 1 abatement due to comparably small retrofit costs for the capture plant (e.g., 10% capex increase for methanol production from natural gas). In combination with low fossil feedstock costs, CCS as an abatement option is very competitive when compared to processes using alternative feedstocks instead.

CCS faces significant drawbacks that must be factored into any reliance on this technology, including:

Full CO_2 capture from CCS is not currently being pursued and is technically challenging. An incomplete capture rate of typically <97% - and sometimes as low as 50-60%[60] – entails that some residual Scope 1 emissions will be unavoidable. In this report, an optimistic 95% capture rate is assumed, without which scaling CCS is unlikely to be an attractive climate mitigation tool. In addition, as Scope 3 upstream emissions from production/transport/storage of the fossil fuel remain unmitigated, even with high capture rates, the fossil + CCS pathway is still (standalone, without offsets) incompatible with a net zero system. While it might be theoretically possible to compensate residual emissions from use of fossil feedstocks + CCS, there may be scarcity of biogenic carbon compensations. Any form of compensating via negative emissions will be competed for by other sectors such as agriculture, aviation, and for ultimately lowering the CO_2 concentration in the atmosphere.

Local storage availability and lack of transport and storage logistics. The proximity of the CO_2 source and capture plant to the nearest CO_2 storage site is essential as captured CO_2 needs to be safely transported before being permanently stored underground. The size and scale of this infrastructure at a global level is vast,[61] and building it is politically and geographically complex.

60. Current efforts in CO_2 capture often only capture process CO_2 emissions, which have much lower capture cost due to higher CO_2 concentration in the stream. Flue gas from process heat/steam/power creation remains unabated.

61. CO_2 storage will be on the same scale as today's natural gas production infrastructure with regards to volumes/mass moved: today's natural gas production is in the order of 4000 billion cubic meter natural gas, equivalent to ca. 3.2 Gt natural gas.

Leakage avoidance: While it is technically feasible to permanently store CO_2 via CCS, site management and maintenance are critical to avoid leakages of CO_2 at the borehole or via adjacent wells that may have already been abandoned.[62]

Long lead-times and high project failure rates. Development of suitable CO_2 storage sites is slow and typically requires 7+ years. Over the last decade many projects have been shelved due to technical difficulties or lack of sustainable business models.

Engineering challenges around retrofitting existing plants. Integrated refineries and chemical industrial clusters are commonly custom-designed plants specific to local feedstock supply conditions and production capabilities. The integration of CCS requires a careful re-engineering of steam and power balances and typically requires significant plant downtime, which would affect the operator's cashflow.

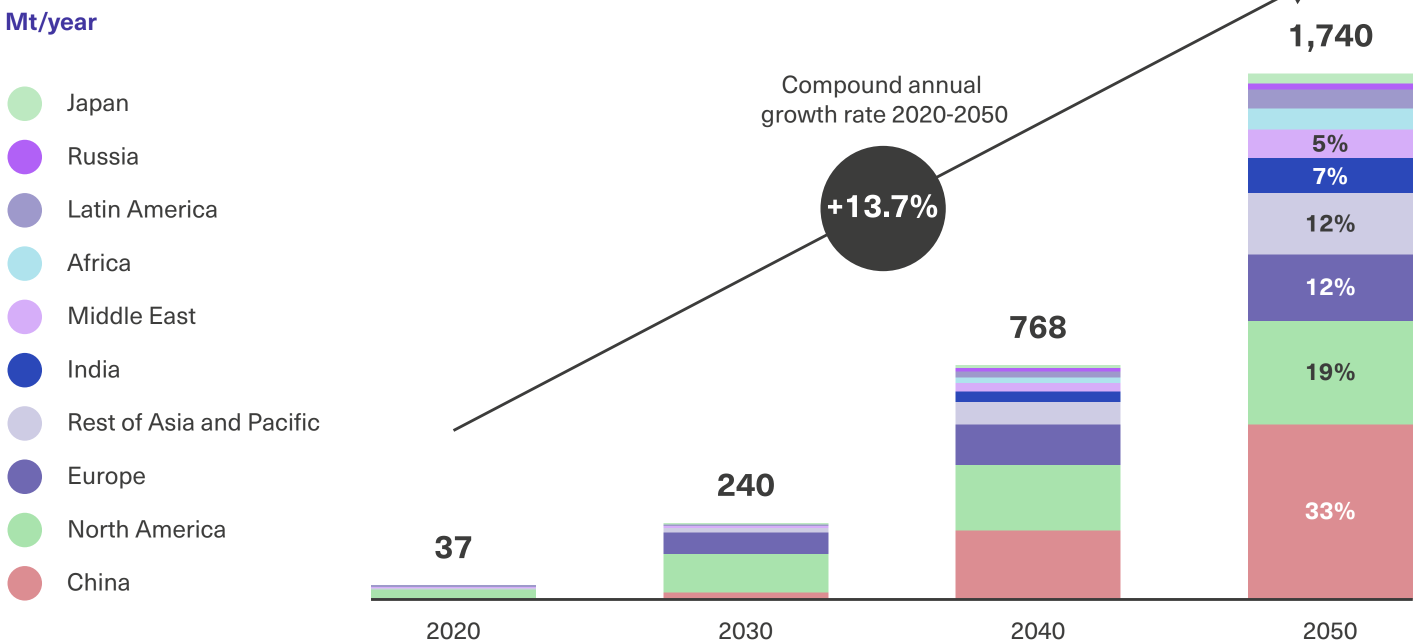
Financing of CCS projects will require $4.5bn globally.[63] While the direct cost to the chemicals system is $850bn, distributing and coordinating the financing of this shared service between sectors will not be straightforward.

Despite all the above hurdles, CCS could play a significant role in abating GHG emissions under certain circumstances, but it should be used selectively to address residual emissions that cannot be mitigated by alternative feedstock and energy levers.

Total global CCS technology capacity scaling is forecast to reach around 7 Gt per year by 2050 for all sectors.[55, 63-65] The realistic deployment rate of CCS as a GHG emissions abatement technology is expected to remain conservative – and be led by Europe and North America – for the initial decade between 2020 and 2030, before increasing at varying degrees for most regions of the world, most notably in China.[63]

Figure 24: CO_2 storage technology scaling capacity cap for CCS in the Chemical Industry

CCS availability is constrained due to project pipeline, North America and Europe lead the way in 2020s

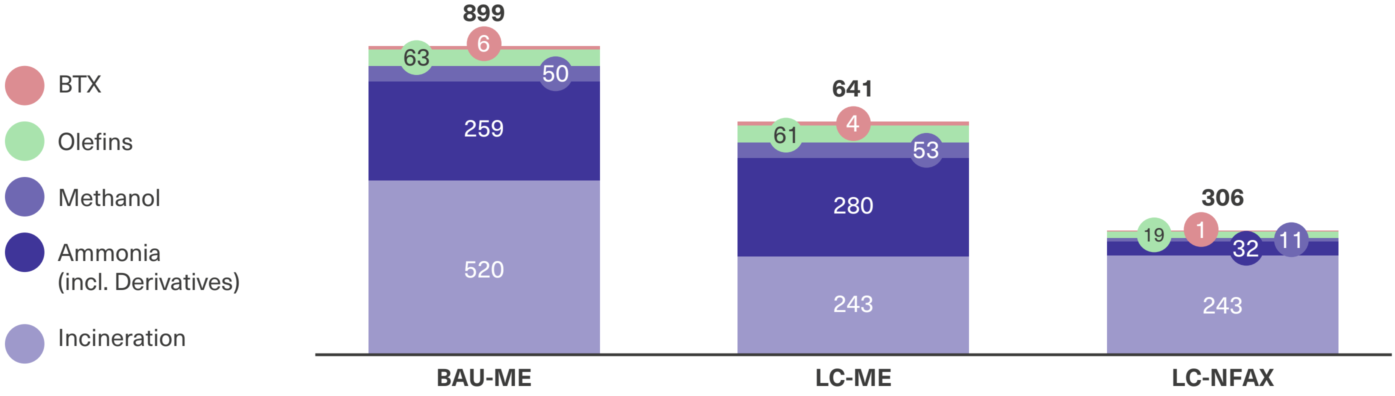


62. This is true for depleted oil and gas reservoir storage, but not true for saline aquifers, which have not been drilled prior to use for storage.
63. While there are fewer developments today in China, it does possess suitable sites which are mainly located in northeast, northwest, southern North China, and the Sichuan Basin.

This study has apportioned the chemicals system a maximum of 25% CCS. That limits the volume of chemical production and end-of-life incineration that can be abated by CCS to 1.75 Gt in 2050, and in a constrained sensitivity where the technology struggles to scale, a third of this.

Figure 25: Impact of CCS on production and end-of-life incineration related emissions (Mt CO_2 captured and stored) (2050)

CCS will be responsible for abating the 0.6-0.3 Gt of residual CO_2 not abated by alternative feedstocks in LC-ME and LC-NFAX scenarios respectively



As shown in Figure 25, BAU-ME is a fossil intensive scenario with no demand reduction, creating a larger dependence on CCS of 0.90 Gt for end of life abatement of non-ammonia chemicals. In the LC-ME scenario the need for CCS is reduced to 0.64Gt, the majority of which is scope 1 ammonia (blue hydrogen) production abatement and end-of-life abatement (i.e., CCS on incinerators). Alternatively, in a world where no new fossil-based production plants are given the license to build past 2030 (the LC-NFAX scenario), the only major residual requirement for CCS is on incinerators for end-of-life abatement of non-ammonia chemicals (0.24 Gt). Unless circularity scales beyond all expectations, some form of end of life abatement will be essential for the non-ammonia system in 2050 to reach net zero.

The end-of-life challenge; no good answer today

Abating Scope 3 CO_2 emissions in the non-ammonia system requires better end-of-life control through reduced open burning and improvement on existing end of life abatement technology options.

In this study, it has been assumed that in 2050 ~100% of waste incinerators will have CCS applied to them. As discussed, Scope 3 downstream[64] (end-of-life) emissions in the non-ammonia system represent the bulk (35%) of total emissions today. However, the 100% CCS assumption is vulnerable to challenge for three reasons: i) geographical reach of CCS infrastructure may be limited, for example inland; ii) while geological storage capacity is massive, some regions lack suitable storage; iii) even in 2050, rollout of CCS in some Global South economies is still a stretch target from a development perspective. Irrespectively, continued unabated incineration in 2050 is incompatible with a net zero world, thus the study has assumed that some form of abatement at end-of-life for controlled disposal of waste will be a necessity. Several alternative abatement options can be considered:

64. Scope 3 downstream emissions refer exclusively to end-of-life emissions.

Increase gasification of waste. Gasification is a feedstock quality tolerant technology. Therefore, rather than incinerate, a larger proportion of residual waste might be economically gasified and then converted from syngas into methanol for MTX, if the upstream and waste system removes the worst contaminants from the system. Gasification is a more waste-to-energy efficient means of energy recovery than incineration, with lower emissions and comparable by-products but, as already discussed, it is under-represented due to the lengthy/expensive process to manufacture polymers. However, the lowest quality feedstocks are likely to drive ever greater operational and therefore economic inefficiencies, making this route challenging.

"Controlled disposal" vs landfilling of plastic waste. Landfilling is rightly highly stigmatized today due to methane emissions from organic contamination, toxic leakage from lower quality landfills, and risks of geological erosion and environmental pollution, but most importantly the social issues arising from living near to landfills. Unfortunately, landfilling is a very low-cost, scalable, simple and readily available technology option that crowds out other circular and end-of-life models. However, controlled disposal of carbon through higher quality plastic landfilling where methane emissions are mitigated has been discussed in expert circles as an economically viable and, (with the right controls such as biological stabilization),[66] a climate neutral end-of-life option. In light of the risks around CCS scaling, exploring methane mitigation in high quality landfilling may offer an alternative, lower-risk option for sequestering carbon at end of life. It would likely consume around half a cubic km per year globally.

Carbon capture and utilization on incinerators overcomes some of the geographical infrastructure challenges of CCS, as discussed earlier in the chapter. The chemicals system may wish to source its point source carbon from incineration + CCU within its own system for feedstock security reasons. It will avoid the incremental cost of sequestering its carbon via CCS, and thus is more aligned with the LC-ME scenario. It will also reduce the risk of guaranteeing fossil emissions off-taking thus abatement from other sectors, and thus the potential for a hidden Scope 3 emissions upstream. Finally, it will augment levels of carbon circularity within the system. However, it also raises new questions, for example how will the carbon be used, does it need transporting, if it is to be converted to green methanol where will the green hydrogen be produced?

There is no simple solution to end-of-life olefins and aromatics, which is why every effort at circularity must be made to keep waste away from an end-of-life fate. Limiting demand growth through circularity means that – should CCS technology, or any other end-of-life technology, fail to scale – the chemicals system would need to rely on negative emissions from biogenic or direct air capture to achieve net zero.

Ultimately, the market will decide between two future paradigms: LC-ME with higher levels of carbon circularity, or LC-NFAX and high levels of carbon negativity and the non-ammonia chemicals system becoming a carbon sink.

Chapter 4:

Can the global chemicals system become a carbon sink?

Utilizing the same approach as is required to reach net zero can reinvent the chemicals system as a climate solution to regenerate the planet.

Chapter summary

The global chemicals system has the potential to pass net zero by the early 2040s and become a carbon sink, sequestering 0.5 Gt of CO_2 p.a. and deriving economic value from carbon use and sequestration.

“Carbon negativity” offers a complementary model to circularity that can hedge system transition risk related to operating within planetary boundaries while reinventing itself as a climate solution. If circularity fails, carbon negativity scales. The most important factor is that the whole system shifts to a model of either circularity or carbon negativity – and does not maintain is current emissions intensive, linear model.

Unlike more linear, pure cost driven but not necessarily more technologically mature carbon removals pathways,[65] the chemicals system is uniquely positioned to make use of carbon to provide social and economic value, potentially multiple times through material or carbon circularity, before it is ultimately sequestered. For this reason, CCS capacity should be prioritized for chemicals carbon negativity above more direct uses.

The accreditation of system wide sequestration of carbon will require collaboration between the chemical industry, as controllers of system feedstock inputs, and incinerators. However, if this can be achieved, commercial value may be attached to this service, offering a new revenue stream as well as the ability to attach a carbon negative Scope 3 value to all non-ammonia products.

65. Bio energy with carbon capture and storage.

Shifting the source and final destination of carbon in the chemical system is a requirement to reach net zero Scope 1-3 emissions. Scope 3 in the chemicals system is so large that the total emissions of the system are highly sensitive to this shift. That's why it is the most powerful abatement lever. If the same levers used for switching the carbon source and end-of-life destination of carbon are extended, the chemicals system can pass through net zero, invert the carbon vector of the system, and – rather than emit – begin to sequester carbon as an externality.

Figure 26: Scope 1, 2 & 3 emission profiles by 2050 in the LC-NFAX scenario

Carbon negative feedstocks and end-of-life abatement can rapidly bring the carbon-based chemical system below net zero

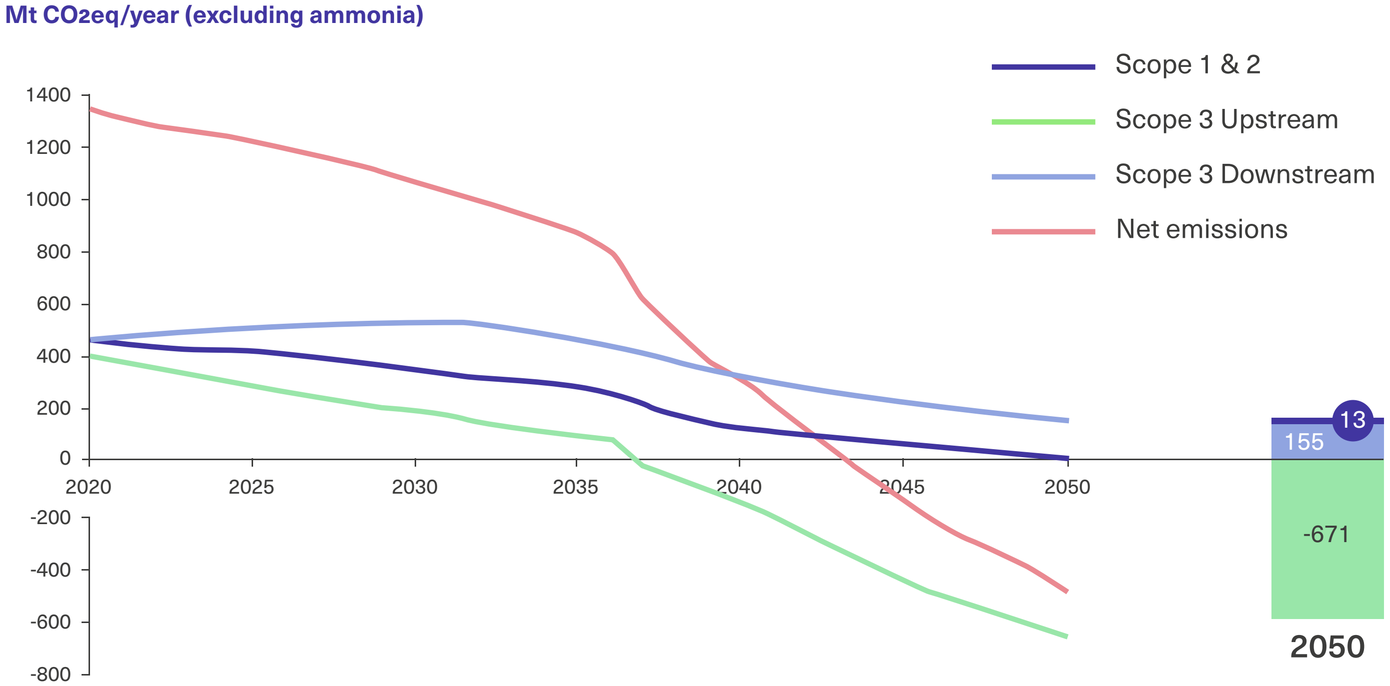


Figure 26 shows the emissions breakdown between Scope 1,2&3 upstream and Scope 3 downstream for the LC-NFAX scenario (excluding ammonia), which achieves net zero by 2043, and reaches ~0.5 Gt of carbon sequestration per year by 2050 rather than consuming the carbon budget. This scenario is driven by a preference for abating feedstocks rather than choosing the most economic feedstocks, but does not deliberately target carbon negativity; it places limitations on the use of fossil after 2030, which results in an uptake of alternative feedstocks. This has the potential to grow further and thus establish the non-ammonia chemicals system as a source of carbon removals in the latter half of the 21st century, thus becoming a climate solution and playing a climate stabilization role in a net zero world.

This sequestration may act as a new source of revenue for the chemicals system akin to carbon "offsets" or "compensation". The global carbon offsets market is forecast to grow to between 7-13 Gt p.a. by 2050.[67] Based on the expected increase in carbon price by 2050, the sequestration described in the LC-NFAX scenario has been conservatively estimated to be worth ~$55bn a year.[66] This new revenue stream may act to offset the costs of the transition to net zero. Notably, by inverting the carbon vector, not only are plastic emissions avoided,

66. Project offset price increase to $110, 0.5 Gt sequestration.

atmospheric carbon is simultaneously sequestered, thus one tonne of carbon inversion causes as much as 7 tonnes of CO_2 in the atmosphere to be avoided.[67] In order to accredit this offset, the chemicals system would need to ensure that the carbon sourced from the atmosphere did indeed end up sequestered, requiring close collaboration, partnership or even acquisition of incinerators with CCS applied to them, or other means of sequestration. Further analysis is required to establish the most appropriate model.

Carbon negativity acts as a risk hedge with circularity. If circularity should fail to scale, carbon negativity and thus climate benefit increases. However, circularity should still be a primary system objective because, while a larger chemicals system would lead to greater volumes of sequestration (~1.4 Gt for business-as-usual demand growth with no unabated fossil installation after 2030), as discussed there are multiple other feedstock/energy/technology scale constraints and non-GHG planetary impacts that require the system size to be kept as efficient as possible.

The chemicals system is uniquely positioned to be repurposed to play this role. Other forms of carbon removal make less efficient or no use of the carbon; bioenergy with carbon capture and storage (BECCS) provides energy only once, while the chemicals system is positioned to derive commercial value from both the repeated carbon use and sequestration.[68] What's more, there may not be time to construct a carbon removal industry at sufficient scale to drive the negative emissions necessary to achieve a 1.5 degree or even 2 degree scenario, thus the chemicals system is at a strategic advantage today as it can repurpose itself rapidly to become a commercially driven engine of carbon sequestration. It makes more productive use of carbon than comparable carbon negative routes such as BECCS, making it an appropriate use of whatever limitations in CCS capacity arise. Furthermore, in ascribing value to waste, this may have the positive impact of reducing mismanagement through open burning and system leakage.

Therefore, by taking a disruptive approach to GHG emissions, the chemicals system has opportunities to disrupt its future role within the global economy, including:

i. By scaling use of biogenic and DAC feedstocks towards 2050 to reposition itself as a commercially driven means of climate stabilization and regeneration.

ii. By driving CCS and green hydrogen rollout it can be a major contributor to scaling out those sectors, thus lowering costs and enabling sectors that require smaller volumes of CCS and green hydrogen to participate in these essential new net zero services.

All these roles could be considered positive contributions to protecting planetary boundaries and providing effective stewardship of the global commons.

67. (1.9 tonnes CO_{2eq} in production, ~2.7 at end of life and ~2.7 in the production of biogenic feedstocks).

Chapter 5:

Implications of the transition on infrastructure, production geography and employment.

The new net zero system model will reshape the location of global production infrastructure, trade patterns and value chains.

Chapter summary

A holistic system production infrastructure shift is required from the fossil orientated technologies of unabated steam cracking, gas reforming, and catalytic reforming (86% of production in 2020) to either abated production through retrofitting or to low-emissions orientated technologies of electrolysis, gasification, and carbon capture and utilization (79% of production in 2050 LC-NFAX scenario). Catalytic reforming will decommission completely, whereas steam crackers and gas reforming will be predominately retrofitted with abating technologies.

Energy demand of the chemicals system will increase by 4-6 times by 2050, driven by the 100% shift to renewable sources. This increase originates from the overall demand increase and the replacement of fossil fuel energy input with the production of green hydrogen. This translates into very significant RES growth, in the order of 9-13% of global electricity production in 2050.

The renewable energy requirements for the production of net zero enabling chemicals (ammonia and methanol) will likely drive greenfield capacity installation to gravitate towards regions with abundant, affordable renewable energy such as Latin America, the Middle East and North America. Olefins production via brownfield steam cracker retrofits will remain in their current location.

This will also likely lead to major shifts in the import/export patterns of ammonia and methanol around the globe, potentially benefiting the Global South, as well as restructuring the value chain for waste and biogenic feedstocks, which will require feedstock densification at point of generation to ensure logistics do not become prohibitively expensive.

The reshaping of the value chain necessitates a broadened span of control by the chemical industry to secure sustainable feedstock and collaborate with other adjacent sectors involved in CO_2 and H_2 handling (e.g., steel).

Low growth in olefins and aromatics, and the need for capex efficiency, will require existing legacy production capacity, such as steam crackers, to remain in situ in industrial clusters. This will enable them to benefit from downstream integrations, synergies and undergo retrofitting with low-emissions technologies, such as green hydrogen firing with off-gasses upgraded rather than burned.

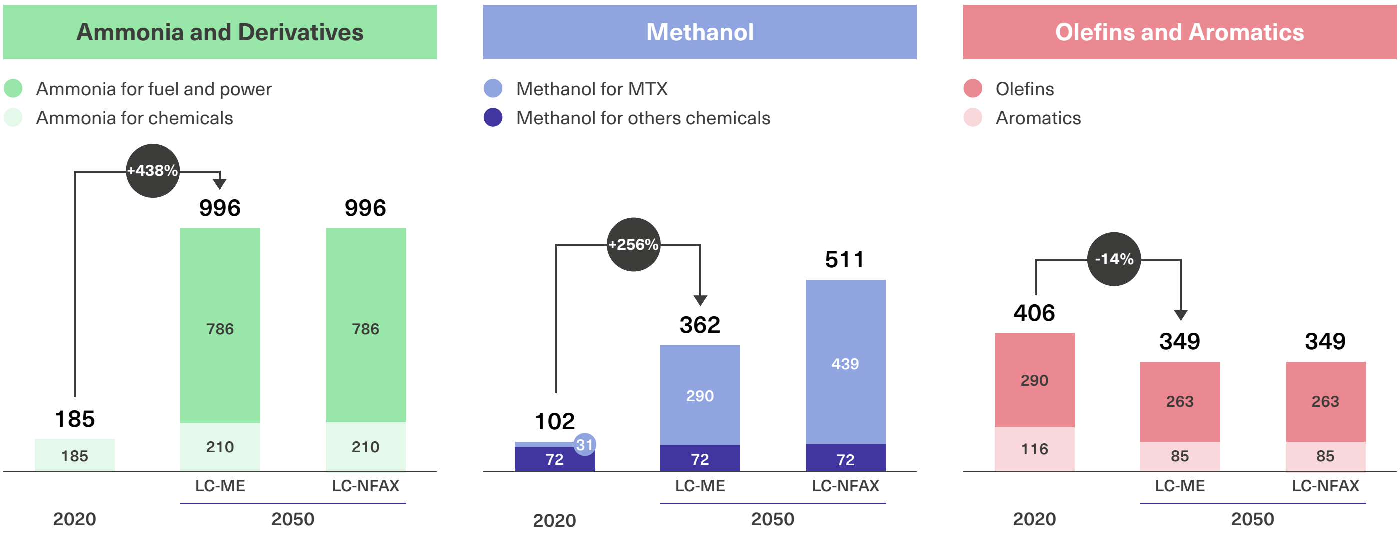
Lower-TRL technologies in inorganic catalysis, biotechnology, alternative energy provision, and process innovation may disrupt the chemicals system and offer lower cost alongside decreased energy intensity and higher feedstock utilization. Further R&D investments are required to enable these nascent technologies to reach commercial scale within the next 10 years.

The new chemicals system will create 29 million more direct and indirect jobs compared to business-as-usual by 2050 despite demand reduction.

Figure 27: Demand growth for primary chemicals

3-5x Growth in ammonia and methanol vs. declining demand for olefins and aromatics reshapes future of chemical industry

Mt chemicals



Ammonia and methanol are set to dominate new infrastructure buildout.

The largest growth opportunities for the chemical industry lie within the ammonia and methanol markets, with 5x and 4x demand growth respectively, necessitating major greenfield infrastructure build out.

Methanol will play a central role in the future of a net zero chemicals system and become the cornerstone to circulate carbon in the economy via MTX routes (i.e., carbon circularity) (Figure 27). It will thereby displace a significant share of naphtha used as most common primary system input feedstock for non-ammonia chemicals in-scope. Methanol combines several advantages:

- it can be transformed into most basic chemicals: olefins via methanol-to-olefins and methanol-to-propylene route (MTO, MTP – both well established), and aromatics via methanol to aromatics (MTA, currently at TRL 7)[69]
- it can be produced from a variety of sustainable feedstocks via gasification (bio, waste) and direct hydrogenation (CO_2) in combination with green hydrogen
- it is a liquid, shippable commodity (20% of its production is already shipped today)

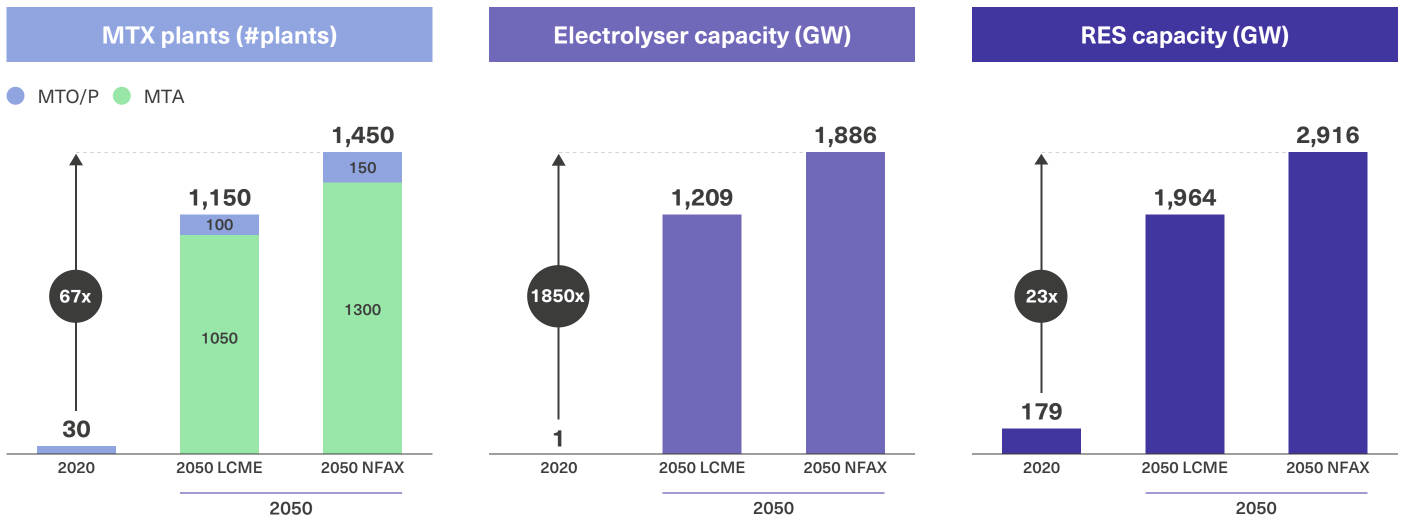
A significant share of both olefins (15 % in LC-ME, 27% in LC-NFAX) and aromatics (87% in LC-ME, 95% in LC-NFAX) will be produced via MTX routes, highlighting the significant infrastructure shifts required from steam cracking and catalytic reforming towards MTX. This corresponds to approximately 100-150 MTO/MTP and 1,000-1300 MTA plants required by 2050 (Figure 28).[68] In addition, small scale methanol production and MTO conversion is used to abate steam cracker off-gases via conversion into olefins. While this is more costly, due to the smaller scale of the methanol and MTO plants, it can be a powerful method to avoid any Scope 1 CO_2 emissions.

Beyond the small growth in ammonia demand for fertilisers (0.2% CAGR, 132 to 140 Mt ammonia equivalent), ammonia will enable a net zero world as a shipping fuel (625 Mt ammonia) and play a role as chemical energy storage molecule for total power system decarbonization (161 Mt).

68. Approximate estimated MTO/MTP plant capacity: 0.5 Mt/annum and MTA plant capacity: 0.1 Mt/annum based on existing plants, literature and expert input.

Figure 28: Production capacity for key enabling technologies

MTX, Electrolysers and RES require exceptional scaling



ote: (1) Plant sizes for MTX are approximate. (2) For electrolyser and RES, the total global installed capacity was multiplied with the chemical industry emission share (6.4 %) to reach a representative share for the chemical industry. Sources: IEA (2019), Future of hydrogen; IRENA (2021), Renewable capacity highlights; (3) a load factor of 50% was assumed for electrolysers, and 35% for RES.

Renewable energy infrastructure scaling implications.

The chemical industry will consume 9-13% of total electricity generation and 20-50% of global green hydrogen consumption by 2050.

The chemical industry will require significant amounts of RES (8,000 and 12,000 TWh/annum in 2050 for LC-ME and LC-NFAX respectively), in particular to produce green hydrogen for use as feedstock. This is in the order of all RES capacity in 2020[69], and about 9-13% of total electricity generation in 2050.[26,70,70] The total green hydrogen consumption (147-234 Mt) by the chemical industry will be in the order of 20-50% of global green hydrogen consumption by 2050 and requires significant ramp-up of electrolysers (500-4000 GW).[71] The lower energy density of new feedstocks in the net zero chemical industry (e.g., CO_2) compared to fossil feedstocks require significant energy input via green hydrogen (see Chapter 3). The overall primary energy input (feedstock + process energy) from fossil feedstocks was about 46 EJ in 2020 and declines towards 24 EJ (LC-ME) and 5 EJ (LC-NFAX) in 2050. This energy was embedded in the fossil feedstocks and did not require any additional input, thus switching to a alternative carbon source means RES alongside bio and waste are required to compensate for this decline in fossil energy input.

The main consumers of green hydrogen will be ammonia (136-161 Mt H_2 in LC-ME and LC-NFAX) and methanol (17-73 Mt Hydrogen in LC-ME and LC-NFAX). The energy use of green hydrogen (e.g., for steam crackers) is significantly smaller (0.5-1.2 Mt). Other minor energy consumption stems from direct electrification of heat provision and DAC. The growth in RES requires a significant infrastructure build out for the entire power system value chain, from transmission grid to power system balancing. Nevertheless, no physical or technical barrier is foreseen for this global electrification of the global economy.[26]

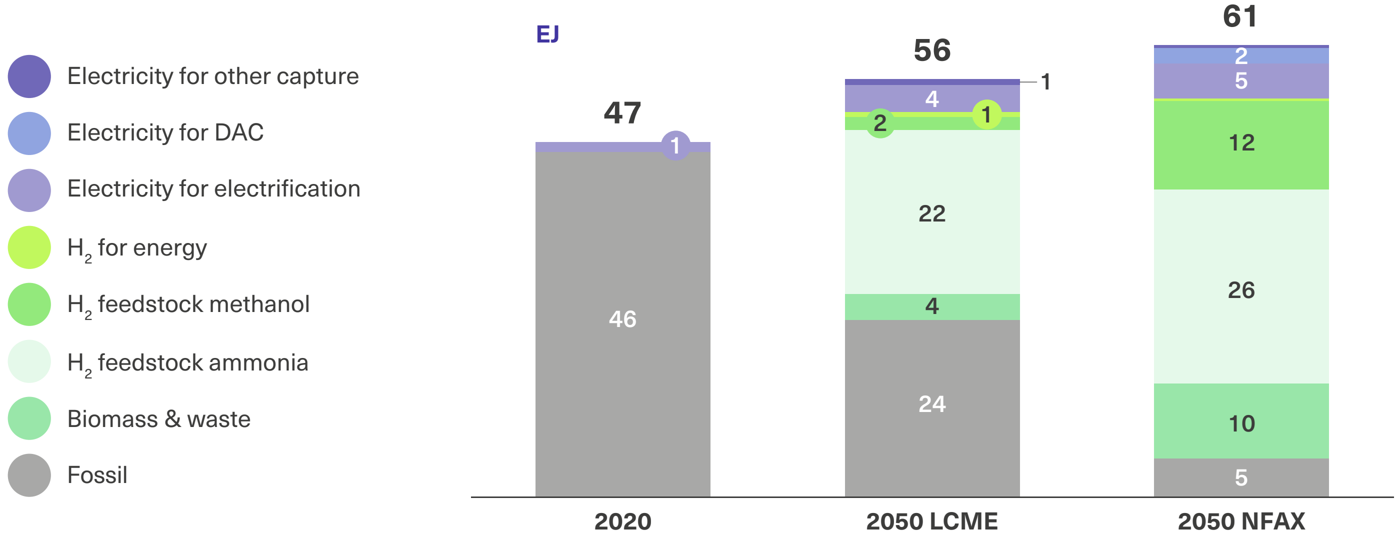
69. Ember Global electricity review 2022 suggests a total of ca. 7000 TWh generation by hydro, wind and solar in 2050. Nuclear, bioenergy and other renewables would add additional ca. 3500 TWh but are considered to only contribute minor shares in 2050.

70. Compared to 90,000 TWh required by the "supply-side decarbonization plus maximum energy productivity improvement" in the ETC scenario.

71. Strongly dependent on load factor. For 50% load factor, 900-2650 GW for LC-ME and LC-NFAX, respectively.

Figure 29: Total feedstock and energy input in the chemical industry

Fossil feedstock is displaced by green hydrogen as an energy and feedstock carrier



Geographic implications and opportunities.

Low-cost abundant RES regions will dominate the future production of ammonia and methanol creating significant opportunities for the Global South.

Global greenfield production will shift to regions with low-cost and abundant RES (ammonia) and carbon sources (methanol). This will lead to a subsequent restructuring of the global production value chain, decentralizing production away from fossil-based economies and often towards Global South economies, and enabling a truly global transition. Some of the lowest cost RES in the world is found in the Global South due to more favourable solar irradiance coupled with strong winds, making some locations particularly attractive for ammonia and (if carbon source is available) methanol production. While no region experiences an absolute decline in the total volume of chemical production by 2050, there is high variance in growth. With the re-location of large volumes of primary chemical production, new trade patterns may emerge, with local production of methanol and ammonia in locations of abundant cheap RES followed by shipping to markets for further downstream processing.

This offers a development opportunity stemming from the excellent natural renewable resources of many Global South economies (e.g., Namibia, Chile) that can decentralize and de-risk global production from where it is today. The knowledge, capital and technology to reach net zero by 2050 exists in abundance in the Global North but transitioning the system in these economies while neglecting the Global South will undermine the impact of this achievement. The time-series to 2050 is too short to transition the Global North system first and then begin transitioning the Global South – they need to be done simultaneously. In the Global South, the mechanisms for IP, capital and knowledge transfer are currently not well established from a legal, technical, commercial or social perspective. Therefore, there is a risk of the Global South lagging, or worse, being overlooked entirely.

Sustainable bioethanol as feedstock may take up a significant role in ethylene production, but will be locally limited to low-cost production regions, e.g., North and South America. It will be critical to ensure that growing of crops for bioethanol production does not compete with food production or have negative consequences on land use (e.g., deforestation). In addition, recent studies have highlighted that an assessment of the full life-cycle emissions of bioethanol production, including emissions associated with fertiliser use for crops growth, will be needed to ensure this route is emissions neutral/negative.[71]

Value chain shifts in the future chemical industry.

The transformation of a linear chemical industry based on fossil feedstocks to a more circular system opens vast opportunities for vertical and horizontal integration in the market.

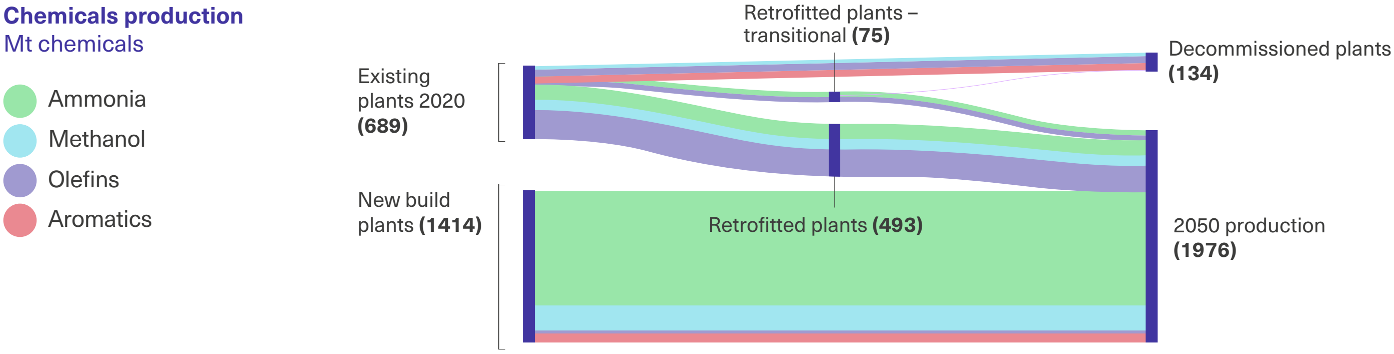
The chemical industry has all the means to be the cornerstone of CO_2 and hydrogen handling, two critical enablers for the transition of the global economy. Synergies with, for example, steel companies to utilize their valuable off-gases for chemicals production are already being explored today.[72] Similar synergies exist with the aviation sector, where naphtha like by-products during Fischer-Tropsch based synthetic aviation fuel synthesis could become critical feedstocks for steam crackers. Beyond CO_2 and hydrogen, waste (including CO_2) management will become feedstock management for the chemical industry, with growth opportunities in the re-use/substitute/recycling and biomass & waste sourcing. Sustainable carbon sources are very geographically dispersed (see chapter 3).[72]

Transport of carbon sources (biomass, waste, CO_2) in a densified form (e.g., conversion to methanol or pyrolysis oil) is therefore essential to reach centralized chemical industrial clusters, especially in rural and remote areas. The growth of methanol is key in this shift, as methanol is far denser and more easily transported compared to some of its raw feedstocks. The methanol production process (i.e., gasification>syngas>methanol) may be redistributed, followed by a more centralized MTX downstream infrastructure. Similarly, pyrolysis of waste may develop in a distributed fashion, with pyrolysis oil transported back to steam crackers. As such, the improvement of methanol production and pyrolysis processes to allow small scale operations at a low cost will be one of the keys to enable distributed operations. Significant waste management infrastructure developments, in particular in the Global South, will be required to ensure low plastics leakage, high recycling rates, and high waste feedstock utilization.[8]

The flat demand for olefins, combined with their large brownfield asset base, means industrial clusters may remain intact (Figure 30). Retrofits of existing chemical industry assets (e.g., steam crackers) are less capex intensive than newbuilt and capitalize on existing experience in the workforce, downstream processing,[73] and value chain connections (i.e., geographic stickiness). However, limited availability of non-fossil feedstocks that can be utilized in steam crackers (i.e., pyrolysis oil, bio-oils) and the need to avoid prolonged dependence on CCS highlight that 55% of steam cracker capacity would retire in the LC-NFAX scenario compared to only 14% in the LC-ME scenario (Figure 31).

Figure 31: Global production infrastructure shift (LC-ME)

Ammonia & methanol greenfield plants dominate infrastructure changes while olefin production is largely retrofitted with only a small role for transition technologies



Note: Decommissioning is performed if there is no abatement technology available or if production > demand. Retrofits are preferred over new-build if more economic. Transitional plants allow for partial abatement.

72. With the exception of DAC, which can be positioned wherever there is cheap RES. Point source CO2 and waste availability is associated with industrial sites and urban clusters. Sustainable biomass availability is dispersed, typically low volume and at the point of generation are much less energy dense than fossil feedstocks due to inherent physical properties (including high water and oxygen content).

73. High levels of integration within chemical industry clusters to increase energy and resource efficiency and leverage downstream synergies will continue to play a critical role.

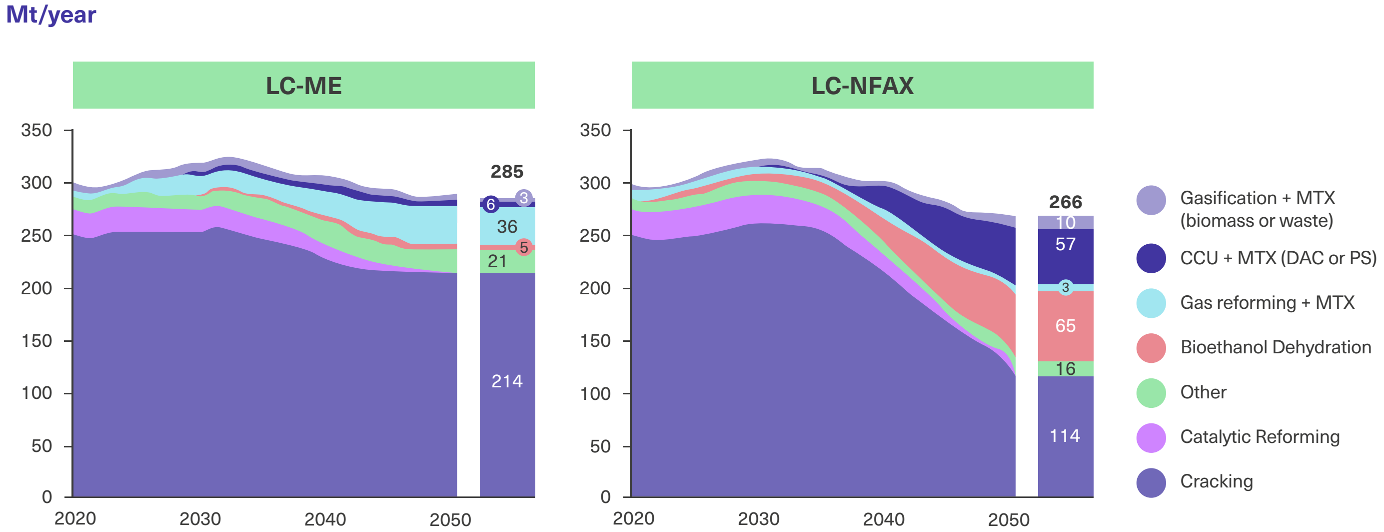
Steam cracker assets can live on if retrofitted.

Brownfield transformations are the lowest cost option for the transition of olefins business, whereas catalytic reforming for aromatics will retire.

Abating steam crackers gives rise to strategic trade-offs between capex/opex and between CCS and energy abatement approaches (green hydrogen and ammonia abatement and electrification) (Figure 32).[74] Green hydrogen firing is anticipated to be less capex intensive[75] compared to electrification due to lower retrofitting costs. However, due to lower energy efficiency, the opex are higher for green hydrogen fired crackers. If the goal was to sustain a steam cracker portfolio in the long term, electrification would make sense, however, in light of the imperative to drive away from fossil feedstock + CCS and subsequent decline in steam cracker portfolio, a capex efficient retrofit makes more sense. Therefore, retrofitting with green hydrogen firing is a more capex efficient and strategically less risky approach, especially due to the impending green hydrogen price reductions (to 1-2 $/kg) expected towards 2030 and beyond. Several industry players are nevertheless gearing up to commit to electrified steam crackers (e.g., BASF, Total, and Linde's E-Furnace project in EU). This is expected to boost innovation and development efforts, which in turn are the primary driver of cost reduction. Thus the relative economics of electrified high temperature heat could become superior over time. In addition, while smaller in overall energy consumption, direct electrification of ancillary equipment (e.g., compressors) with renewables can be used to abate some fossil fuel and steam usage. These retrofits are commonly easier to perform and available at low cost.

Figure 32: Olefins production evolution by 2050

Steam crackers will continue to play a central role in the chemical industry in both main scenarios



Refinery assets face risk of being stranded due to falling demand for transport fuel, largely driven by road transport electrification. Aromatics production via catalytic cracking as part of the fuel production process cannot be abated and will retire. By 2050, burning fuel for either electricity generation or transportation will not be socially acceptable in a net zero world. So-called hard to abate sectors, including road transportation, aviation, shipping and energy, will transition to RES, hydrogen, biofuels or ammonia. The infrastructure implications will be massive for the vast oil and gas industry, both upstream and in downstream refining. Repurposing this infrastructure will be challenging.

74. Tail-gas from the steam cracker is abated via a methanol synthesis and MTO conversion step. Energy abatement in combination with this off-gas upgrade therefore leads to full Scope 1&2 abatement.
75. The assumption is based on grid-connected hydrogen production via a power purchasing agreement where the capex heavy RES capacity build-out is done by another party.

Early-stage disruptive technologies development.

A range of low TRL disruptions may offer the opportunity to fundamentally change the rules of the system.

The above transitions will require a very significant innovation agenda to lower energy intensity, increase cost efficiency, and improve feedstock utilization.[76] Disruptions will come as direct substitute of either existing chemical pathways (including intermediates) or in the form of new synthetic routes, subsequently removing the need for some basic intermediaries. Four technological fields with all the ingredients required for a significant disruption have been identified (Figure 32):[77]

Figure 33: Low TRL technology mapping in the chemical industry

Plethora of low TRL technologies are awaiting to disrupt the industry

Impact to the Industry	Field of Technology: Inorganic Catalysis	Industrial Biotechnology	Process Innovation	Alternative Energy Provision
Primary chemical	• CO_2 electrocatalysis • Thermochemical CO_2 conversion • Dry reforming • NH_3 electrocatalysis	• Fermentation processes with established microorganisms	• Membrane separation (polymers or metal/ covalent organic frameworks) • Plasma (e.g. CO_2 conversion or gasification)	• Med. temp. heat pumps (<200C) • New electric heat sources (ohmic) • Geothermal • Solar thermal • Microwave heating
Novel feedstocks & end-of-life mitigation		• Microorganisms digesting polymers • Synthetic biomass (from CO_2, e.g. algae reactors)	• CO_2 mineralization • Densification of biomass/plastics waste • Microwave based plastics separation	

Existing downstream chemical	• New metal catalysts allowing multi-step reactions (one pot)
	• Electrochemical synthesis
	• Integration of multistep bio (cell & cell-free)/ inorganic reaction cascades
		• Cell-free system (incl. immobilized enzymes)
		• Micro-organism mediated reactions (incl. new biodegradable polymers)
		  • New microorganisms
		  • Standard microorganisms
		• Utilization of new feedstocks (biogas, syngas, formate, methanol) instead of sugars
			• Sonochemistry
			• Mechanochemistry	

Novel downstream chemical			• Synthetic biochar synthesis	

76. This study has focused on technologies with a TRL of >7, but due to the long timeseries to 2050 the potential for breakthrough innovation to offer opportunities for faster, cheaper, more efficient emissions reduction can be neither ignored nor predicted.

77. This overview excludes digitalization of the chemical industry, although the impact on process optimization and R&D (especially artificial intelligence when it comes to catalyst design or microorganism optimization) is likely going to enable the innovations discussed in this section.

1 **Inorganic catalysis has been a field of innovation for decades and is expected to continue to disrupt the industry as our understanding of the chemical processes continues to grow. The number of potential catalysts to explore is almost infinite.** Enablers, including artificial intelligence[73] and lab robotics,[74] will drive faster, cheaper catalytic screening, while nanotechnologies will provide an opportunity to increase surface area and selectivity. Carbon dioxide conversion is expected to receive most attention as carbon capture at scale becomes commonplace. Electrocatalysis (e.g., to produce ammonia) will continue to be an important area of research given its potential impact and declining grid electricity emissions and prices. MTX catalysts will also be an area of focus to enable the tuning of output product ratio to match demand at scale (e.g., ethylene vs propylene, xylene vs benzene). Another interesting alternative may be the development of catalysts similar to MTG (methanol to gasoline) that can produce "green" naphtha from methanol and allow continued use of the steam cracker infrastructure in an abated fashion. More broadly, finding new pathways to control the production ratio of the different aromatics will be key to ensure production matches demand beyond the currently used toluene disproportionation reaction (e.g., toluene methylation). A special emphasis will be put on catalysts that allow multiple reaction steps in one pot without the need for energy and cost-intensive intermediate isolation and purification to decrease energy intensity.

2 **Industrial biology and biochemistry are expected to become more competitive as the high processing costs are offset by the promise of low energy intensive processes.** From the development in mapping living organisms and enzymes, new routes will emerge to produce basic chemical intermediates (e.g., ethanol, butanol), new polymers (e.g., PHAs) and targeted molecules. The field will be boosted by its ability to use a versatile array of feedstock (raw biomass, syngas, methane etc.) and its low energy profiles.

3 **Alternative energy provision (e.g., geothermal), as well as new forms of power integration (e.g., higher temperature heat pumps), may play a critical role in the provision of zero-carbon heat and steam, essential for the chemical industry.** Low (< 100°C) and medium temperature (100-400 °C) heat provision accounts for more than 90% of total heat demand across all industries.[55] Heat pumps alongside solar, thermal and geothermal heat could provide some of the lower temperatures required. Scale-up and the need for economic as well as energy efficient heat integration remain bottlenecks for implementation. Very high temperature heat pumps may reach up to 200°C but require further development.[75] Very high temperature heat will be created via ohmic, plasma or microwave heating. The latter may also be used to influence the chemical reaction itself towards new synthetic routes.

4 **Process innovations, such as innovative chemical separations, have the ability to lower energy requirements and fundamentally change value chains.** Examples of high-energy intensity processes include carbon capture, water/ethanol separation via distillation, and xylene separation.

The promise of job creation.

The new chemicals system will create 29 million direct and indirect jobs vs BAU by 2050 despite demand reduction.

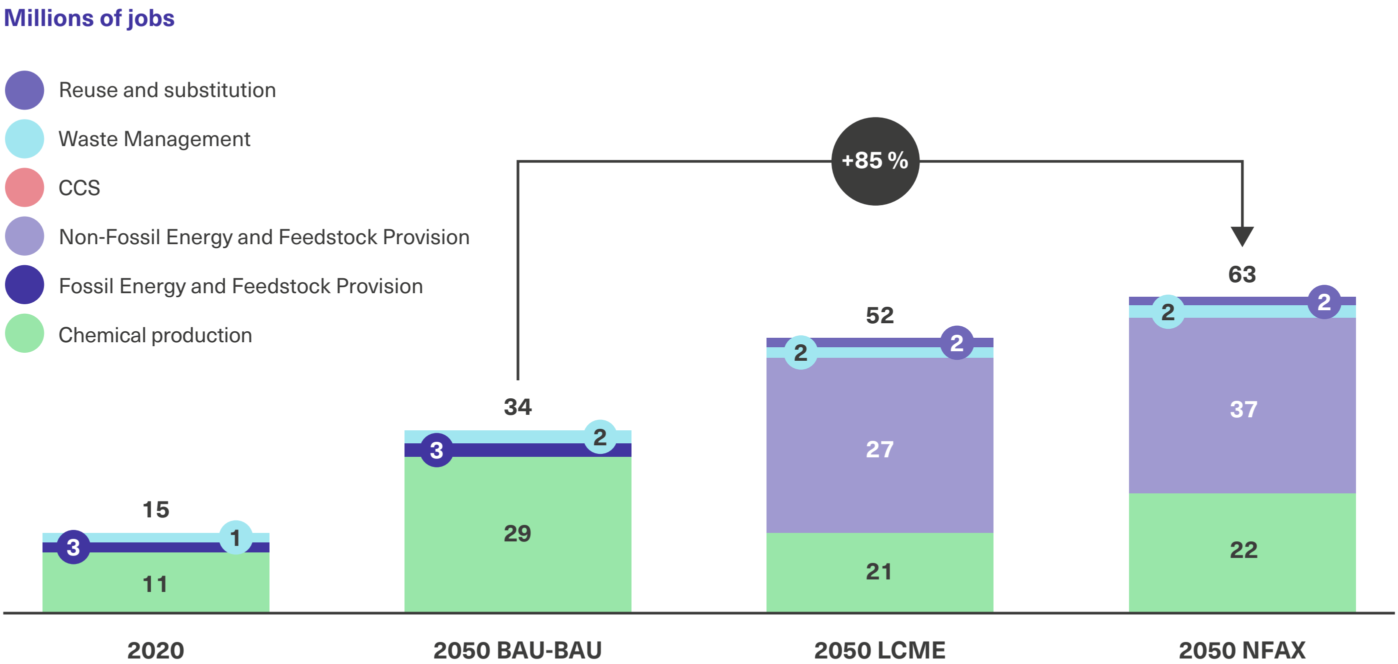
The chemical industry at large employs 15 million people worldwide and indirectly supported 105 million jobs in 2017.[76] The future of the chemical industry heavily depends on its ability to continue to create a pool of knowledge intensive jobs that are invaluable to society and the economy. Demand reduction levers are expected to create a dent in the job market for the industry; 8 million jobs fewer than in a BAU demand growth scenario, the analysis suggests.[8,77–83] However, this will be largely offset by the industry's ability to expand its span of control to other industries.

Overall, we expect the LC-ME and LC-NFAX scenarios to provide 18 and 29 million additional jobs compared to the BAU-BAU scenario respectively (Figure 34). These additional jobs will be predominantly upstream, with 21-22 million jobs for the production of hydrogen, RES and biomass, but the circular economy can also provide up to 2 million jobs for the industry by 2050. The waste industry will grow from 1 million jobs in 2020 to 2 million in 2050, driven by additional collection, sorting and recycling infrastructure, although this increase will be marginal in comparison to other industry potential.

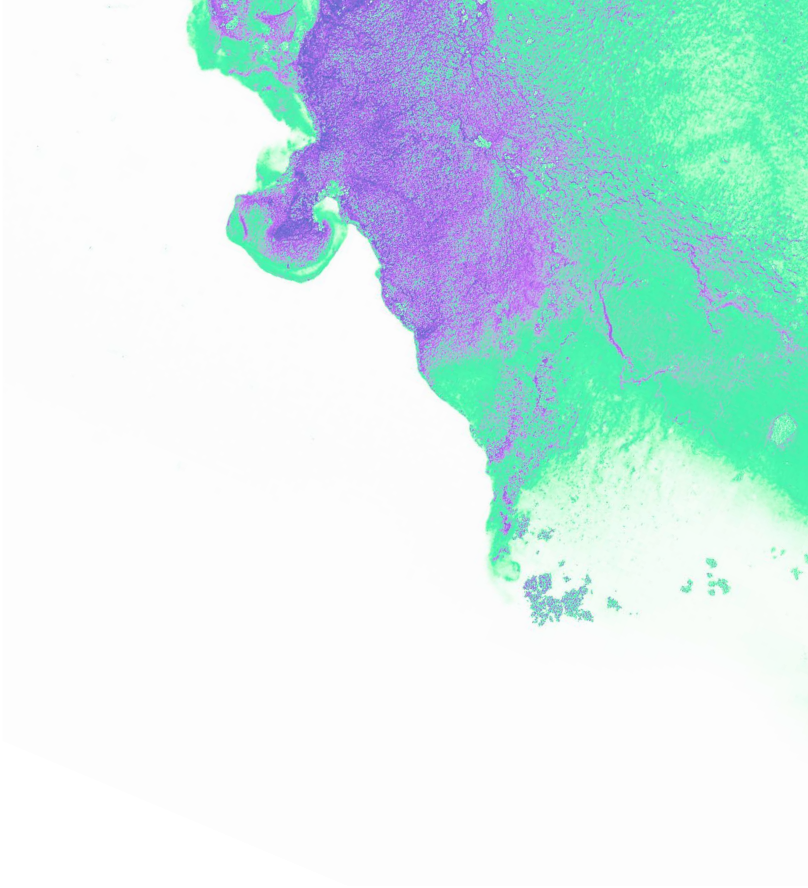
The industry is currently facing a problematic skill gaps, which is unfortunate timing for the 'decade that matters' – between now and 2030 – and could be exacerbated if the industry does not take climate action rapidly.[84] Therefore, to attract talent from the highly educated cohort most sought after in the job market, many of whom are actively seeking environmental and social purpose at work, the chemical industry needs to reposition itself as a climate champion and steward of the Global Commons.

Figure 34: Sources of employment in the chemicals system 2020 vs 2050

Up to 29 million direct and indirect jobs could be created in the LC-NFAX Scenario (+85% compare to BAU-BAU) in energy, feedstock and the circular economy, despite demand reduction



Note: Includes ammonia for fuel and power provision.



Chapter 6:

Chemicals system economics – overcoming the financing wave.

Chapter summary

Net zero ammonia and methanol production cost will be competitive with today's cost by 2050 and potentially even be cheaper. In contrast, the production cost of net zero olefins and aromatics could be 50-200% higher than their fossil-based counterparts in 2050.

Driven by massive infrastructure needs in ammonia and methanol production, there will be cumulative $2.7-3.2 tn investment needs by 2050, 7-9 times the current requirements. For olefins and aromatics, 28-38% of capex investment will be from the waste management sector.

The market will ultimately need to change its perception of the value of chemicals. The end user impact will result in a lower single digit % increase in production costs for most products that use the net zero basic chemical intermediates. Therefore, in the absence of sufficient carbon pricing to fill the price gap, re-valued and re-priced low-emissions chemicals should be pioneered, starting in premium markets that recognize their value and can absorb the fully loaded costs to the economy and planet, including market externalities that society has not paid.

In the near term, a step change in policy interventions is likely required to cushion economic shocks, incentivize preferred actions, and disincentivize harmful actions. This may be in the form of a carbon tax between low-emissions intensity and high-emissions intensity products, in order to put the businesses cases for low-emissions technologies on-par or better than the traditional technologies.

Finally, with the wider adoption of a circular economy and limited access to biogenic and fossil feedstock, decoupling from a volume based business model will likely be required, which in turn will require the chemical industry to explore a longer-term shift to new business models, of which three have been identified: (1) **Engagement in circular economy models**, e.g. Chemicals-as-a-Service models; (2) **Broadened spans of control**, e.g., lateral and vertical integration of i) renewable energy ii) biogenic feedstock iii) waste feedstock and iv) end-of-life disposal; and (3) **Carbon negativity**, where value is attached to sequestering emissions (assuming the adequate system certification of source and carbon destination e.g., through carbon tracking and tracing).

The true cost of low-emissions chemical products.

Green ammonia and methanol are expected to be competitive by 2050, while the cost of olefins and aromatics could increase by 50-220% by 2050.

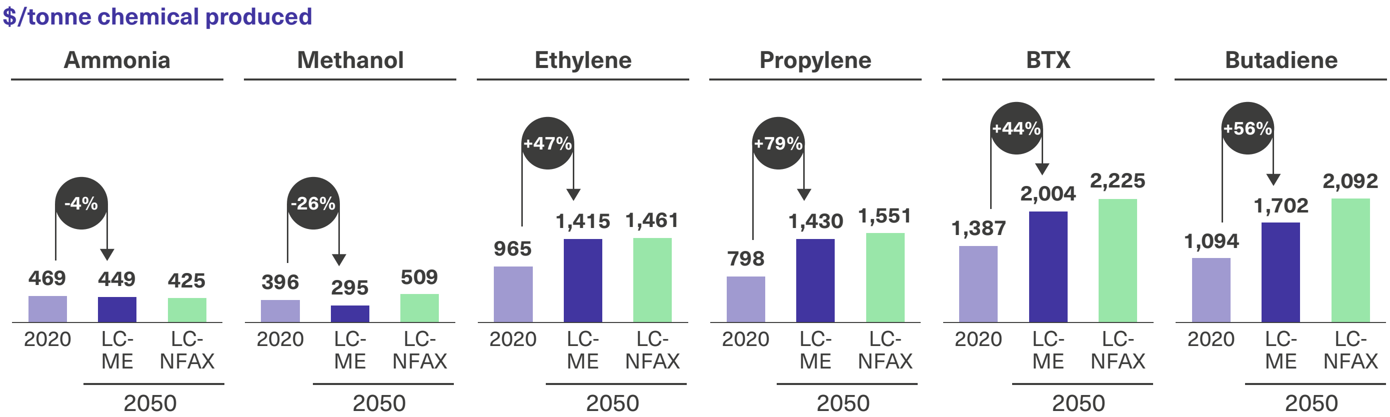
Achieving net zero will rely on much more expensive technologies than those used today, but in most regions this will not always be the case towards 2050 due to lower capex, lower feedstock cost, and lower energy cost. New technologies for olefins and aromatics are unlikely to compete with conventional ones even by 2050, after which the expected cost reductions due to scaling factors lead to a very different cost baseline. However, the expected decrease in cost from both RES and consequently hydrogen will make green methanol and ammonia competitive by 2050. Technology costs are widely influenced by regional factors, as the cost of feedstock (especially hydrogen but also biomass) and energy have important regional variations, creating very different local economic outlooks.

For olefins, the cost of production through upgraded steam crackers will be on average ~$100/tonne of chemical output cheaper than MTX. Cracking will either require costly upgrades to reach net zero (e.g., hydrogen/ammonia heat or electrification etc.) or will need more expensive feedstock (e.g., bio-oils, pyrolysis oil), which will drive cost up by ~60% on average. Shifting away from crackers to an MTX economy will require expensive new builds and are typically lower scale, and thus less economic, processes. Therefore, a clear shift to MTX will only occur at a global scale if fossil is phased out as a feedstock for Scope 3 emissions, or in a high fossil price scenario, as only a fraction of crackers will be able to feed on pyrolysis oil and bio-oils. Ethanol dehydration for ethylene production will only be competitive with the other two technologies in North America, where ethanol is significantly cheaper than other regions, but otherwise will likely remain more expensive. Conversely, gas reforming cost will only marginally increase as the only upgrade needed is CCS.

For hydrogen and syngas production, CCU and to a certain extent gasification will be increasingly competitive compared to gas reforming + CSS, which will remain relevant in the regions where cheap gas is available. Electrolysis, gasification and CCU will be within the same global cost range by 2050: ~$120-190/tonne of chemical output, with regional differences. In regions where cheap RES and therefore cheap hydrogen is available, those technologies will be particularly competitive, even to gas reforming. Gasification, while more capex intensive, might be favoured by the availability of cheap biomass or waste, and will be especially relevant in countries which can be paid to process such residual feedstock, turning the economics upside done.

Figure 36: Levelized production cost of chemical products

By 2050, olefins and aromatic will cost 1.1-3x more than today, ammonia is expected to see cost decline by 2050 supported by fall in hydrogen prices, for methanol cost will dependant on reliance to CCS or CCU



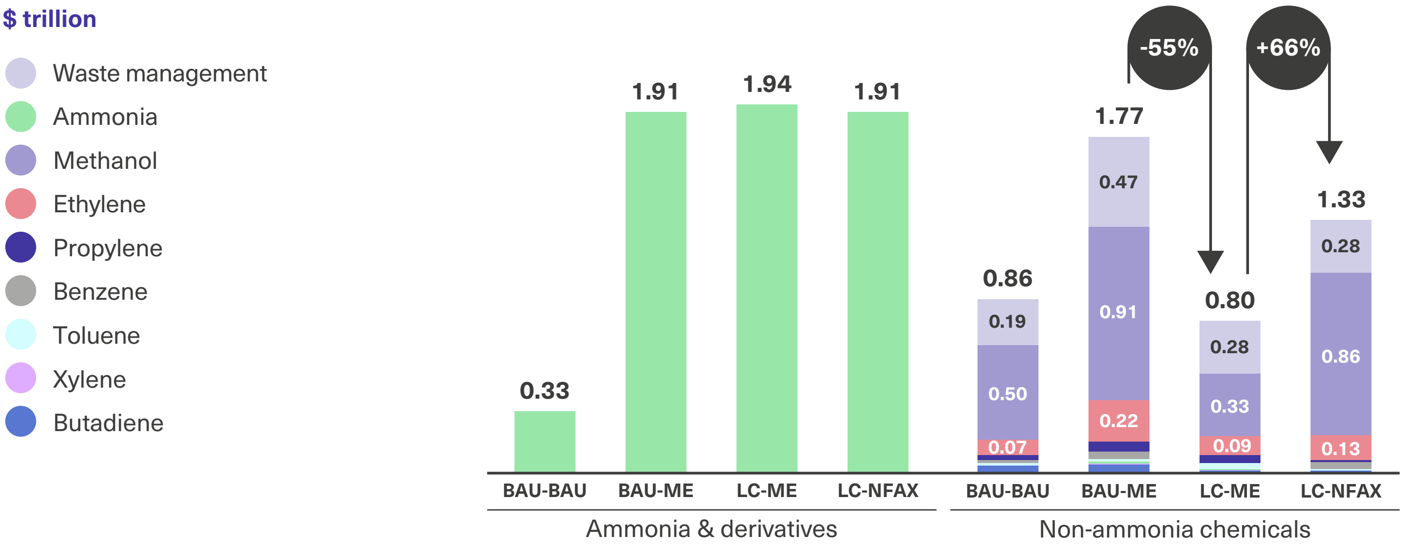
Note: (1) 2020 and 2050 levelized cost are blended average across all relevant technologies.

Overall, the analysis suggests that green ammonia and methanol will be competitive by 2050 and that the cost of olefins and aromatics could increase by 44-79% in a LC-ME scenario and even more in a LC-NFAX scenario (Figure 36). The increase in production cost is directly linked to the increase in technology cost discussed above, which would affect olefins and aromatics. While the most economic scenario will quite probably be preferred by industry, it will remain incredibly challenging for individual players without radically different business models or financial mechanisms to support the transition.

The shift in infrastructure will require the largest financing effort the industry has ever experienced. By 2050, cumulative $2.7-3.2 tn capex need to be invested (LC-ME and LC-NFAX), equivalent to ~$0.11 tn /year between now and 2050 (Figure 37). Given the maturity of most technologies today and the typical lifetime of such assets, this represents a significant risk for the industry. The transition will likely require new investment tools and partnerships (e.g., blended finance), especially in region where the cost of capital is the highest.

Figure 37: Cumulative investments per chemical

The chemicals value chain will need to deploy an incremental $2.7-3.2 trillion capex by 2050 to achieve net zero, 51-70% of which is for ammonia

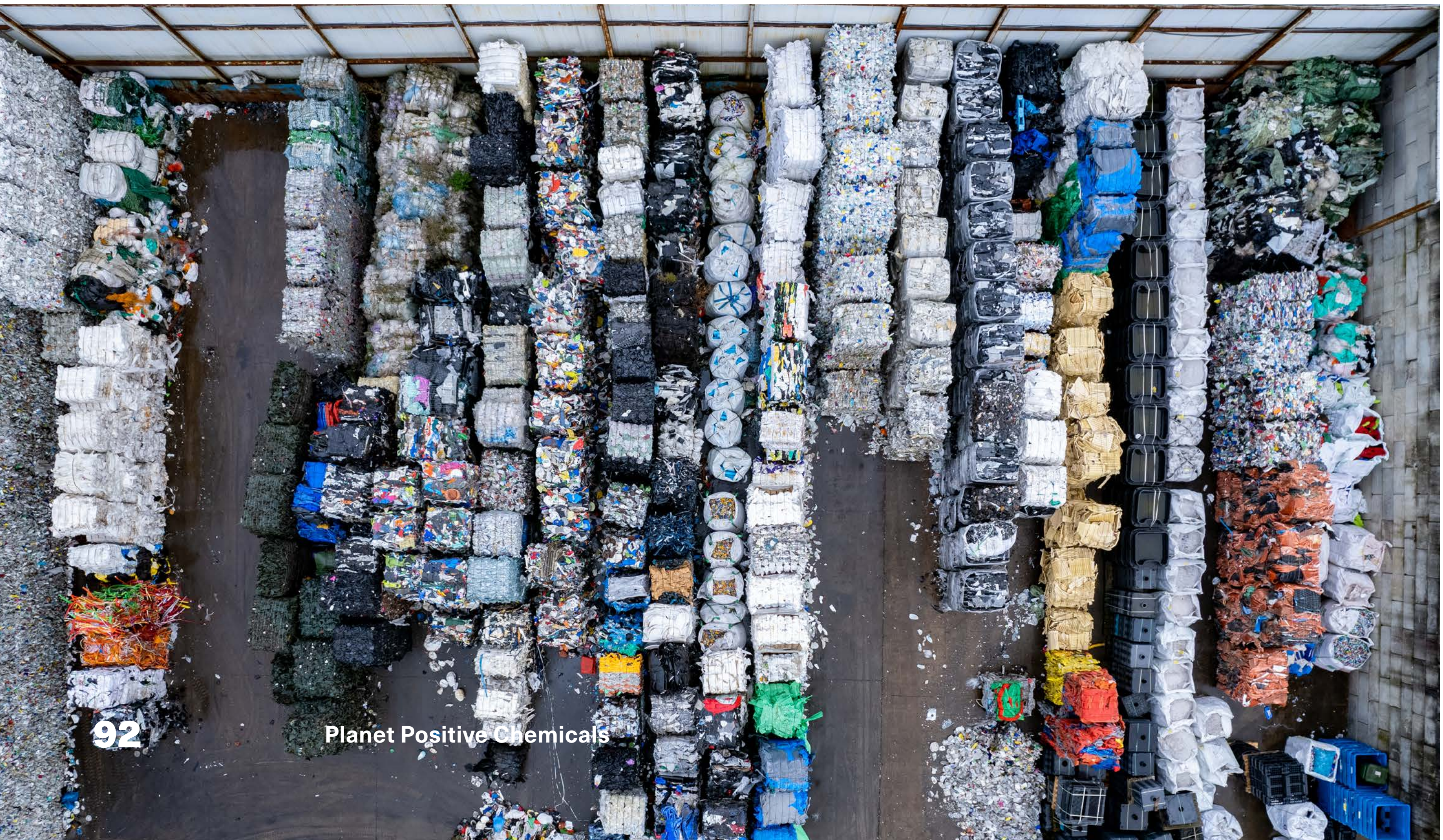


Note: BAU-BAU production only considers incremental capex for scaling unabated technologies (e.g., grey ammonia and black methanol production).

By 2050, out of the total capex needed for chemical production, roughly one third needs to be invested in retrofit and two thirds in greenfield production to achieve net zero. Maximizing the value of existing assets will remain the most effective short-term strategy. However, the lion's share of investment will support additional capacity and necessarily lead to new build plants. Most of the expenditure will come from the need to enable ammonia (60-70% for LC-ME and LC-NFAX respectively). As ammonia becomes the strategic fuel of the shipping industry and broader enabler of a sustainable global economy, investment in electrolysis will represent the vast majority of capital expenditure by 2050. While the cost of this technology is expected to decrease significantly with scale, first movers are likely to have a significant advantage in a market driven by climate urgency, due to demand for low-emissions products.

While ammonia investment stays consistent at $1.9 tn across scenarios, the non-ammonia system costs vary considerably. The LC-ME scenario costs slightly less than the BAU-BAU scenario, meaning that abating the non-ammonia system via supply and demand side measures is more economically efficient than unmitigated scaling of the emissions intense system. LC-ME is 55% lower than BAU-ME, meaning that circularity in the non-ammonia system results in a halving of incremental abatement expenditure. The cost of methanol production is the main variable, with circularity efficiencies reducing total methanol production investments by ~$0.6 tn. Conversely, the fastest abatement approach to net zero (LC-NFAX) requires ~$0.6 tn additional cumulative incremental investment than the most economic approach (LC-ME) for methanol production build out, which is largely the price of establishing a carbon negative non-ammonia system.

$0.3 tn in waste management infrastructure investment (~10% of incremental system capex) will be required to achieve net zero in the two main scenarios, representing a significant investment for non-ammonia chemicals (23-38%) just to mitigate scope 3 downstream and waste leakage. The cost of infrastructure from adjacent industries, including waste, CCS and RES, represents a major challenge for the chemicals industry. What's more, the fully loaded cost of CCS infrastructure, including transport and storage (CO_2 capture is included in production cost), will actually be much higher than the figure stated because it only represents the chemical system's share. The full cost of this infrastructure will typically need to be shared between multiple industries if not countries. Similarly, investing in waste management to collect, sort, recycle, landfill or incinerate plastic will be critical. The $0.3 tn represents only a fraction of the total cost needed to manage all waste streams, as it excludes waste streams which are not derived directly from the chemicals industry (e.g., organic waste, paper waste). The chemicals industry is unlikely to be able to finance this transition alone, and this creates a major risk as the delivery will necessarily be performed by external sectors. The industry therefore needs to strategically position itself to ensure its transition is not jeopardized by the slow development of other hard to abate sectors, such as steel, cement and aluminium.



Who will pay for low emissions chemicals?

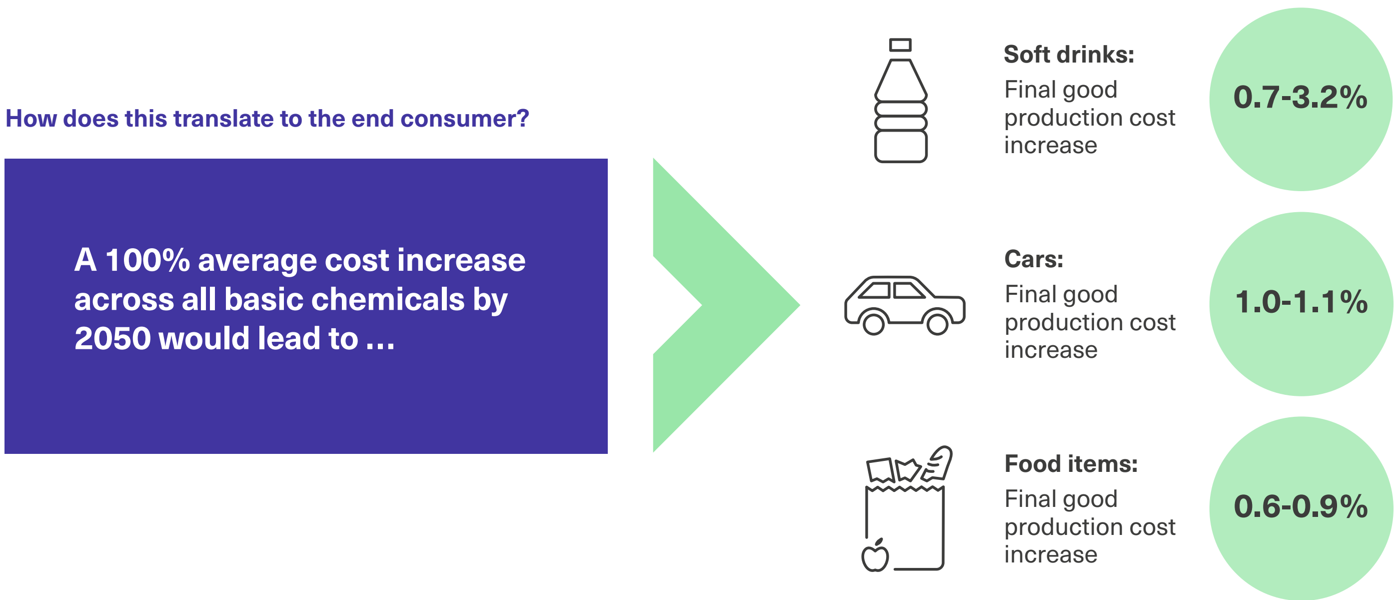
The downstream impact from the cost increase in basic chemical intermediates will result in a low single digit % increase in production costs for most consumer products.

The market will ultimately need to shift its perception of the value of chemicals. The downstream impact will result in a low single digit percentage increase in the production costs for most consumer products, therefore re-valued and re-priced low-emissions chemicals should be pioneered in premium markets that recognize their value and can absorb the true costs.

Analysis of the downstream price increases caused by the higher production costs of net zero emissions chemicals suggest that the impacts on consumers will be limited (Figure 38). An analysis was conducted using Leontief's inverse matrix for two countries – the US (2012 data) and Japan (2015 data) – using publicly available government data to estimate the ripple effect of cost increase on the production cost of consumer products.[85,86] The analysis, which assumes cost increase is passed along the value chain without inflation or absorption, and without changing the demand size shows, that a 100% cost increase of the basic chemical intermediates would have a 3.2% (US) and 0.7% (Japan) cost increase on soft drink manufacturing, 1.1% (US) and 1.0% (Japan) cost increase on passenger car manufacturing, and a 0.9% (US) and 0.6% (Japan) cost increase on food (Figure 38). and Appendix). It was concluded that the effect on the consumer would be lower than most people would assume but still noticeable. It is important to remember that the cost of the transition for the consumer will not be limited to the chemical cost increase, as the transition costs of other sectors (e.g., steel, cement, transportation) will be added, the magnitude of which requires a dedicated cross-sectorial analysis.

Figure 38: Analysis of the economic impact on the end consumer

Large upstream cost increases of 100% have modest impact on consumers of only 1-3%



Note: Economic analysis using Leontief's inverse matrix (input output tables) for Japan (2015 data) and US (2012 data) based on publicly available data from respective government and only representative of the industry structure of those respective countries; assuming the cost increase is passed down to the next player in the value chain, in which no one absorbs or inflates the cost increase, or changes production volumes; assuming the cost of imported products are impacted similarly; cost increases shown here include all direct and indirect cost repercussion in the manufacturing of consumer goods (e.g., the impact includes not only ethylene used in the PET bottles or car parts directly, but also ethylene (plastic) used in the equipment used to manufacture bottles or car parts etc.) but exclude distribution and retail sectors

Policy will still accelerate the scaling of low-emissions chemicals.

While the chemical industry should not wait to establish net zero emissions chemicals markets, policy interventions such as carbon pricing would support the mainstreaming of low-emissions technologies. Establishing net zero emissions chemicals markets will necessarily create market opportunities and shortfalls.

The chemical industry should not wait for the right policy environment to overcome the economic barriers associated with low emissions chemicals. Industry pioneers should focus on establishing premium consumer markets (e.g., for certain products, industries or regions) to seize first mover advantage.
The risk for the industry is to wait for technologies to be cheaper and less risky to invest in. The demand for Scope 1-3 net zero from a broad range of policy, value chain, and multi-lateral bodies, such as the IPCC, is here to stay and will only get stronger. There is a long-term but clear demand signal in the chemical industry and, while this market is niche today, it is rapidly growing and demand arguably already outstrips supply. While the eight basic chemical intermediates are all highly commoditized, net zero basic chemicals could be considered highly differentiated value-added products by downstream customers willing to pay a "green premium". Formalizing this demand into offtake agreements may de-risk projects and thus help unlock the required capital outlay from the chemical industry.

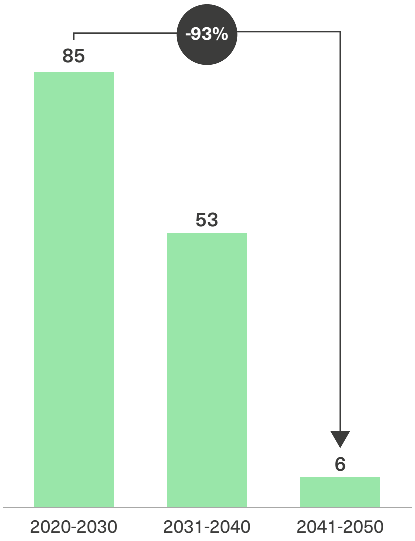
First movers in the chemical industry should not wait to establish net zero chemicals markets in the near future, irrespective of policy environment.
While there is investment risk around which technologies will win out in the future, this analysis aims to bring increased clarity around which high TRL (≥7) technologies can be scaled with lower risks. Moreover, while the increased product cost per tonne is not trivial, the impact on consumer prices is limited. Therefore, in light of i) the clear pressure for low-emissions chemicals markets, ii) the potential guaranteed demand for such differentiated products, iii) the increased clarity around production technologies, and iv) analysis suggesting that the commercial impact on customers is limited, first movers in the chemical industry should not wait to establish net zero chemicals markets in the near future, irrespective of policy environment. In taking these early steps, companies can place themselves at a significant advantage regarding market capture, intellectual property, talent attraction, brand, cost optimization, and scale.

A step change in policy will help to re-engineer economics in the medium term to overcome systemic intransigence, incentivize mainstreaming of net zero technologies, and disincentivize the most actively harmful activities.
The global chemicals system is currently confronted by a tension between short-term and long-term risk that is causing systemic intransigence. On one hand, the long-term risks of inaction – in the form of global warming, environmental pollution and damage to human health – threaten the system's fundamental license to operate and progressively erode its net value proposition to society. On the other, shifting from a stable, profitable, low-risk model of production to less mature, more expensive technologies and business models requires placing capital at risk without the certainty of recovering that investment. Industry pioneers who embrace this inevitable future first, risk being economically punished for their leadership in the near-term, while laggards embracing the status quo may be rewarded with profit for not acting. There is a strong temptation to be in the middle of the pack, waiting for some technologies to be proven out further before deploying capital, but this risks all stakeholders waiting for others to make the first move: thus nobody moves.

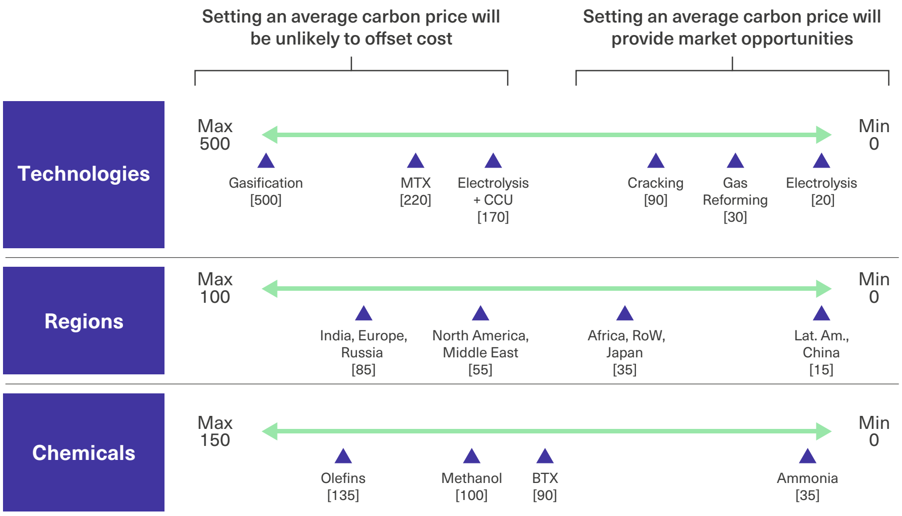
Figure 39: Estimated carbon tax required to support the chemical industry's transition to net zero

Carbon price are likely to be a necessary tool but have huge variance with time, technology and regions and will necessarily create market distortion regionally

The paradox: a higher carbon price would be needed today than in the 2040s



A carbon price is a necessary solution but need to be complemented by other tools, $/tonne CO_2 abated, Most Economic Scenario



Note: Calculation performed for LC-ME Scenario. Carbon Tax was calculated as ratio of Delta between LCOX and Delta of emissions along scope 1&2&3. Plants were compared against levelized greenfield cost and emissions of initial technology plant in that given region in the year of plant construction. Cases were the new plant was cheaper than the old plant were assigned 0 $/t CO2 tax. Plants with higher emissions vs. the initial tech were ignored.

A global carbon price would be the most appropriate incentive to support the chemicals system to transition collectively to low-emissions technologies, but establishing it will necessarily create market opportunities and shortfalls (Figure 39).

- **As in all sectors of the economy, a high carbon price is required to overcome the excessively high-cost gap between conventional technologies and net zero technologies.** However, our analysis suggests that by 2050, the carbon price needed for the chemical industry[78] could be 93% less than what would be required today, dropping from $85/t of CO_{2eq} to $6/t of CO_{2eq}. Concretely, that means the industry has even less incentive to start the transition today than it will in the future, and in an economically driven world, the status quo is thus likely to continue for the lion's share of the market. As such, policy makers should rapidly encourage the development of carbon markets for the industry and aim for a high carbon price as quickly as possible to shift the market.

- **While a carbon price is essential, there is no single and fair carbon price that will incentivize all technologies across all geographies.** Carbon price for chemicals can vary from $15 to $85/t of CO_{2eq} globally. Ammonia, and to some extent methanol, will be easiest to align with net zero pathways from an economic perspective because of the low carbon price requirements for gas reforming, electrolysis and CCU. However, olefins and aromatics will remain much more challenging, despite effort from regulators, due to the much higher carbon price needed for cracking and MTX. As a result, a carbon price mechanism might have a distorting effect on markets where some chemical routes are more heavily supported by policy over others (e.g., MTX).

78. Average across all technologies, all regions, and all chemicals.

- **Therefore, a tailored framework of regional or national carbon prices per basic chemical intermediate is likely needed to make most sense to ensure fair distribution of incentives.** The required carbon price can vary from $15 to $85/t of CO_{2eq} between regions of the world. This range is mainly driven by a few factors, including the cost of RES and hydrogen, but most importantly by the different production mixes in each region.[79] That range could be even larger if a more granular analysis was made. As a result, it is unlikely that a global carbon price would make sense if single countries were to incentivize the production of chemical in their territory.

- **A low future carbon price risks distorting the market and disincentivizing, for example, the production of aromatic and olefins.** A low carbon price coupled with new zero emissions production technology buildout could also lead certain chemical streams to become economically unviable. This could directly affect demand and shift consumption toward more affordable or carbon-friendly molecules (or resins in the case of polymer), assuming substitution allows. This is especially true for aromatics and to some extent olefins, which on average require higher carbon prices. The decline in fuel production for aromatics, coupled with setting a low carbon price, might result in a disincentive to build on-purpose aromatic production.[80] Similarly, if MTO is allowed to control olefins production ratios, a different carbon price might incentivize the production of ethylene over propylene, leading to a market distortion and artificially phasing out propylene-based chemicals or ethylene-based substitute where possible.

Who pays? It is the role of governments to overcome market failure through policy interventions such as carbon tax, but they will need to arbitrate on a national or regional level to determine who ultimately pays for the increased costs of production: investors or the public, with historical precedent suggesting the public in the long term. Society has long been free riding on market externalities such as emissions and pollution, and has not paid enough dividend back to nature by absorbing the true cost of non-harmful production models. On the surface, the debate over who should pay this increased cost is a discussion of consumers versus corporations, but ultimately it is between consumers and investors. Both groups have long benefited from un-costed impacts on nature, thus both should be required to pay the dividend owed.

The balance between consumers and investors needs to be determined by each country's government as the ultimate arbiter to maximize the well-being of its people. This will manifest very tangibly in forms such as sales tax and capital gain tax. Carbon price will also not transfer directly through to consumers, similar to the limited impact the increase in chemical price will have on the customer downstream discussed above. Ultimately, materially efficient strategies are unlikely to be prioritized by the consumer and more direct regulation will often be needed to catalyse circularity in addition to supply side interventions such as carbon tax (e.g., in the case of plastic, recycling targets and recycled content targets). Irrespective of how this is applied, consideration must be given from a just transition perspective in order to protect financially challenged consumers.

79. Regions producing larger amount of ammonia compared to others will in this analysis require a lower carbon price (e.g. Africa, Latin America, North America); in contrast regions producing more olefins will require a higher carbon price (e.g. Europe and China).

80. Interestingly, aromatics are also the set to have a lower cost in 2050 than conventional technologies and therefore (see previously in this chapter) might cancel each other out.

Disruptive approaches to value creation.

Decoupling the chemical industry from a volume-based growth model will require disruptive approaches to value creation. Three approaches have been identified: 1) Engaging in circularity, 2) broadening spans of control, and 3) carbon negativity.

1

Engaging in the new circular economy would enable the chemicals system to overcome its volume-based business model by participating in service-based and reuse type offerings. Currently, ownership of chemicals usually ends at point of sale to customers, after which no further value is derived by the chemicals sector. However, in a circular, resource efficient system there are a range of reuse models that would require retained ownership of the chemical through the consumer use phase, coupled with a service component. The below section on Chemicals-as-a-Service describes some approaches to how industry can engage in this volume-decoupled model.

Chemicals-as-a-Service

Chemicals-as-a-Service (CaaS) describes a set of business models that shift value creation from volume-based sales to a stronger focus on service and utility provision (Figure 40). By placing the function and performance of the chemical at the center of the commercial agreement, rather than the volumes, service-oriented models can lead to a more efficient use of chemicals that translates into environmental and economic benefits.[87,88] As such, CaaS models can drive the green transition of the industry. The model incentivizes producers to extend responsibility and effectively engage in the management of the lifecycle of chemicals while incorporating circular economy strategies. Depending on the type and design of the respective model, CaaS models are characterized by a closer supplier-customer relationships as well as stronger partnership and integration approaches to the provision of solutions. These are enabled by new technologies and emerging policies that increasingly focus on resource efficiency and sustainable lifecycle management.[89]

Figure 40: Overview of chemical-as-a-service business models

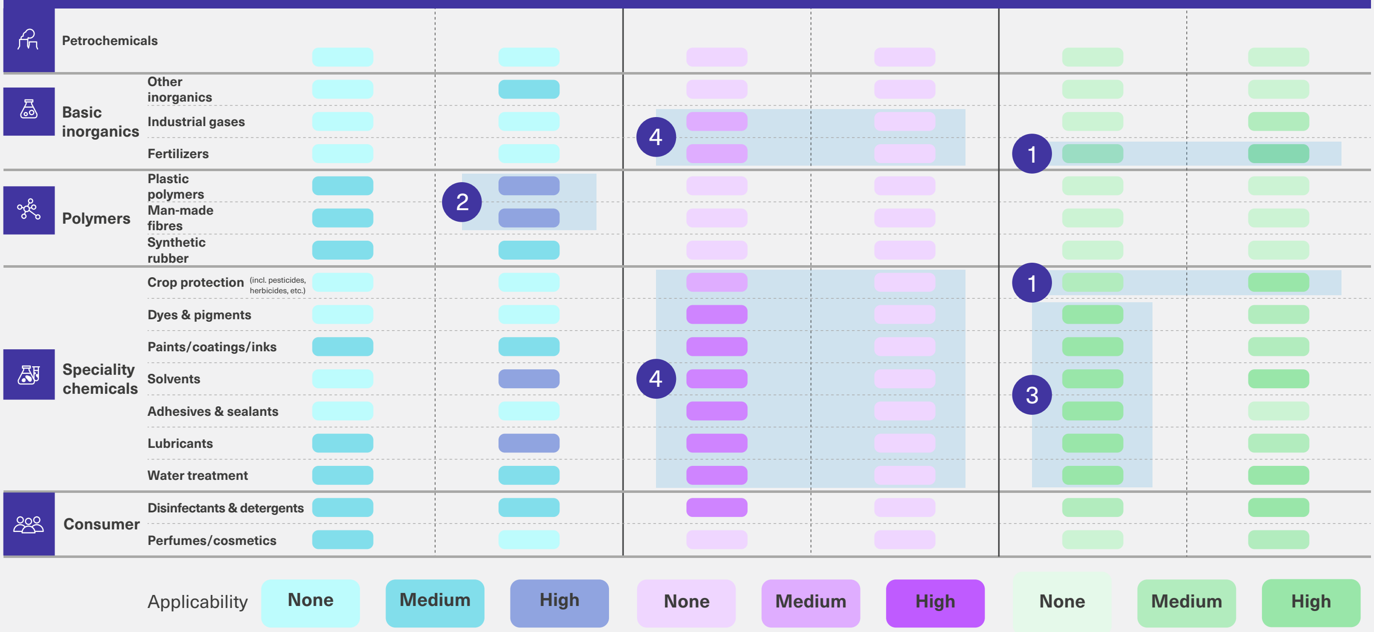
Chemical-as-a-service is not a silver bullet but provides a wide diversity of relevant leverage points to facilitate the transition in specific sub-sectors

WHAT ARE VIABLE MODELS TO OFFER CHEMICALS-AS-A-SERVICE?

Business Model Category	PRODUCT-ORIENTED MODELS Addition of (circular) services to existing chemical products		PROCESS-ORIENTED MODELS Services that yield process and product delivery improvements (might include performance compensation)		RESULT-ORIENTED MODELS Management of total product (systems) to deliver outcomes instead of volumes	
Types of Business Models	**1) Molecule and material leasing** A financial model where the supplier remains the owner of the chemical but payment is based on volumes, typically coupled with recovery schemes	**2) Take-back schemes** The supplier recovers chemicals for reuse, typically in partnerships and/or enabled by digital technology recovery schemes	**3) Chemical Management Services** A service provider supplies and manages the customer's chemicals, potentially incl. non-core activities and processes being outsourced to a specialized third party	**4) Process equipment as-a-Service** The equipment, process and delivery of chemicals (i.e. technology) is offered as a service	**5) Chemical Leasing** The functions performed by the chemical serve as the unit of payment and chemical suppliers and users work together to optimize chemical use in fulfilling the function	**6) Ecosystem solutions** Equipment, technology, service expertise and chemicals are bundled in one system solution and payment is based on performance of this system
	There are 6 types of CaaS business models in the chemicals industry, all differentiating in the way utility is delivered					
Examples	• BASF battery metal leasing	• BMW/Alba/BASF closed-loop automotive plastics recycling • Renault/Veolia/ Solvay battery recycling	• PPG Optima Solutions Chemical Management • Ecolab Global Chemical	• Linde hydrogen plants-as-a-Service • Aker Carbon Capture-as-a-Service	• BASF Coatings-as-a-Service based on number of cars • SAFECHEM COMPLEASE • Jotun Hull Performance Solutions	• BASF Xarvio Precision farming-enabled Crop-yield-as-a-Service • CWS Hygiene-as-a-Service
	Several example are being established across industries and illustrate impact potential					
Potential*	Relevance Efficiency Impact	Relevance Efficiency Impact	Relevance Efficiency Impact	Relevance Efficiency Impact	Relevance Efficiency Impact	Relevance Efficiency Impact
	Take back schemes, chemical leasing and ecosystem solutions show the highest impact on industry					

*Relevance: occurrence in the market and potential applicability. Efficiency: estimated environmental improvements through the model on /plant process level. Impact: overall estimated impact on industry in terms of potential penetration and efficiency

HOW DOES THIS APPLY TO DIFFERENT PRODUCTS?



1. **Outcome-based precision/smart agriculture models** emerge and agrochemical companies shift to becoming solution providers
2. **Take-back schemes are initiated and** polymer/fibre producers leverage their increasing recycling capacities
3. **A shift to performance-based Chemical Leasing models** could enable new value-based models for speciality chemicals and increase resource efficiency
4. **Process-oriented models** are already widely applied and exist since decades, providing basis for shifting to outcome-based models

Sources: SYSTEMIQ analysis based on 15 expert interviews, UNIDO (2020), UNEP (2019), OECD (2017), Federal Environment Agency (2018), Lay et al. (2014), European Commission (2009).

There are three main categories of CaaS model, product-oriented, process-oriented and results-oriented, within which there are six viable archetypes, each with differing applicability, efficiency and impact on the industry (Figure 40). The applicability of CaaS to product categories depends significantly on the type and properties of the chemical product, the application process, and economic criteria.[90,91]

- **Product-oriented CaaS models** are mostly applicable to high value recoverable materials and receive most attention in short-term company strategies aimed at securing feedstock in closed loops models. Take-back schemes show great potential to have an impact on the industry, with polymer and synthetic fibre producers in increasing competition over secondary feedstocks. Cooperation-based models with producers, chemical companies, and waste management companies engaging in partnership in closed loop take-back schemes are emerging (see the take-back schemes examples in Figure 40).

- **Process-oriented CaaS models** are already widely applied in the industry, especially where non-core processes can be more efficiently performed by chemical suppliers. Chemical companies extend value creation through services tied to the equipment and process execution. Chemical Management Services in sectors such as the automotive industry or water treatment are widely applied, providing the basis for more ambitious performance-based business models (see Chemical Management Services examples in Figure 40).

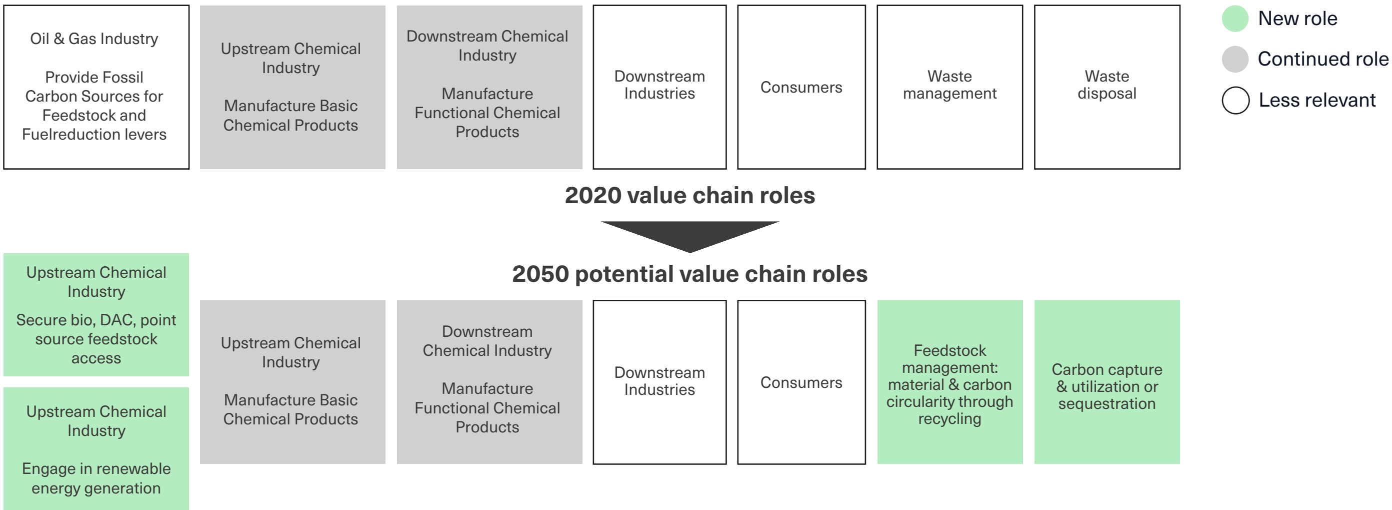
- **Result-oriented CaaS** models represent the most disruptive approach due to incorporating a performance-based compensation mechanisms in the business model (see examples in Figure 40). In Chemical Leasing models, lifecycle management, cost internalization, performance guarantees, and close supplier-user relationships lead to a more efficient resource use. However, these models mostly apply to low-volume, high-value speciality chemicals. It is expected that another type – Ecosystem Solutions – will become more and more relevant in the wider industry to solve sustainability problems based on closer partnerships as well as shared expertise and technology.

Agrochemicals (fertilizer and crop protection), speciality chemicals and polymers are the three most attractive product areas for CaaS, based on an estimated applicability and impact potential. A high-level impact estimation shows that these models, if scaled in these three product categories, could yield an overall reduction of virgin materials by 57 Mt (7%) and corresponding downstream emissions abatement of 255 Mt CO_{2eq} (16%). Secondary effects include an increase in high-quality recyclates for polymers and synthetic fibres (34-45%) from take-back schemes.

In addition to the volume reduction and abatement potentials, producer lifecycle management technologies yield important environmental benefits as leakage is reduced. This is especially true where inefficiencies in the application process exist. The United Nations Industrial Development Organization (UNIDO) has shown with its Chemical Leasing programme that this business model can yield significant benefits.[91] It is being actively promoted as a model for emerging markets, as environmental pressure points are reduced and economic benefits can be achieved. Already nine governments have signed the joint declaration, facilitating knowledge exchange and supporting the implementation of Chemical Leasing projects.[92]

Figure 41: Shift in value chain roles in the chemical industry and adjacent sectors

In a net zero system, the chemical industry will require a broader span of control through a framework of vertical/lateral integration, greenfield build out, and partnerships to own areas that will become "core business



Increasingly stringent environmental regulations, sustainability demands, and customer centricity are driving the chemical industry towards a new phase in which digitalization, resource efficiency, and environmental impact form the central pillars of future operations and value creation.[93] Pioneers show that service-based value creation is a feasible model with promising impacts on the sustainable use of chemical products as well as lifecycle emissions and pollution (see for instance Jotun,[94] SAFECHEM,[95] Ecolab,[96] Yara[97] or BASF[98]). Chemical end users increasingly indicate interest in engaging in such models to strengthen the efficient management and application of chemicals, supported by the technology and expertise of the chemical supplier. Yet, uncertainty remains with respect to the long-term viability and scalability of these models across different product categories and end-use sectors.

A widespread adoption of CaaS models is currently limited by external barriers, but these can be overcome through changing framework conditions for these models (e.g., policy, digitalization, and the increasing need for value chain integration). CaaS models are complex and require bold leadership by industry decision makers as new forms of collaboration, internal capabilities to deliver the service provision, and technological innovations must be built and pursued. Progressive companies are already showing that this is feasible, but policy support incentivizing dematerialized business models will be required. Policymakers should assess the environmental potential of CaaS business models in the chemical industry and enable collaborative models, support on-the-ground implementation, and set suitable incentive schemes. At the same time, the increasing internalization of the costs of negative externalities (e.g., through a carbon tax) will increasingly favour dematerialized business models.

2

Broadening spans of control through vertical expansion and integration (build, buy or partner) will be required to secure access to: i) renewable energy / green hydrogen generation; ii) renewable carbon feedstock sourcing i.e. biogenic and waste feedstocks; and iii) end-of-life disposal i.e., CCUS, all of which present synergies and new potential revenue streams (Figure 40).

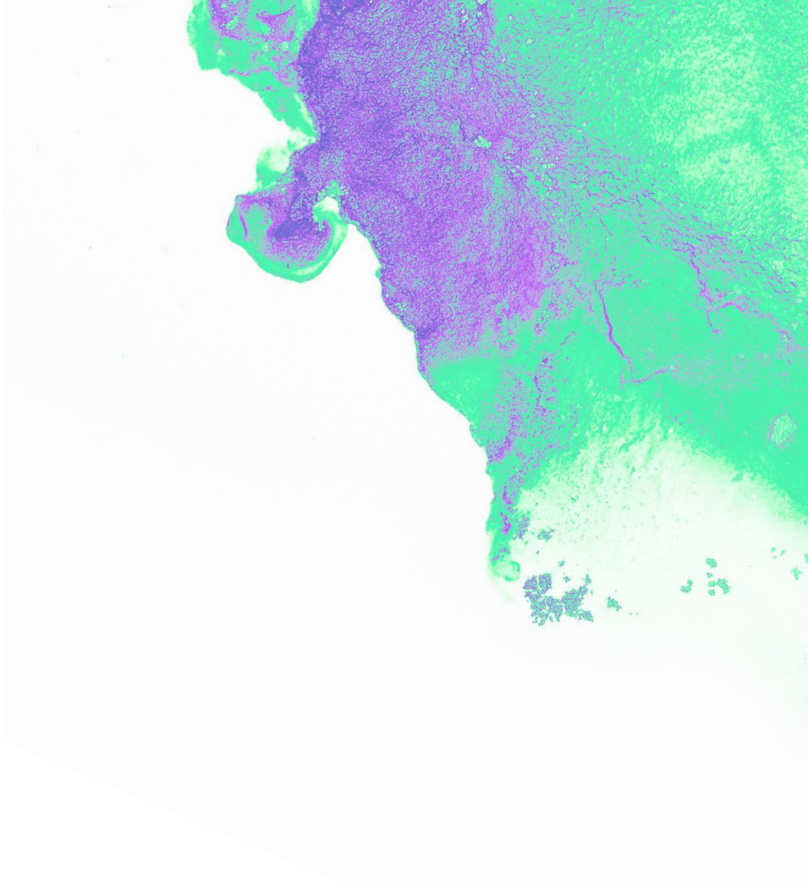
1. **Participate in renewable energy/green hydrogen generation.** The net zero chemicals system is highly energy intensive. There is a up to a 6-fold increase in demand for (renewable) electricity, either directly through electrification or indirectly via green hydrogen production. Therefore, securing means of direct generation will improve production economics across the chemical product slate, and the chemical industry should explore approaches to acquire or establish its own generation capabilities.

2. **Sourcing non-fossil feedstocks.** As explored previously in this report, there is a need to shift from an almost entirely fossil-based feedstock system to renewable feedstocks, such as biogenic, direct air capture, point source carbon, waste, and green hydrogen. Capturing feedstock production sources during this transition will be a core differentiator for future chemical industry system players. The particular feedstock mix will depend on multiple factors but will be primarily driven by geography.

3. **Partnerships with end-of-life disposal players e.g., CCUS**, as previously discussed.

3

Carbon negativity: As discussed in Chapter 4, value may be derived from carbon negativity (assuming an adequate system certification of source and carbon destination e.g., through tracking and tracing).



Chapter 7:

Urgent action is required now – 10 recommendations to transform the system

Chapter summary

Given the urgent need to shift climate trajectory articulated by the IPCC AR6 III and the relatively low agility of the chemicals system to change operating models, 10 immediate actions are recommended to catalyse the system transition.

Figure 42: 10 recommendations to the chemical industry

10 recommendations to the chemicals system

Accelerating the Transition

New Governance

1. Establish first movers coalition(s) to seed markets for net-zero chemicals

- Establish a demand side coalition of players downstream of the chemicals industry to formally signal demand for low-emissions chemicals (and end of use abatement)
- These niche market technology demonstrations can then act as pathfinder models for scaling into the mass market
- Guaranteed offtake agreements can then de-risk investment into supply side joint ventures, in doing so unlocking capital
- Can also prove cost impact on end consumer is low

2. Establish global charter of transition principles

Align system stakeholders on a common pre-competitive approach to the transition including:

- System 2050 vision & "acceptable pathways playing field"
- North/south transition & just transition
- Simplification, standardization of chemical portfolio & system input standards
- What not to do: reduce or ban harmful products and activities e.g. production of harmful or non-recyclable products and stop new fossil production installation post 202X
- Commit to purchase low-emissions and "circular by design" system inputs from other hard-to-abate sectors e.g. circular grid and transportation infrastructure, green steel in turbines

3. Chemical industry to advocate for a net zero enabling policy framework

- Restructure system economics to make supply side business case work (e.g. through carbon tax/price/EPR)
- Translate global charter into national policies
- Support enabling upstream and downstream circularity policy, e.g. mandatory recycled content targets and integrate it with industrial emissions reduction policy frameworks
- Advocate for streamlining of renewable energy capacity rollout across countries
- Seek accreditation of carbon negativity to incentivize commercialization

Operations

4. Scale circularity

- Implement elimination and design for recycling
- Scale out reuse models and educate consumers to adopt them
- Scale up best practice collection and sorting including separation at source
- Scale mechanical recycling: subsidise best in class technology, introduce mandatory recycled content quotas
- Scale chemical recycling: as complementary not competing for mechanical feedstock, and low-emissions from the start

5. Switch from fossil to renewable feedstock

- Industry procurement functions secure waste, point source and biogenic feedstocks (as most readily available)
- Industry vertical integration or greenfield rollout of renewable generation capacity
- Industry scale up in-house green hydrogen production consider investment in Direct Air Capture technologies

6. Retrofit legacy infrastructure

- Industry players to develop infrastructure transition roadmaps
- Dedicate capability to project mange execution of these roadmaps, including building out relationships with the multitude of stakeholders required e.g. CCS providers, energy industry, policy makers
- Focus on capex efficient approaches i.e. targeting older, less-efficient infrastructure due for replacement or infrastructure requiring partial/ smaller scale infrastructure retrofits. This could include e.g. green hydrogen fired crackers or CCS on gas reforming

7. Abate end of use chemicals

- Unabated incineration is not compatible with the 2020s facing a 1.5 degree scenario, let alone the 2050s, thus establishing a rapid and policy enforced roadmap for CCUS on all incinerators is essential
- Accrediting carbon negativity will potentially allow the costs of this abatement technology to be offset with commercial returns on an either voluntary or policy enforced basis

Three key system enablers

Data

8. Digitize the value chain and disclose key environmental system data

- System is currently data protectionist and given high levels of product and value chain complexity, extremely hard to analyze or understand
- Creating digital information about the entire chemicals system at each stage of the value chain around product, inputs, life cycle, outputs, impact on planetary boundaries/SDGs etc. then disclosing and storing this information publicly in a standardized format will create unprecedented transparency
- This can allow the broad multitude of system policy makers, data players, startups, coalitions and service providers act more effectively in the transition

Innovation

9. Fast track critical innovations to commercial scale

- High investment risk, unclear investment cost, long lead time and high failure rate lead to low willingness to invest into key transition technologies
- Therefore, fast track critical innovations to commercial scale: plastic to plastic methanol to olefins and aromatics processes, gasification, process electrification, cracker retrofit, carbon capture, hydrogen rock cavern storage, freen hydrogen electrolyzer technology.
- Depending on the TRL, different interventions are needed, e.g. for MTA further catalysis research is required to increase the selectivity of the reaction while commercial scale electric crackers need to be constructed and tested to overcome first-of-a-kind technology learnings and drive down costs.

Finance

10. De-risk large-scale financial investment

- Financial industry allocate adequate volumes of capital to the chemicals system transition along the value chain
- Establish financial intermediaries & invest in developing the expertise to deploy capital
- Develop the financial mechanisms and products to de-risk large scale investment in new or early stage technologies and bring them quickly to mass market, possibly including concessional capital within the development agenda
- Establish with industry a robust and investible project pipeline of Joint Ventures between peers and supply chain actors for lower risk co-investment activities to establish track record and bring investment costs down

Role of the Chemical Industry:

Supply and demand

- De-risk supply side technology investments by forming a precompetitive industry coalition[81] to precipitate a pipeline of competitive joint ventures that demonstrate technology operations and economics. This can create a track record, prove out the economics and models, bring prices down, and lead to mass market tipping points.
- Reinforce future demand by engaging with a first movers coalition via long-term offtake contracts with the above-mentioned competitive joint ventures. Demands for low carbon chemicals from brand owners and financial institutions are clear as long as the cost increase of end-user products is limited. Therefore, consolidating demand for these chemicals can de-risk investment into supply side technologies by guaranteeing the market.
- Invest in the key technologies highlighted in this report (i.e., MTO/MTA, gasification, carbon capture, biobased feedstock utilization, chemical recycling, cracker retrofit/upgrade, process electrification) as most likely technologies needed in the Scope 1-3 net zero world.
- Embrace the scale out of the circular economy as a means of preserving the chemical industry's license to operate, prepare for a cap in demand, and pursue new revenue streams decoupled from purely volume-driven sales, as described in the new roles section below.

Pursue new roles

- Invest in and secure non-fossil carbon source as a new feedstock. This will be a rare value creation opportunity for the upstream chemical industry that has long been regarded as a commodity supplier.
- Drive rollout of green hydrogen generation capacity (potentially as a direct owner given its importance in the future of methanol and ammonia production) to enable a net zero global economy.
- Seek new revenue sources by turning the chemical industry Scope 1-3 negative. Scope 1-3 decarbonization activities do not need to stop at net zero. The chemical industry can provide value to society with chemical products while also reducing atmospheric carbon dioxide levels. This will require close coordination with the end-of-life sector (e.g.; incinerators) to ensure that Scope 3 emissions downstream are abated.

81. The Low Carbon Emitting Technologies coalition hosted by the World Economic Forum is the incumbent coalition in this space and offers significant potential to fulfil this role, depending on the development of its governance and operation.

Policy & governance

- Pioneer a global transition charter to align the broader stakeholder community around how to approach the transition.
- Advocate for mandates on non-virgin fossil based and recycled contents percentages.
- Advocate for a carbon tax to level the playing field for pioneer chemicals players in order to accelerate the development of a low carbon chemicals market.
- Advocate for support in transition investments and the government purchase of products based on low carbon chemicals.

Other enablers

- Support digitization of the value chain and disclose key system data.
- Collaborate with the financial community to articulate financing need, develop business cases, and establish the performance track record of technologies and infrastructure to unlock large scale investments.
- Actively engage with nations in the Global South with abundant renewable energy sources to explore greenfield production opportunities that will bring technology, expertise and capital into these markets.
- Support the transition of other hard to abate sectors by seeking low-emissions materials for infrastructure build out, for example green steel.

Role of the Converters, Brands and Retailers

- Establish 1st movers demand coalition and engage with the chemical industry via offtake contracts to drive investment into low-emissions production.
- Accelerate the scaling of circularity upstream, leading to the elimination of unnecessary chemicals and adoption of reuse models, and support substitution where appropriate.
- Drive design for recycling by demanding mandatory recycled content in all products.
- Send strong demand signals for carbon negativity upstream to the chemical industry and downstream to incinerators.
- Engage with the establishment of a global charter on transition principles.

Role of the Energy Sector

- Own the controlled and responsible rollout of renewable energy such that it is circular by design and in harmony with sustainable existing and future land uses.
- Support the scale up of green hydrogen production, storage and transportation at a global level.
- Pioneer CCS rollout to achieve scale and affordability before the end of the 2030s to de-risk the transition.

Role of Feedstock Producers & Other Industries

- Biogenic feedstock producers should seek to scale supply where possible and make it available to chemicals producers on a fair basis, while at all times maintaining careful control over the sustainability of its production methods and avoiding any adverse impacts on land use or biodiversity.
- Other industries will need to focus on capturing Scope 1&2 emissions as point source CO_2 and identifying a suitable destination for this carbon. Allowing the chemical industry to use this carbon will require careful infrastructure planning and coordination within industrial clusters as well as long term agreements.

Role of the Waste System

- Optimize collection and sorting infrastructure at a local and national level, including separation of waste at source by the public and businesses, with a particular focus on organic matter separation to avoid landfill methane generation.
- Optimize mechanical recycling and scale out best practices, including leading technologies such as robotic sorting and artificial intelligence, for more effective waste recognition and leverage enhanced system data where possible to increase recyclate yield and quality.
- Scale out chemical recycling alongside the chemical industry in a complementary fashion.
- Ensure landfilling is high quality and, where possible, biologically stabilized to reduce methane emissions.
- Ensure all incinerators are fitted with CCUS as soon as possible and that incinerator emissions are accounted for transparently.

Role of Governments, Policy Makers and Regulators

- Establish a carbon tax framework at a national or regional (e.g., E.U.) level that considers local variance in product economics. Identify inelastic product markets to legislate as carbon taxable to act as beachheads for carbon tax application, while ensuring a just transition by protecting any financially vulnerable consumers within these markets.
- Ensure the decommissioning of legacy assets within the chemicals value chain is conducted responsibly from an environmental and material efficiency perspective, and in accordance with just transition principles.
- Increase the scale of concessional capital available for chemicals production rollout in developing markets and the Global South, and enshrine global charter principles in the development policy agenda to seed low-emissions production abroad if conditions for local low-emissions production is not favourable.
- Explore regulatory action on the most harmful practices if no action is taken as we approach the 1.5 degrees carbon budget threshold.
- Legislate for mandatory recycled content in plastics products to scale recyclate markets.
- Enforce Extended Producer Responsibility schemes, coupled with banning unabated incineration, as soon as CCUS has achieved sufficient technological maturity.
- Incentivize collection and sorting systems and harmonize these at a regional level.
- Reduce the international trade in waste exports so that waste is dealt with locally and does not slip to countries with the weakest governance (i.e., via supporting further strengthening and implementation of the Basel Convention).

Role of Financial Services Industry

- Allocate adequate volumes of suitably risk-orientated capital to finance the transition.
- Develop capital deployment infrastructure, intermediaries, and legal entities, as well as cultivating the talent required to deploy it successfully.
- Construct a suitable suite of financial products to finance the transition all along the maturity cycle from concept pre-seed development to large scale infrastructure debt financing. Identify gaps in the maturity cycle.
- Collaborate with development capital to finance Global South transition.
- Co-develop a pipeline of joint ventures for investment with the chemical industry, establishing the metrics and key performance indicators to build their track record and enable subsequent mainstreaming of investment.

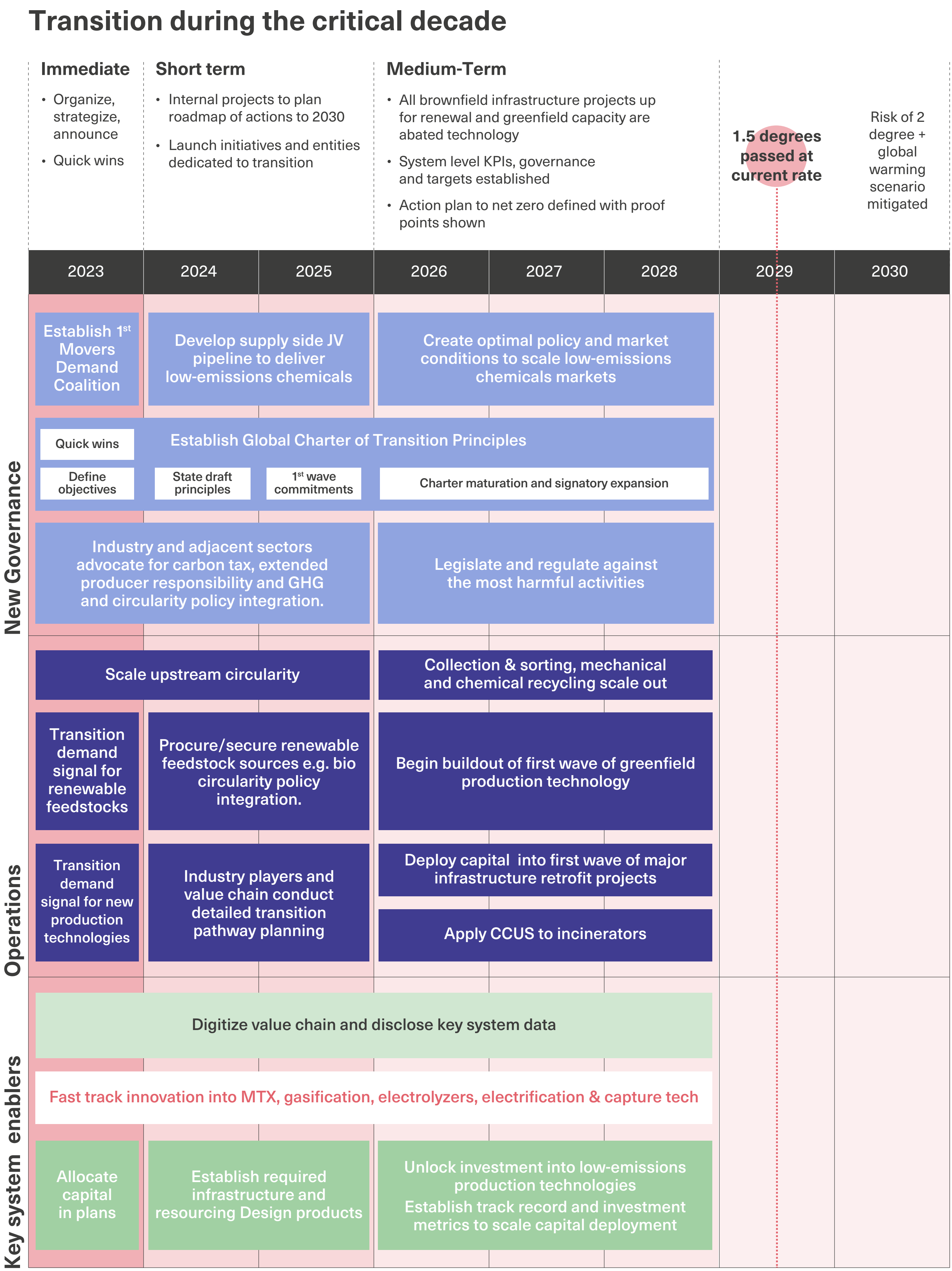
Role of the Consumer

- Engage with circular economy models, such as new delivery models as offered by retailers and fast-moving consumer goods engaging in direct-to-consumer offerings.
- Deliver demand signal through self-education and behavioural shift.
- Conduct separation of waste at source.

Role of Innovators and Academia

- Develop optimizations and efficiencies within carbon capture technology, gasification, MTX, electrification of processes, carbon storage, electrolyzers, and associated green hydrogen transportation and storage technology.
- Use artificial intelligence and big data capabilities to map the chemical products in the global value chain in order to identify where the most harmful and largest volumes of novel entities are escaping from the system with regards to chemical type, region, step in value chain, impact, root cause, etc.

Figure 43: Transition timeline of action in the critical decade to 2030

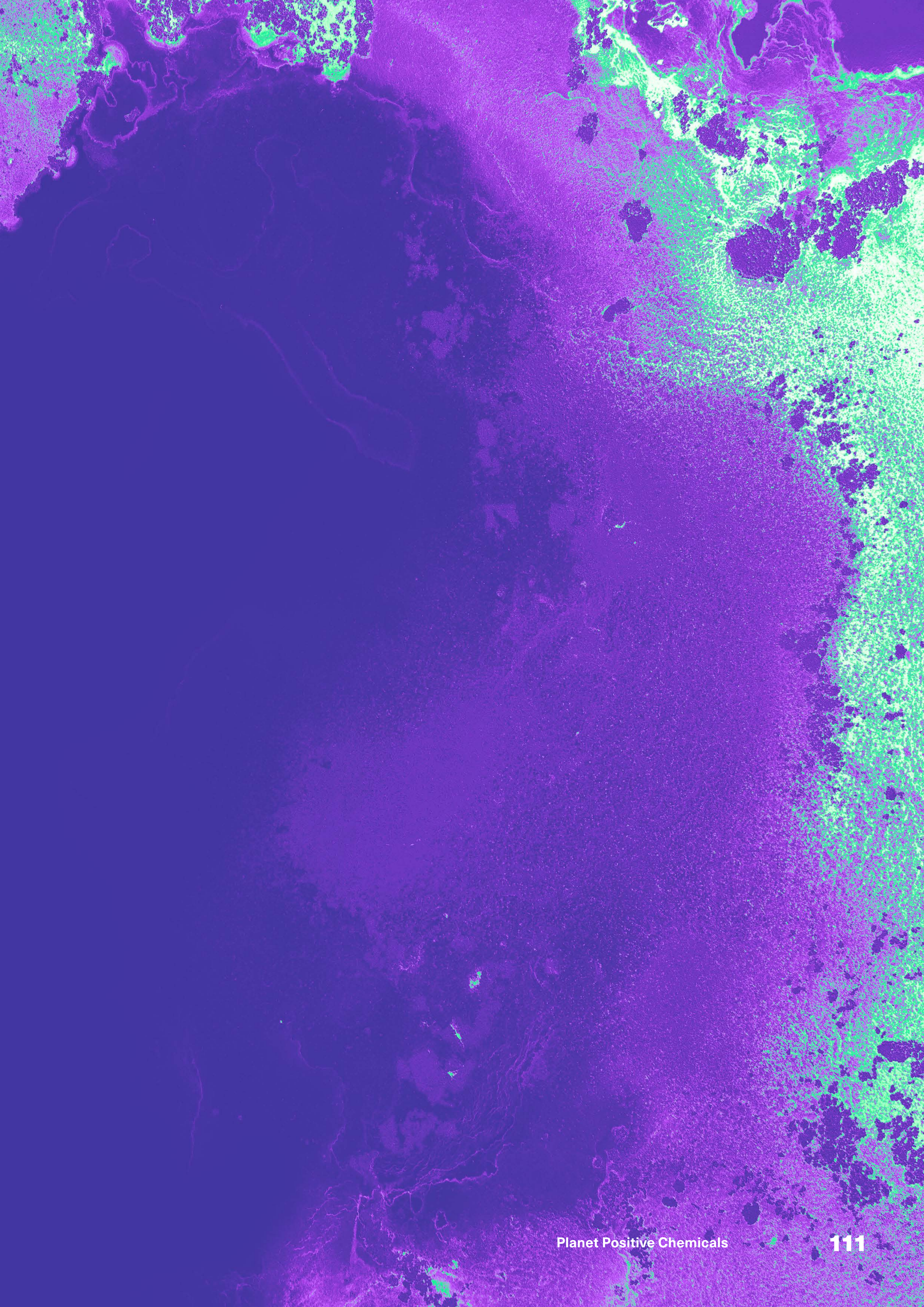


Conclusion

This report aims to highlight the vast potential for the chemical industry to build a fundamentally new social contract while creating unprecedented value for the global economy and society as it transitions to a net zero future, rather than put additional pressure on the industry's licence to operate. While the industry has set up various initiatives at the company or industry level to work toward achieving Scope 1&2 emissions targets, it is important to recognize that these efforts are not nearly sufficient, and that they do not address the Scope 3 emissions which represent the bulk of emissions most relevant for society. The analysis demonstrates that bringing demand within an acceptable range is a pre-requisite for the industry, and that in parallel it must develop CCUS, a new feedstock supply chain, vast renewable energy sources, and a balanced zero emissions technology portfolio to mitigate transition risk. Failure to do so is likely to have dramatic consequences.

This report aims to present honest yet feasible pathways that offer industry leaders and decision makers the insights needed to navigate the transition to net zero emissions in the 'decade that matters' between now and 2030. Acknowledging the structural changes and enormous infrastructure shift required, the report also highlights that there is an opportunity for the chemical industry to provide additional value to society through circularity and by broadening its span of control over new industrial territories. Along this journey toward a new chemical industry lies the potential for the industry to act as a carbon sink, or a carbon management vehicle. With the proximity of a 1.5-degree world, this is a once-in-a-century opportunity and the industry cannot afford to miss it. In essence, the vision for a 2050 chemical industry requires investment and innovation today, or risk rapidly following an irreversible business-as-usual trajectory.

Safeguarding the global commons is special mission for the chemical industry, given its role across all nine planetary boundaries, and represents an opportunity for the industry to pioneer a lasting vision. Through the products of every-day life, radical re-design of the system will affect almost every single human being on the planet. It is hoped that this vision will catalyse action so that the chemical industry, value chain, policy makers, financial community, innovators, civil society and academia will join forces to achieve this critical transition and build a planet positive chemical system.



Appendix: Scope, Approach and Methodology

A high-level overview of this work's scope and approach is elucidated here. A more detailed methodology can be found in the accompanying scientific article.[82]

General Overview

Drawing upon an optimized simulation model, the intent of this work is to identify and outline the key conditions required for the chemical industry to reach net-zero GHG emissions between 2020 and 2050 along circularity-enabled pathways. The report was prepared by the Center for Global Commons at the University of Tokyo and SYSTEMIQ, with support from University of Cambridge and a panel of seven global experts.

The deterministic model built for this project quantifies five metrics: (i) tonnage of feedstock consumed and chemicals produced, (ii) energy consumption, (iii) GHG emissions, (iv) costs,[83] and (v) net jobs growth. The uniqueness of the project lies in a powerful modelling approach; the construction of a dynamic optimized supply model which can respond to different inputs (e.g., cost, carbon abatement, feedstock) drawing from ~50 production technologies. While environmental pollution and the impact on the health of human and other species are both of major concern, they remain out of scope of this work and are covered in other studies.[3,99]

The report is constructed around three main scenarios, which were identified as most relevant from among the 60 the model calculated This will offer decision makers a means by which to understand the economic, environmental and social implications of building a planet centric chemical industry in alternative futures. The intent is not to provide a blueprint or a master forecast for the sector to achieve this objective. Rather, it aims to showcase a series of possible scenarios towards an objective in order to guide discussion, and ultimately demonstrate the key enabling levers across scenarios required to (i) maximize recycling and substitution while minimizing demand for virgin production of chemical products, and (ii) reduce GHG emissions associated with the production of said demand and end-of-life treatment of its downstream products.

These scenarios are not roadmaps, as roadmaps are a programme of sequential activities to be completed by specified individuals in order to bring about transformation. An exploration of what could be included in such roadmaps – enablers - is discussed at the end of the report where we present recommendations and propose the most important roles for different players in and connected to the chemical industry. We conclude by considering how different intervention strategies available to stakeholders can drive impact towards a net zero world and be supported from both investment and regulatory points of view.

82. DOI: 10.26434/chemrxiv-2022-hx17h-v2.

83. Including capital expenditure and operational expenditure.

Scoping a large share of the complex chemical industry

In Scope. Our techno-economic pathway analyses consist of eight key commodity and basic chemical intermediates[84] including: ammonia, methanol, ethylene, propylene, benzene, toluene, xylene, and butadiene. Those eight chemical products were chosen on the basis that they are precursors to a large array of chemical products used across multiple industries and account for significant footprints of the entire chemicals sector: 2/3 of energy used, ~50% of Scope 1 & 2 GHG emissions, and 40% of annual volume produced. Two key derivatives of ammonia: urea and ammonium nitrate – both fertilisers – were additionally modelled as they represent the largest growth in demand for ammonia and the lowest emission factors upon application, respectively.

Out of Scope. The remaining Scope 1 & 2 GHG emissions and volumes from the chemical industry are largely accounted for in three main categories of products: chlorine, soda ash, and downstream derivatives of the eight key chemical intermediates we cover. While these other chemicals are beyond the scope considered within this work, much can be inferred from our work on the eight primary chemicals about the fate of these out-of-scope chemicals in a net zero chemical industry, either because they are downstream of the primary chemicals and/or will benefit from macro trends outside of the chemical industry (such as grid decarbonization).

These other chemicals can be described as belonging to one the following categories:

1. **Already-electrified processes:** the combined production of chlorine and sodium hydroxide (caustic soda) consume almost 1% of global electricity production today via a well-established electrolysis process. Industrial air separation via cryogenic distillation to produce nitrogen, oxygen and argon are similarly electrified. The production emissions of these chemicals are dominated by these Scope 2 emissions but will fall to 0 upon grid decarbonization.

2. **Calcination processes:** sodium carbonate production and calcium carbonate calcination produce process CO_2 emissions. These can be abated via CCS.

3. **High temperature processes:** oxides production require high temperatures (>800 °C). Both the electrification of and the use of green hydrogen in these processes are at lower TRLs but can be feasible with further technological advances.

4. **Downstream processes:** most processes downstream of the eight major chemicals are low-to-medium temperature processes that can be electrified relatively easily if not already done so (e.g., polymerization reactions, fine chemical synthesis), and therefore will have reduced emissions when the grid decarbonizes. The overall carbon footprint of these downstream products will also naturally benefit from their chemical precursors (eight primary chemicals) being produced with reduced emissions.

84. In parts of this report, 'olefins and aromatics' will be used to refer to the grouping of ethylene, propylene, benzene, toluene, xylene and butadiene, while 'aromatics' refers only to benzene, toluene and xylene.

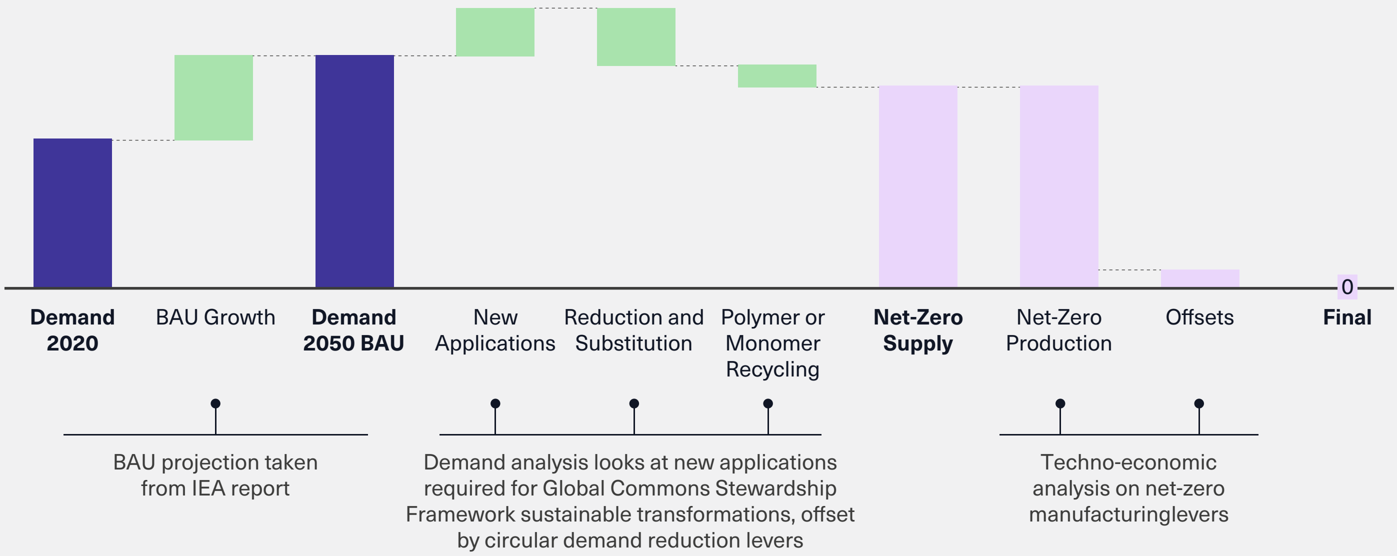
Modelling Supply and Demand GHG reductions

For each chemical we look at defining pathways to maximize resource-efficiency and minimize absolute emissions of Scopes 1, 2 and 3 by 2050 from the perspective of changes in both demand and supply. A key assumption of the modelling is that resource-efficiency through materials circularity is a pre-requisite enabler to optimize the size of the chemical industry and thus reduce demand for virgin chemical products (see section 3.2). It is therefore critical that both angles (e.g., demand and supply) are considered simultaneously and married together in our analyses.

Appendix Figure 1: Demand and supply methodology to achieve net zero Scope 1, 2&3

Both resource efficiency and cleaner production technologies will be required to reach net-zero by 2050

Annual Emissions of Chemical X, Mt/year



Note: Polymer and monomer recycling include mechanical recycling, depolymerization and solvent recycling (or dissolution/purification recycling)

The approach taken by the project can be broken down into two general phases: demand modelling that are then met by optimized supply (production) scenarios. This logic has several major implications but the most notable is that demand is calculated independently from supply, the results of the supply model calculations will therefore not be used to refine demand projections. In practical terms, it means that over supply, under supply, or an increase in production cost calculated by the supply model, which would be expected to have an impact on demand, will not affect it in order to simplify model logic.

Demand for each chemical in a 2050 post-transformation world is the combination of the following:

- Business-as-usual demand from IEA projections for 2020 to 2050.
- New sources of demand for new applications in a net zero world (e.g., ammonia for shipping, electrification, new energy infrastructure, solar and wind development, electric mobility, etc.) based on existing net zero pathways for relevant sectors.
- Circularity levers, defined in this report as including both demand reduction and resource efficiency shifts (elimination, reuse, recycling and substitution), in existing applications are taken into account where relevant for four industrial sectors: agriculture for fertilizer; packaging, transportation, construction and textiles for plastic materials; and transportation for fuel additives. Maximum potential was assessed in the above to offer a low demand (or high implementation of circular levers) sensitivity for each corresponding chemical referred to as high circularity (HC). To translate the sensitivity of those levers, as well as different levels of ambition, a high demand (or low implementation of circular levers) sensitivity was also created referred to as low circularity (LC).[85]

While our model examines all scenario combinations, the supply scenarios discussed in this report are drawn from the high demand scenario (low implementation of the circularity levers) which display the most interesting view of the future.

Appendix Figure 2: Circular levers considered in this study

Main circular levers were examined along five key industrial sectors: agriculture, transportation, packaging and household goods, textiles and buildings and construction

		Fertilizers	Reuse	Substitution[1]	Recycling
Ferti-lizers	Agriculture	• Precision agriculture • Diet change • Food waste reduction	• N/a	• Organic farming • Fertilizer switch from urea to ammonium nitrates	• N/a[2]
Methanol, olefins and aromatics	Packaging and fast-moving goods	• Packaging elimination	• New delivery model (e.g. refill)	• Paper • Bio-based compostable materials (e.g. PHA)	• Mechanical recycling • Depolymerization • Solvent-based recycling technologies[3]
	Transportation	• Vehicle lifetime extension • Fuel additive obsolescence	• Mobility-as-a-service	• N/a	
	Construction	• More efficient building spaces for offices and households		• Bio-based materials (e.g. wood)	
	Textiles	• Waste elimination upstream		• Man-made cellulosic fibers substitution (e.g. lyocel, viscose)	

Note: (1) Substitution encompasses all materials which are not made from the 8 chemical intermediaries in scope for this project. Materials of substitution might still arguably be made by the chemical industry (e.g., bio-based compostable materials) (2) The production of ammonium nitrates from wastewater treatment and nitrogen recovery was considered in the supply model. Composting was not considered (3) other chemical recycling technologies such as pyrolysis and gasification were considered in the supply model as they produce basic chemicals

85. The high demand scenario corresponds to the implementation of 50% of most circularity levers, except for packaging levers which was set at 70-80%, and based on penetration market rates by 2050, elimination of fuel additives, and development of mechanical recycling, for which the same level of ambition is assumed in both scenarios.

Supply scenarios to meet the high demand scenarios for each chemical by net zero manufacturing technologies are assessed:

- Techno-economic assessment of net zero production technologies for each chemical (TRL ≥ 7 only). Less mature technologies (TRL < 7) are discussed separately and qualitatively only.[86]

- Broader system implications and how to consider them cross-chemically: technology maturity of key enabling technologies (e.g., CCS, green hydrogen), resource limitations (e.g., electricity, green hydrogen build-out, biomass and fossil sources).[87] See section 3.3 for details.

The above was taken into consideration in five simulation supply pathways that explore how shifting key variables would impact the model outcomes, given that the model is not deterministic.

These five scenarios were: (1) **BAU** (to serve as a baseline in a non-net-zero world) (2) **Most Economic (ME)**, (3) **Fastest Abatement**, (4) **No New Fossil after 2030 (NFAX)**, and (5) **Strictly No New Fossil**.

Appendix Figure 3: Main supply pathways described in this report

Three main supply pathways offer a combination of pragmatism and greatest variance in system operation

Scenario	Scenario Description	Key Assumptions
Business-As-Usual Scenario (BAU)	No commitments made by the public and private sector are achieved by 2050.	• Low implementation of circularity levers. • No emissions reduction mandate. • Conventional technologies allowed to continue to persist and even built anew to meet increasing demand. • If low-emissions technologies are built, it will only be because they have achieved cost competitiveness with conventional technologies. • New production capacity ultimately optimized for lowest cost per year.
Most Economic Scenario (ME)	The chemical sector is committed to achieving net-zero by 2050 within its own scope and is doing so in the most economic fashion possible.	• Low implementation of circularity levers. • Industry-wide net-zero mandate by 2050. • Phase out of existing conventional technologies by 2050 and new builds of conventional technologies no longer allowed after 2025. • New production capacity ultimately optimized for lowest cost per year.
No New built Fossil after 2030 Scenario (NFAX)	The chemical sector is committed to achieving net-zero by 2050 within its own scope and is doing so in the most emissions-abating fashion possible, with a strict ban on even abated use of fossil feedstocks after 2030 to avoid scope 3 emissions.	• Low implementation of circularity levers. • Industry-wide net-zero mandate by 2050. • Phase out of existing conventional technologies by 2050 and new builds of conventional technologies no longer allowed after 2025. • No new plants with fossil feedstocks or energy provision of any kind can be built after 2030, even if process emissions of chemical production are abated (e.g., with CCS). • New production capacity ultimately optimized for largest GHG emissions abatement available for scopes 1+2+3 upstream per year.

86. There is historical evidence that energy and industrial technologies take many decades to become a large player in a market. But the urgency of the climate crisis may accelerate scaling up of technologies and result in shorter timelines compared to what has been witnessed so far, making lower TRL technologies important to consider at least qualitatively.

87. In this work, sources have two fates of consumption: either as 'feedstock' or as 'energy source'. 'Feedstock' is referred to as any raw material whose constituent atoms are either partially or wholly embedded into the target chemical molecule after the reaction (therefore constituting the bulk of the mass of the chemical produced) with any remaining non-embedded atoms usually released as process emissions or side-products. 'Energy source' is referred to as any raw material or source that is consumed for the primary purpose of providing thermal energy to drive the conversion of feedstock to target chemical. It is important to note that several materials can serve as both 'feedstock' and 'energy source'.

After observing the results from these five scenarios, it was concluded that the focus of discussion would be given to the **BAU** scenario, **Most Economic (ME)** scenario, and **No New Fossil after 2030 (NFAX)** scenario. In sum, they provide the optimal combination of real-world pragmatism coupled with the greatest variance in system operation, and therefore can provide the greatest level of illumination for readers.

In addition to these three supply scenarios, there is a high degree of uncertainty around two key input assumptions across the board. For these, sensitivity analyses were built in order to offer the opportunity to derive insights on the nature and size of these key swing factors that could shift the outcome of our model.

i. **Applying a more stringent ramp up on CO_2 storage availability.** A ramp up curve on CO_2 storage availability is already implemented by default in the model. The sensitivity tests an even more stringent ramp up (i.e., slower, therefore less CO_2 storage availability), as this may be pertinent in the event that any of the following occur and slow scale-up: lack of transport and storage logistics; engineering challenges in ensuring no leakage at storage site; long lead-times and high project failure rates; engineering challenges around retrofitting existing plants with CO_2 capture units.

ii. **Lowering future fossil feedstock costs.** A set of higher fossil prices is implemented by default in the analysis. Performing the sensitivity towards lower fossil prices addresses the two fundamentally different views on whether fossil fuel prices will increase or decrease in the future. This would be pertinent in light of competing driving factors, including, among others: shifts in the volume of fossil supplies in a net-zero world; changes in the degree to which fossil resources are shipped; efforts to lower upstream emissions in the extraction processes; and shifts from high-cost locations to low-cost regions.

As the extent to which circularity levers will scale is also uncertain, bringing both demand and supply scenarios together offers a further opportunity to study a different demand scenario as a sensitivity, where high demand is the model default and low demand is a sensitivity.

Key Parameters

1 **Emissions:** The emission scopes considered for the supply model in this report cover the chemical sector's emissions following a cradle-to-gate approach. How and when these scopes are taken into consideration for optimization is outline below.

- Scope 1&2: it includes emissions starting at the factory gate (Scope 1 and 2 of chemical processes), before transport to the end user. It excludes all emissions from downstream processes or further chemical transformation (e.g., polymerization).

- Scope 3 upstream: includes resource extraction. Fossil feedstock associated emissions are based on extraction and accounts for fugitive methane. Biomass associated emissions are calculated on a carbon basis. Waste and recirculated carbon Scope 3 upstream emissions are 0 (given associated emissions are already accounted for elsewhere in the model).

Appendix Figure 4: TRL≥7 technologies considered in this study

Combining a least two of the three strategies (1) feedstock switch, (2) carbon switch and (3) CSS will be a pre-requisite to achieve net zero

Energy Source	Fossil	Waste[1]	Biomass[3]	Captured CO_2	Green Hydrogen
	End-of-use CCS-equipped incineration is required to achieve carbon neutrality	End-of-use CCS-equipped incineration is optional[2] but can lead to carbon negativity			
Green Hydrogen	• Naphtha/Ethane fed H_2-fueled steam crackers • Coal Gasification	• Pyrolysis fed H_2-fuelled Crackers • Municipal solid waste Gasification	• Biomass-fed H_2 fueled steam crackers	• Carbon Capture Utilization • Direct Air Capture	• Co-feedstock relevant for other processes (gasification, CCU, DAC)
RES	• Electric Naphtha/Ethane Crackers • Electric fossil gas reforming	• Pyrolysis fed electric Crackers	• Biomass Digestion • Biomass Gasification • Biomass-fed Electric Crackers • Ethanol Dehydration	• Carbon Capture Utilization • Direct Air Capture	• Electrolyser • Co-feedstock relevant for other processes (DAC, CCU)
Same as Feedstock	• Naphtha/Ethane fed steam crackers • Catalytic Reforming (refineries) • Propane dehydrogenation • Coal Gasification • Fossil gas reforming	• Pyrolysis fed steam crackers	• Biomass-fed steam crackers	• N/A	• Co-feedstock relevant for other processes
	Carbon Feedstock				Hydrogen Feedstock

Note: (1) Depending on the original feedstock, waste is between fossil and carbon negative feedstocks
(2) Optional CCS would lead to the industry being carbon negative
(3) Includes biomass waste (e.g. from organic from municipal solid waste, forest residues or agricultural sector)

- Scope 3 downstream: Emissions associated with end-of-life are subsequently calculated and therefore are not used in the optimization model. Rather, end-of-life Scope 3 downstream emissions are calculated based on a dynamic modelling of waste management flows at the end-of-life per industry.[6,8] They are therefore used to inform the view on how different end-of-life treatment options come into play in order for true net-zero to be achieved. Scope 3 downstream from downstream industries, product manufacturing and product use phase are excluded.

Achieving Scope 3 net zero emissions will require compensating emissions which cannot be abated. It includes (i) emissions from fossil feedstock extractions remaining by 2050, (ii) emissions from CCS units (at chemical production sites and/or incinerators given capture yield is assumed 95%), (iii) emissions from fertilizers at end-of-life (e.g., N_2O), and (iv) emissions from open burning of waste, which is assumed to remain a small practice in certain countries by 2050.

Appendix Figure 5: Carbon accounting methodology

Carbon accounting includes Scope 1, 2, and most relevant Scope 3

	Feedstock Scope 3 Upstream	Chemical Industry Scope 1 + 2	Manufacturing and use Phase	End-of-use Scope 3 downstream
Scope	In scope	In scope	Out of scope	In scope
Main assumptions	• Fossil upstream emissions are constant over time • Biomass, DAC upstream emissions are calculated solely based on carbon content • Waste or waste-based resources, point source have no upstream emissions (already accounted for elsewhere)	• Only includes the emissions associated with the production of the chemical studied • Exclude emissions associated with downstream chemical industries (e.g. derivatives, polymerisation)	N/A	• Includes fertilizer emissions (e.g. N_2O) • Includes emissions associated with waste management (collection, sorting, recycling) which are decreasing over time in all scenarios except BAU due to grid decarbonisation • Assumes end-of-use is a mix of recycling, incineration, landfill, open burning, leakage • Incineration includes energy recovery and by 2050 in all scenarios except BAU, incinerators are equipped with CCS
Modelling net zero logic	• If scope 1+2 carbon abatement from two technologies is the same, models optimize based on scope 3 upstream emissions	• Model optimized technologies based on cost and/or carbon abatement to reach net zero scope 1+2 emissions		• Scope 3 downstream emissions are calculated post optimization
Remaining emissions in needs of compensation	• Scope 3 upstream emissions from left over fossil feedstock in the system	• Scope 1+2 emissions from residual CCS (capture rate 95%) installed at chemical production sites		• Fertilizer emissions (e.g. N_2O) • Emissions from residual CCS (capture rate 95%) installed at incinerators • Emissions from waste open burning

Considerations to reach net zero:
- Net zero scope 1 and 2 is achievable with negligible amount of compensation required
- All scenarios require compensation to reach net zero scope 3 emissions due to fertilizers, fossil upstream and waste open burning.
- Banning fossil from energy and feedstock sources is the only alternative to minimize compensation required

Note: According to the GHG protocol scope 3 definition, is included in this report scope 3 categories 1 (raw materials), 4 (transport) and 12 (end-of-life).

2

Geography: Global demand for chemical intermediates was considered in aggregate – that is to say, without local or geographical distinction. Production, on the other hand, begins by being geographically distributed based on today's production distribution and is expected to remain at least partially so; the degree to which this could occur is explored in our model.

Global production was broken down into 10 (sub-)continental regions: North America, Latin America, Europe, Russia, Africa, Middle East, China, Japan, India, and the Rest of Asia and Pacific. We employed country-level focus on Russia, China, India and Japan due to differences between their political and economic landscapes and those of their neighbouring sub-continents.

The significance of this regional view is two-fold:

- prices and associated emission factors of various technology inputs have regional differences that ultimately result in region-specific costs and emissions of chemical production on a per tonne basis;[88]

- the present-day location and technology type of plants producing these eight chemicals is the starting line from which all future infrastructure changes towards net-zero production must begin.

88. Note that in some cases where data was not available for all 10 regions (e.g., power price projections), 4 regional data sets (Europe, China, India, USA) were used as proxies and assumptions derived thereof for the other 6 regions.

3

Time: The model considers 2020 as its baseline year and runs between 2020 and 2050 – the deadline by which it seeks to reach net zero – with annual incremental steps.

While conventional, unabated technologies are allowed to be deployed by the model in the BAU supply scenario right up until the year 2050, they are only allowed as new builds in all the other (i.e., net-zero) supply scenarios up until the year 2025. This achieves two objectives. Firstly, it captures the key assumption in our model that external drivers will kick in to incentivize the net zero transition by 2050 (e.g., in the form of a carbon tax; note that a value for the carbon tax is not baked into the model but rather is assumed will exist through the forbidding of conventional technologies). Secondly, it nevertheless captures the new fossil-based plants that have been committed, financed and are already under construction between the years 2020-2025, therefore maintaining a level of realism.

New technologies that offer some forms of emissions abatement are each designated a start date from which the model thereafter considers the technology available and therefore ready for deployment. In order to ensure a realistic rate of penetration into the market, a controlled but nevertheless generous technology ramp-up rate of 20% (of the given technology's previous year's global capacity) is implemented as a cap.

The start dates of large-scale key abated technologies are as follows:

- **2020:** Methanol-to-olefins
- **2025:** Green hydrogen, CCS, gasification, methanol-to-aromatics, hydrogen-fuelled steam cracking, methanol-to-aromatics
- **2030:** Direct air capture, electric steam cracking, electric gas reforming

Note that cost reductions across time that reflect technology learning are implemented for key technologies, most notably green hydrogen and gasifiers. These are performed on a fixed year by year cost decline based on external resources and are not dependent on levels of deployment (i.e., not learning rate based approach).

4

Plant fate: With an annual global demand volume from 2020 through to 2050 to meet, a 2020 view on regional production capacity of all chemicals today, and various technology options available to kickstart the road to net-zero chemicals production, the model brings together all of the above information in one place through a simulation of production capacity on a per plant basis.

For any given year, five possible actions can be taken for a given amount of production capacity:

A. Decommission a plant from year X-1 to year X.

B. Retrofit a plant from one technology type to another technology type on the same site.

C. Decommission a plant + build a new plant with another technology on the same site.

D. Build as a new plant, independent of existing sites.

E. Retain plant from year X-1 to year X on the same site.

A is triggered if demand in year X is lower than supply of year X-1. **B** and **C** are directly compared according to the optimization variables described for that particular scenario. The sum of **B** + **C** effectively constitutes a technology switch and occurs following a forced technology switch rate of 5% of the previous year's production capacity of a given chemical. This forced rate of switching from conventional to emissions-reduced production technologies along the 2020-2050 timeframe therefore suggests an industry consensus to reach net-zero by 2050. **D** is triggered to fulfil any remaining demand in that year. **E** occurs naturally to a proportion of production capacity as a sum effect of steps **A**-**D**.

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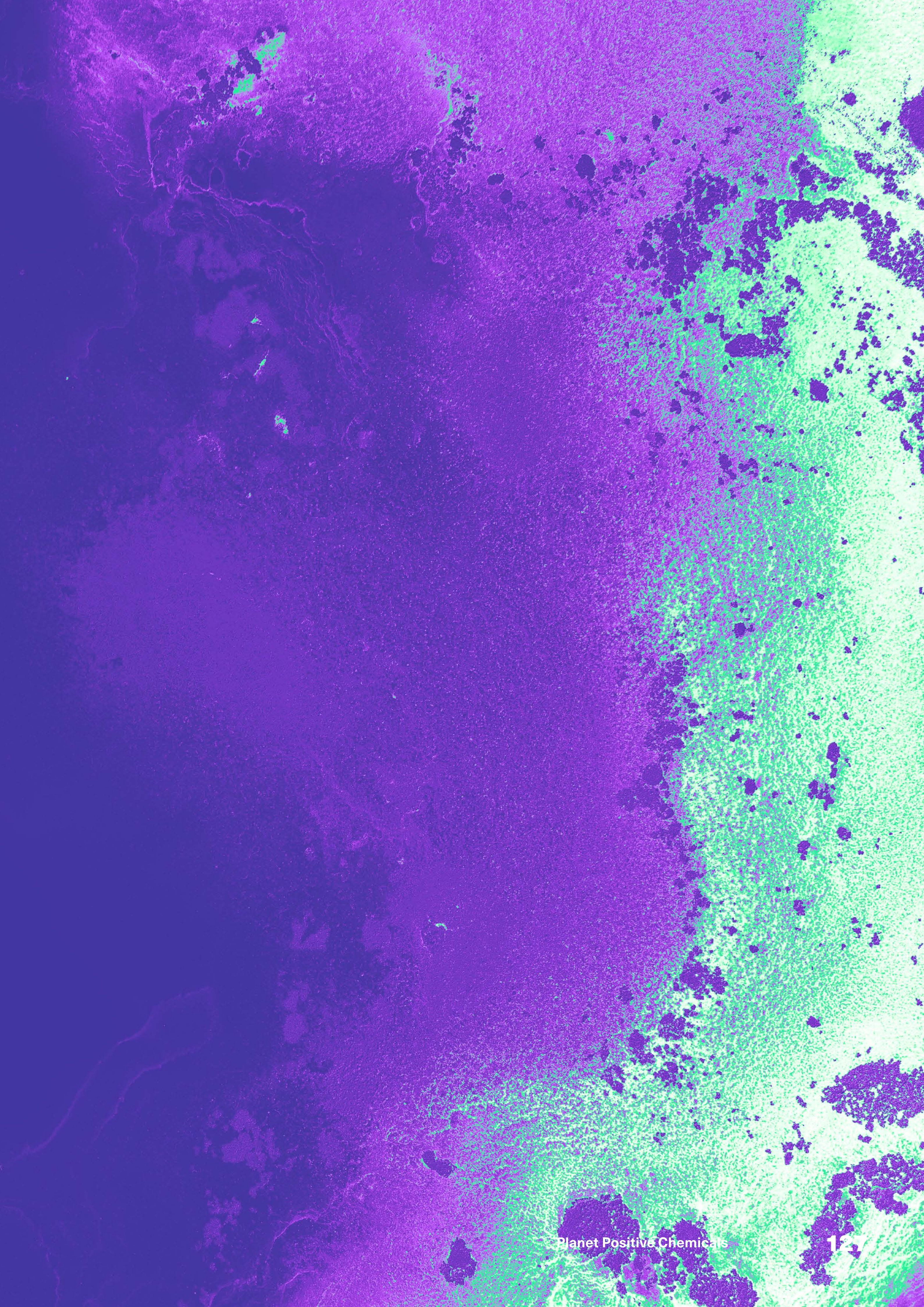

Glossary

Abatement Cost
The cost of reducing CO_2 emissions, usually expressed in US$ per tonne of CO_2.

Additives
Plastic is usually made from polymer mixed with a complex blend of materials known as additives. These additives, which include flame retardants, plasticisers, pigments, fillers, and stabilisers, are used to improve the different properties of the plastic or to reduce its cost.

Agrochemicals
Chemicals employed in the field of agriculture and can include pesticides and fertilizers.

Ammonia
Gas that is made up of nitrogen and hydrogen (NH3). It has a host of different uses, including as an intermediary in the production of fertilizers, refrigerants and explosives.

Aromatics
Ring-shaped, hydrocarbon molecules with conjugated double bonds. The most important examples include benzene, toluene and xylene (together BTX).

Autothermal Reforming (ATR)
A method of gas reforming using oxygen to combust part of the input methane within the reformer to directly provide heat for the reforming reaction. It therefore does not require an external steam input and no external heater due to the heat released in the oxidation process. The ATR process therefore only has CO_2 in the process stream and hence lower capture costs compared to SMR.

Baseline
The baseline (scenario) serves as a primary point of comparison for an analysis. In this study, the outputs of the BAU scenario are referred to as the baseline.

Basic Chemical Intermediates
Chemicals that are manufactured in order to be converted into another substance.

Bio Energy with Carbon Capture and Storage (BECCS)
A carbon negative technology that combines biomass energy generation with carbon capture technology. Note that BECCS is distinct from BiCRS (biomass carbon removal and storage) which describes a range of processes that use plants and algae to remove CO_2 from the atmosphere and store that CO_2 underground or in long-lived products.

Benzene
A colourless aromatic organic compound that is widely used as an intermediary in the production of substances like plastics, resins, nylon etc.

Bio-Based Chemicals
Chemicals that are wholly or partly derived from biomass.

Bioethanol Dehydration
A process through which ethylene is produced from bioethanol.

Biomass or Biogenic Feedstock
Organic matter, i.e. biological material, available on a renewable basis. Includes feedstock derived from animals or plants, such as wood and agricultural crops, organic waste from municipal and industrial sources, or algae.

Brownfield Production
Brownfield production refers to scenarios where organisations utilise existing assets for production activities. In this report, this refers to existing assets in the chemicals sector like steam crackers and steam methane reformers.

Business-As-Usual, Most Economic (BAU-ME)
The context wherein growth of the chemicals sector continues in line with expected business-as-usual demand growth and chemicals are produced using the most economic methods available to achieve net zero.

Butadiene
A gaseous hydrocarbon that is primarily used in the production of synthetic rubber.

CAPEX (Capital Expenditures)
Funds used by an organization to acquire or upgrade assets such as property, buildings, technology or equipment.

Carbon Capture and Storage (CCS)
Use of carbon capture technology to extract CO_2 from potential system emissions streams, followed by transport and storage of CO_2 long term in underground saline aquifers or depleted oil and gas fields on a permanent basis.

Carbon Capture and Usage (CCU)
Use of carbon capture technology to extract CO_2 from potential system emissions streams and to then use it. In the context of this report to make methanol from CO_2 and hydrogen.

Carbon Emissions / CO2 Emissions
We use these terms interchangeably to describe anthropogenic emissions of CO_2 into the atmosphere.

Carbon Emissions Vector
The net-direction of carbon flow, either from the ground to the air or air to ground. The source of carbon in the ground is fossil which ultimately leads to CO_2 emissions in the atmosphere. Taking carbon from air can be via CO_2 captured through DAC or by the use of biomass (which has used CO_2 in the air during its growth). Carbon underground can for example be via CCS of waste incineration emissions or permanent storage in the form of plastic in controlled landfills.

Carbon Offsets
Reductions in emissions of CO_2 or greenhouse gases made by a company, sector or economy to compensate for emissions made elsewhere by the entity.

Carbon Price & Carbon Tax
A government-imposed pricing mechanism, the two main types being either a tax on products and services based on their carbon intensity, or a quota system setting a cap on permissible emissions in the country or region and allowing companies to trade the right to emit carbon (i.e., as allowances). This should be distinguished from some companies' use of what are sometimes called 'internal' or 'shadow' carbon prices, which are not prices or levies, but individual project screening values.

Catalytic Reforming
A process used in refineries to upgrade fuel by converting naphtha into hydrocarbons with a high-octane rating. It leads to branching and cyclisation of hydrocarbons and produces significant amounts of aromatic by-products which are often isolated for BTX production.

Cellulosic Fibres
Fibres that are structured from cellulose and that are produced by dissolving natural material like wood pulp. Examples include hemp and lyocell.

Chemicals as a Service (CaaS)
Describes a set of business models that shift value creation from volume-based sales to a stronger focus on service and utility provision. There are three main categories of the CaaS model are product-oriented, process-oriented and results-oriented.

Chemical recycling
While the term is used in different ways, in this report, chemical recycling refers to processes that converts the plastics waste into pure polymer or breaks the polymers into individual monomer. Since these technologies remove demand for primary production, these were considered as part of the circularity levers in the demand model. Note that other technologies like pyrolysis and gasification, that return the polymer to other hydrocarbon products that can then serve as building blocks or feedstock to produce polymers again are considered as supply technologies for primary polymer production and not considered as chemical recycling

- **Dissolution / Solvent Based Recycling:** Dissolution describes a process where plastic waste is dissolved in a solvent-based purification process to separate polymers from additives and contaminants. Note that dissolution is often referred to as "physical recycling" rather than chemical recycling since the chemical constitution of the polymer remains intact throughout the process.

- **Depolymerisation:** Depolymerisation is a chemical process that utilises different combinations of chemistry, solvents and heat to break up the polymer into monomers or shorter fragments. It is thus the reverse process of polymerisation under application of chemical solvents.

Chemical Reforming
Chemical process wherein naphtha is converted into high-octane liquid products called reformates.

Circularity
Circularity is a measure of resource efficiency, i.e. the degree to which (re)used materials replace new virgin materials.

Circular Economy Models
Economic models that ensure the recirculation of resources and materials in the economy, by recycling a larger share of materials, reducing waste in production, producing products and structures of a lighter weight, extending the lifetimes of products, and deploying new business models based around the sharing of cars, buildings, and more.

CO_{2eq}
Also referred to as CO_2 equivalent, this is a standard unit of measurement used to measure the environmental impact of one tonne of a greenhouse gas vis a vis one tonne of CO_2.

Contamination
Contamination occurs in waste disposal when certain non-target materials are placed in a waste stream. In a recycling waste stream for instance, these non-target materials include organic waste, other chemicals, or polymer mixtures. Contamination alters the physico-chemical properties of the secondary raw material.

Controlled Disposal
A potential carbon neutral, high quality method of landfilling, wherein carbon is disposed off in a controlled manner in a landfill, regulating the amount of methane released through this process.

Closed Loop Recycling
Closed loop recycling describes the recycling process in which the output (recyclate) is included in a product of the same sub-system (i.e. packaging) and which in turn can be recycled again.

Compostable (materials)
Materials, including compostable plastic and non-plastic materials, that are approved to meet local composability standards (for example, industrial composting standard EN 13432 where industrial-equivalent composting is available).

Demand Side
Refers to the growth of interventions that influence the demand of chemicals by end-consumers or allied sectors.

Dehydrogenation
A process that describes the removal of hydrogen from a molecule leading to the formation of a double bond. Examples include propane dehydrogenation producing propylene.

Direct Air Capture (DAC)
The collective term for various technologies which use chemical processes to separate CO_2 from the atmosphere. This term does not carry any implications regarding the subsequent treatment of the CO_2 – it may be utilised or stored. Direct Air Carbon Capture & Storage (DACCS) specifically refers to post-capture subsurface sequestration as the explicit end of life destination. Direct Air Carbon Capture & Utilisation (DACCU) refers to utilisation of captured CO_2 after capture. In this report, DAC refers almost exclusively to DACCU in the form of methanol synthesis derived from DAC CO_2.

Digestion
Fermentation of biomass with high water content (e.g. manure) to form biogas (a mixture with high concentration of CO_2 and CH_4).

Downstream
Solutions or interventions applied post-consumer. In the non-ammonia chemicals sector, this includes collection, sorting, mechanical recycling, chemical recycling and disposal.

Disposal
The end-of-life deposition of waste materials. Disposal routes are defined in this study as incineration with energy recovery, landfilling.

Electrolysis
A technique that uses electric current to drive an otherwise non-spontaneous chemical reaction. One form of electrolysis is the process that decomposes water into hydrogen and oxygen, taking place in an electrolyser and producing “green hydrogen”. It can be zero-carbon if the electricity used in the process is zero-carbon.

Electrolyser
Apparatus through which electrolysis is carried out.

Elimination
Practices that reduce unnecessary plastic packaging directly, through reduced production at source or through innovative product design and solutions.

Embedded Carbon Emissions
Lifecycle carbon emissions from a product, including carbon emissions from the materials input production and manufacturing process.

End-of-Life (EOL)
End-of-life is a generalised term to describe the part of the lifecycle following the use-phase. This is often used in the context of End-of-Life disposal or End-of-Life emissions.

Epoxy
A class of adhesive that is produced from epoxy resins.

Ethanol Dehydration
A process whereby ethanol is dehydrated in the presence of sulfuric acid to produce ethene.

Ethylene
A hydrocarbon gas that plays a key role in the production of chemicals like polyethylene.

Ethyl Vinyl Acetate (EVA)
A thermoplastic that is often used as a resistant adhesive, including in the production of solar panels.

Extended Producer Responsibility (EPR)
Schemes that enable producers to contribute to the end-of-life costs of the products they place on the market.

Feedstock
Any bulk raw material – virgin or secondary – that is the principal input for an industrial production process.

Fischer-Tropsch process
This is the process wherein carbon monoxide, hydrogen/ water gas is converted into liquid hydrocarbons in the presence of metal catalysts, heat and pressure. It is primarily used to produce liquid fuels from coal and/or natural gas.

Fluoropolymer
A polymer that has a flourine atom included in its structure. Examples include polyvinyl flouride (PVF), which is used as a flame retardant surface in photovoltaic cells, as well as polytetrafluoroethylene (PTFE), used as water repellent coating material.

Fugitive Emissions
Any unintended release of gas or vapour from anthropogenic activities such as the processing or transportation of gas or petroleum.

Gas Heated Reforming (GHR)
A special type of gas reforming where the gas is pre-reformed and pre-heated prior to an ATR type reformer.

Gasification
Gasification is a process where mixed, end of life materials are heated in the presence of limited oxygen to produce syngas that can be converted into polymers again. Compared to waste incineration, the combustion is stopped before the carbon would be fully oxidized to CO_2.

Gas Reforming
A process wherein hydrogen is produced through the heating of a methane source, like natural gas. Steam methane reforming (SMR), autothermal reforming (ATR) and gas heated reformers (GHR) are technologies of gas reforming with slight differences in technical setup.

Global Commons
This is normally used to describe "common" resources, which any one nation does not have jurisdiction over and are hence "common" to the broader global community.

Global South
Refers to lower- or middle-income countries in Africa, Asia, Oceania, Latin America and the Caribbean.

Green Premium
The additional cost a consumer is willing to pay for a "green" or environmentally friendly solution vis a vis one that is not.

Greenfield Developments
Refers to developments that have been made from scratch and are entirely new. They do not rely on or are not constrained by any existing (brownfield) constraints during their development.

Greenhouse Gases (GHGs)
Gases that trap heat in the atmosphere. Global GHG emission contributions by gas – CO_2 (76%), methane (16%), nitrous oxide (6%) and fluorinated gases (2%).

Green Hydrogen Firing
Using green hydrogen to power plants like steam crackers.

Haber Bosch Process (HB)
The process wherein nitrogen and hydrogen are combined in the presence of an iron catalyst to produce ammonia.

Hydrogen production

- **Green Hydrogen:** Hydrogen manufactured using renewable energy exclusively by electrolysing water.
- **Blue Hydrogen:** Hydrogen manufactured through steam methane reforming to split natural gas then sequester the CO2 through CCS.
- **Grey Hydrogen/ Fossil Hydrogen:** hydrogen manufactured through natural gas reforming or coal gasification without any carbon capture.

Incineration
Also referred to as waste-to-energy, this involves the burning of waste with recovery of generated energy. Waste-to-energy schemes use, among other sources, plastic waste as a fuel to generate electricity.

Inorganic Catalysis
Catalysis involves the use of suitable metals to enable or accelerate chemical reactions.

IPCC Carbon Budget
An assessment by the Intergovernmental Panel on Climate Change that lays out the amount of additional CO_2 that can be released into the atmosphere to limit global warming to 1.5 degree Celsius. The IPCC has ascertained that from 2020, an additional 510 GT of CO_2 can be released in order to meet the 1.5 degree Celsius target with a 50% probability.

Landfill
A low cost, readily available and commonly used method of disposal wherein collected waste is deposited in the ground at designated sites. Certain managed landfills include sites where waste is controlled through daily, intermediate and final cover, thus preventing the top layer from escaping into the natural environment through wind and surface water. However, leakage is common from those landfills that are not managed in this way.

Leakage
Materials that do not follow an intended pathway and 'escape' or are otherwise lost to the system. Litter is an example of system leakage.

Levelised Cost of X (LCOX)
A measure of the average net present cost of a given good such as carbon captured from CCU/CCS or electricity generated by a power plant over its lifetime. For example, the LCO of electricity (LCOE) is calculated as the ratio between all the discounted costs over the lifetime of an electricity-generating plant divided by a discounted sum of the actual energy delivered.

License To Operate
Typically refers to the clearances and permissions required to operate in a certain sector. More specifically, in this report, this refers to the steps the chemicals sector would need to undertake to allow it to operate while also fulfilling its environmental obligations.

Lyocell
A synthetic fibre produced from wood pulp and used in the production of a wide range of fabrics.

Low Circularity, Most Economic (LC-ME)
Scenario wherein limited levers related to circularity are utilised, controlling demand and where this demand is met by producing chemicals through the most economic route available to achieve net zero.

Low Circularity, No New Fossil Production Capacity Installed After 2030 (LC-NFAX)
This scenario optimises for fastest abatement (i.e. a new plant is built based on most carbon abated and not lowest cost), with the added lever that after 2030, no additional fossil fuel capacity will be installed in the chemicals system.

Methanol
A colourless, odourless liquid that has a range of uses, including as an intermediary in the production of chemicals like acetic acid and formaldehyde. This also includes green methanol, or methanol made from green hydrogen.

Mechanical Recycling
Operations that recover end of use plastics via mechanical processes (grinding, washing, separating, drying, re-granulating, compounding), without changing the chemical structure of the material.

Microplastics
Extremely small pieces of plastic formed by the breakdown of larger pieces of plastic waste.

Methanol to Aromatics (MTA)
A method of producing aromatics (BTX) from methanol without the use of fossil fuels.

Methanol to Olefins (MTO)
A process of converting methanol to ethylene and propylene.

Methanol to X (MTX)
Term referring to both MTO and MTA.

Mismanaged waste
Collected waste that has been released or deposited in a place from where it can move into the natural environment (intentionally or otherwise). This includes dumpsites and landfills that are not managed by applying daily cover to prevent waste interacting with the air and surface water. Uncollected waste is categorised as mismanaged waste.

Monomers
Building blocks of polymers. Monomers react with each other to form larger molecules called polymers.

Municipal Solid Waste (MSW)
According to the EU Landfill Directive, municipal solid waste is defined as “waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households”. In the scope of this study, it includes all residential and commercial plastic that is collected by or on behalf of municipal authorities and thus excludes industrial packaging waste. MSW-RdF refers to “Refuse-derived fuel”, which is a dried and treated form of municipal waste.

Naphtha
A hydrocarbon mixture typically derived from the distillation of crude oil and which consists of a range of hydrocarbons. It has a variety of uses, including as an intermediary in the productions of olefins.

Negative Emissions
Term coined by the IPCC used to define activities that remove CO_2 from the atmosphere.

Net-Zero
Used in the report to describe the situation in which the energy and industrial system as a whole or a specific economic sector releases no CO_2 emissions – either because it doesn’t produce any or because it captures the CO_2 it produces to use or store. In this situation, the use of offsets from other sectors (“real net-zero”) should be extremely limited and used only to compensate for residual emissions from imperfect levels of carbon capture, unavoidable end-of-life emissions, or remaining emissions from the agriculture sector.

New Delivery Models
Services and businesses providing utility previously furnished by short-lived plastic in new ways, with reduced material demand.

Novel Entities
In the context of the Planetary Boundaries Framework, Novel Entities relate to those entities that are “novel” from a geological perspective and run the risk of endangering the Earth’s systems, e.g. plastic pollution.

Olefins
A chemical compound consisting of carbon and hydrogen wherein one or more pairs of carbon atoms are linked together by a double bond. Olefins are commonly used as building blocks for many commonly used chemicals like plastics and include ethylene, propylene and butadiene.

Open-Loop Recycling
Process by which polymers are kept intact, but the recyclate leaves the sub-system to be converted into another type of product (e.g. park benches, fibres) and is unlikely to be recycled again due to the degraded quality and/or material properties.

Operating Expenses (OPEX)
Expenses incurred during the course of regular business, such as general and administrative costs, sales and marketing, or research and development.

Petrochemicals
Chemicals made from oil and natural gas and with a plethora of uses, including the manufacture of plastics.

Planetary Boundaries
A concept developed in 2009, it identifies nine processes that are critical to the stability of the Earth’s system and places “boundaries” in each of these systems within which humanity should operate.

Plastic
A synthetic material made from a wide range of organic polymers.

Point Source Carbon Capture
CCUS attached to a single, identifiable entity from which CO_2 originates. This is in contrast to of Direct Air Capture which isolates CO_2 from the atmosphere.

Point Source Emissions
Any emissions that are discharged or emitted from a single, identifiable source. This includes effluents from a drain or emissions from a refinery.

Polyethylene Terephthalate (PET)
A synthetic resin made from ethylene glycol and terephthalic acid, widely used to make polyester fibres.

Polyurethane (PUR)
A synthetic resin formed of hydrocarbon chains linked by urethane (carbamate) links and used, for instance, in the production of flexible foams.

Polyvinyl Chloride (PVC)
A synthetic resin produced from vinyl chloride which has a host of applications, including the manufacture of piping.

Polyhydroxyalkanoates (PHA)
Naturally occurring polyesters that are produced by certain microorganisms that can be used in the production of biodegradable plastics.

Polystyrene (PS)
A synthetic resin consisting of styrene monomers and used in the production of foam.

Polypropylene (PP)
A polymer consisting of propylene monomers and used in a range of applications including in the production of plastic containers, furniture and car parts.

Polyethylene (PE)
A polymer consisting of ethylene monomers, and includes low-density polyethylene, used in packaging film and cable insultation, and high-density polyethylene, used in the production of plastic caps and construction films.

Process Emissions
CO_2 and other greenhouse gases emissions generated as consequence of a chemical reaction other than combustion occurring during an industrial process.

Propylene
A hydrocarbon that plays a key role in heating substances as well as in fuelling the plastics and energy sectors.

Pyrolysis
Pyrolysis is the thermal process of heating up plastic under the absence of oxygen. It converts polymers into a range of simpler hydrocarbon compounds in the form of liquid pyrolysis oil.

Pyrolysis Oil
The hydrocarbon by product produced after the heating of plastic waste in the absence of oxygen (pyrolysis). Can have a range of applications, including as a feedstock in new plastic production.

Refineries
A production facility wherein raw materials are refined and upgraded using chemical processes. In this report, reference is normally made to oil refineries, where crude oil is upgraded to form petrochemical intermediaries.

Renewable Energy Sources (RES)
Refers to energy renewable production technologies including wind, solar and hydro.

Residual Emissions
All GHGs that are emitted from a system after all reasonable steps have been taken to abate the emissions of GHGs.

Reuse models
Replacement of single-use packages with reusable items owned and managed by the user or by services and businesses which provide the utility (New Delivery Models).

Science Based Targets Initiative (SBTi)
The Science Based Targets initiative, wherein companies can set near term, long term and net zero targets based on the best available science. The SBTi is a collaboration between the World Resource Institute, World Wildlife Fun and UN Global Compact.

Separation of Waste at Source
The collection of individual components of solid waste (such as plastic) separated into different collection containers by the user, in order to recover the material or to facilitate its collection and disposal. Separate collection of plastic waste is a precondition for high-quality recycling as contamination with other materials is limited.

Sequestration
Removal or separation of CO_2 such that it is no longer freely moving in the atmosphere.

Scope 1 emissions
Refers to emissions from resources that a company owns and controls directly.

Scope 2
Refers to indirect emissions that are emitted due to the electricity purchased by an organisation in the conduct of its operations.

Scope 3
Refers to all emissions that do not fall under the ambit of Scope 1 and Scope 2 and can be linked to an organisation's value chain. There exist 15 categories of Scope 3 emissions and can range from emissions generated due to the transportation and distribution of an organisation's goods to those emitted due to its disposal at the end of life of the goods.

Steam Crackers
Petrochemical process wherein long chain hydrocarbon molecules are mixed with steam and heated to break down into smaller chain hydrocarbon molecules, like olefins and BTX.

Steam Methane Reforming (SMR)
Process in which methane from natural gas is heated, with steam, usually with a catalyst, to produce a mixture of carbon monoxide, CO_2 and hydrogen.

Sorting
Physical processing techniques and processes to separate materials in waste streams. Sorting is typically performed in Material Recovery Facilities (MRFs) or specific Plastic Recovery Facilities (PRFs). Sorting can be performed automatically with sorting technologies or manually.

Sustainable biomass / bio-feedstock / bioenergy
In this report, the term 'sustainable biomass' is used to describe biomass that is produced without triggering any destructive land use change (in particular deforestation), is grown and harvested in a way that is mindful of ecological considerations (such as biodiversity and soil health), and has a lifecycle carbon footprint at least 50% lower than the fossil fuels alternative (considering the opportunity cost of the land, as well as the timing of carbon sequestration and carbon release specific to each form of bio-feedstock and use).

Syngas
Or synthesis gas, it is composed primarily of carbon monoxide, hydrogen and CO_2 and is used in the synthesis of various chemicals.

System Cost
Total system cost comprises of cumulative capex and opex at each stage of the value chain for the respective scenarios and periods, including production and waste management of both plastics and substitute materials. System costs are funded through both capital investment and from profits generated.

Supply Side
Refers to the growth of interventions that influence the production of chemicals by suppliers.

Sustainable Aviation Fuel (SAF)
Aviation fuel produced from sustainable sources, but which have very similar characteristics to traditional jet fuel.

Technology Readiness Level (TRL)
Describes the level of matureness a certain technology has reached from the initial idea to large-scale, stable commercial operation. The IEA reference scale is used.

Toluene
Aromatic compound. Main uses stem from blending into the gasoline pool, producing isocyanate for polyurethanes, and the onward production of benzene and xylene.

Toluene Disproportionation
In this process two toluene molecules are converted into one benzene and one xylene molecule via a process called transalkylation.

Tipping Points
A tipping point describes the moment when mass adoption of a given technology beyond early adopters is achieved.

Upstream Solutions
Solutions applied pre-consumer. This includes design for recycling (D4R); reductioneduce levers such as eliminate, reuse (consumer) and reuse (new delivery model); and substitution levers such as paper, coated paper, and compostable plastic.

Urea
A nitrogen, carbon and hydrogen-based molecule that is used either directly as a fertiliser or as chemical intermediate to produce a wide range of fertilisers.

Virgin plastic
Virgin plastic is the polymer resin produced directly from the petrochemical feedstock.

Viscose
A substitute for silk, which is produced from cellulose and is used in the production of rayon fibres.

Waste Feedstock
Includes waste material that can be used as an input in industrial processes after conversion into hydrocarbon products.

Wastewater
Run-off from wastewater treatment plants that contains elevated levels of nitrate which can be used for ammonium nitrate production.

Xylene
Aromatic compound that is primarily used as a solvent in the rubber, paper and leather industries. Xylene is the umbrella term for isomers ortho-, meta-, para-xylene. Within this report, xylene refers to para-xylene which is the by far most commonly used xylene as starting material for PET synthesis.

Zero-carbon Energy Sources
Term used to refer to renewables (including solar, wind, hydro, geothermal energy), sustainable biomass, and nuclear.

September 2022, version 1.1

Planet Positive Chemicals

Pathways for the chemical industry
to enable a sustainable global economy

This research was funded by Mitsubishi Chemical Corporation

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