In collaboration with Accenture

Implementing Low-Carbon Emitting Technologies in the Chemical Industry: A Way Forward

COMMUNITY PAPER

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Executive summary

The chemical industry is a cornerstone of the global economy and is essential for all goods-producing industrial sectors. Chemical companies are energy-intensive, though they are responsible for producing energy-saving materials and are positioned to drive innovations that enable more sustainable production and contribute to further reductions in greenhouse gas (GHG) emissions across value chains. Leveraging the power and expertise of the industry will be critical to achieving meaningful GHG emissions reductions and represents a unique opportunity to support sustainable change towards net-zero in 2050.

The global energy transition is building momentum, and the chemical industry is ready to contribute to this transition by accelerating the deployment of low-carbon emitting technologies (LCETs), despite technological and economical challenges and barriers. Forging strong collaborations and mobilizing them at speed, enabling prompt action, and being willing to take bold decisions within the sector and beyond are needed to meet the 1.5°C Paris Agreement target. Towards this goal, a group of leading chemical companies has decided to join forces, combining and optimizing their competencies to drive the sector's transformation towards net-zero along a technically and economically feasible pathway. This also includes a joint effort to define agreed metrics that ensure measurable progress towards net-zero within the industry (Scope 1 and 2) and its value chain (Scope 3).

The way forward if we are to accelerate the development and implementation of LCETs will hinge on:

1. Expediting technology innovation as a building block towards net-zero
2. Connecting technologies within chemical value chains to encourage intrasectoral and cross-sectoral collaborations and create net-zero emission products
3. Promoting the development of a supportive policy framework and shifting investment towards higher CAPEX and OPEX technologies
4. Developing tailored financing models and structures to enable a multifold increase in private capital flows needed to develop and deploy critical breakthrough technologies in the coming decades
5. Creating attractive markets for green products to generate a significant pull effect from consumers

With 2.9Gt of CO_2 equivalent (eq.) per year globally, the chemical sector is responsible for 5–6% of overall global greenhouse gas (GHG) emissions.[1] Some 63% of these emissions are energy-related, meaning they arise from the combustion of carbon-containing components to generate the energy that drives the production processes. Chemical processes and value chains are closely interlinked to minimize loss of raw materials or intermediates and to use generated energy as efficiently as possible. Thousands of products are made by these highly interconnected value chains; however, only two processes are responsible for around 44% of the total CO_2 eq. emissions of the industry, namely those used to produce ammonia and petrochemicals.[2, 3]

Accordingly, innovations and collaborations across value chains, in particular these for ammonia and petrochemicals, have the largest impact on GHG emissions reductions: ammonia production, with its integrated generation of hydrogen from natural gas, and olefin production via steam cracking.

While most of the technologies required to transform chemical value chains towards net-zero emissions are already available or in development, strong collaboration by cross-sectoral partners is critical to enable high-impact implementation. Some good examples with potentially high impact include the electrification of fossil fuel-heated processes and the use of alternative technologies to produce basic chemicals such as hydrogen. In addition, alternatives to fossil feedstocks are an important lever towards CO_2 reduction; however, a net-zero industry environment can be achieved only in combination with the use of renewable energy sources and efficient processes.

To objectively judge the efficiency and impact of such LCETs, the cumulated value chain emissions of products (as Product Carbon Footprints [PCF]) need to be assessed and managed. Currently, the chemical industry's efforts are focused on reducing emissions from production processes (Scope 1) and energy procurement from third parties (Scope 2), while evaluating various assessment frameworks to enable a standardized approach across the sector to address supply chain and product use emissions (Scope 3).

The technical principles of how the chemical industry can reduce its carbon footprint are clear, and specific measures to convert traditional modes of operation into net-zero value chain archetypes are on their way. Nonetheless, efforts to deploy such new technologies at commercial scale in this highly complex industry are extensive. This is especially the case in terms of capital and operational cost perspectives and economic risks.

On the one hand, an enabling regulatory framework must be established to support the transformation and provide long-term planning security, and the necessary infrastructure must be created to enable a technically and economically feasible transformation.

On the other hand, LCETs require significant technical innovations and capital expenditure to reach meaningful commercial implementation.

The deployment of LCETs will therefore need to be adapted to be commercially competitive, including in comparison with fossil-fuel projects. LCETs will need to be part of a comprehensive policy agenda – driving investment and innovation while aligning with policy efforts to mitigate carbon, incentivize net-zero initiatives and align with necessary infrastructure to ensure sustainable production.

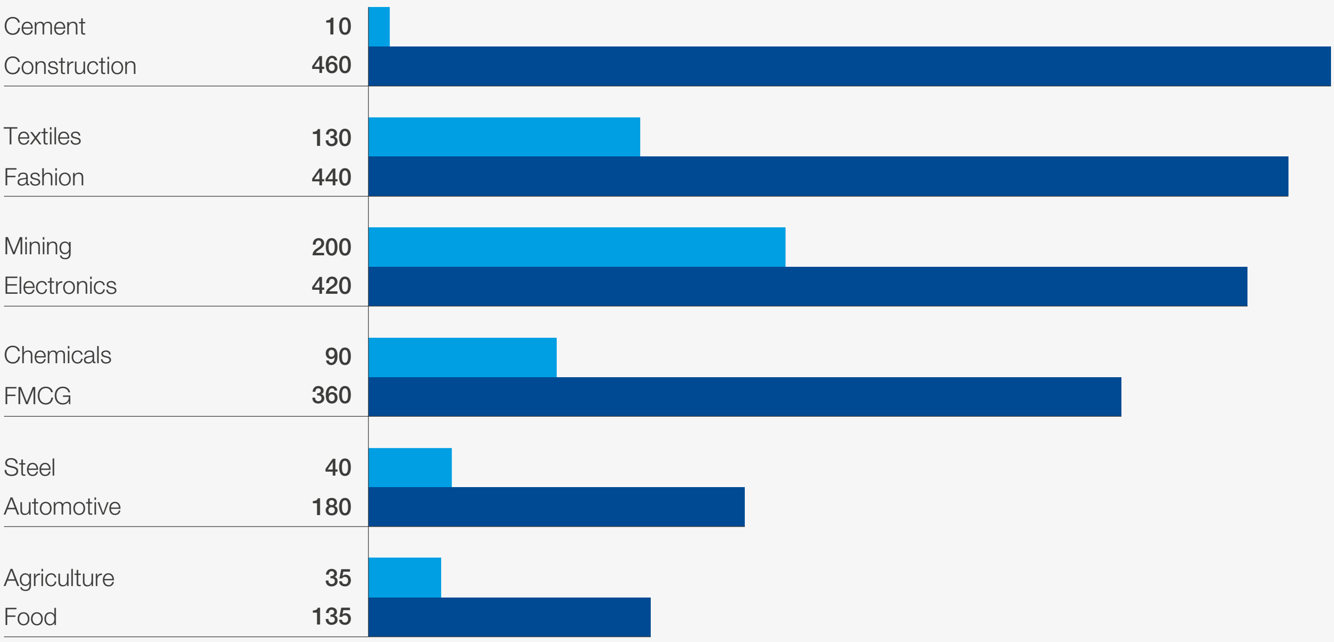
The chemical industry is ready to take on the challenge of transformation and is determined to further continue its enabling role in the global cross-industry network to achieve a "decarbonized" future economy.

1 Introduction: the role of the LCET initiative in reducing the chemical industry's emissions

Global anthropogenic emissions of greenhouse gases (GHG) measured in carbon dioxide equivalents (CO_2eq.) are around 50Gt per year;[4] it is well known and widely accepted that they contribute to ongoing climate change. The chemical industry relies heavily on fossil-based resources for feedstock and energy and is responsible for 5–6% of global GHG emissions, accounting for 2.9Gt CO_2eq. per year[5] (total of Scope 1 and 2). The industry provides essential materials, technologies and building blocks to almost all industries and their value chains, from automotive, aeronautics and electronics, to cosmetics, agriculture and food. Sustainable chemistry therefore is a key enabler for the entire economy. It has an important role to play in bringing about change and finding solutions to problems that affect the whole world, such as climate change, better use of resources and the development of a more circular economy. In addition, the chemical industry itself is transitioning to a net-zero future by innovating to lower its inherent GHG emissions. To fulfil the energy and feedstock needs of the chemical industry in the context of Net-Zero 2050[6] will require new technologies to provide energy for driving chemical processes and sources of alternative feedstocks. Since most reaction pathways for making primary building blocks are endothermic, i.e. energy-consuming, and many unit operations are thermal separation processes, energy provision plays a significant role. Notably, along value chains – for instance, from crude oil to finished industrial or consumer goods – most contributions to GHG emissions are made at the beginning, during the production of base chemicals such as ammonia, olefins[7] and methanol. However, the main value is created in the end (see Section 2.1) by delivering fashion items, vehicles or electronics (Figure 1).[8]

FIGURE 1 **Comparison of value creation to carbon emissions between early and late value chain members**

Net income per ton of emissions (€/tCO_2eq. Scopes 1–3 upstream, 2019)



Note: Top companies selected based on number of reported Scope 3 upstream categories and industry fit; FMCG = fast-moving consumer goods
Source: CDP, BCG

Consequently, addressing this imbalance, new cost-value distribution models along the value chains must be developed. To achieve the goal of net-zero emissions, the chemical industry must urgently master two challenges: 1) gaining access to large quantities of affordable and reliable carbon-neutral energy; 2) quickly developing and implementing new technologies operating on renewable or recyclable rather than fossil sources of energy and raw materials.[9, 10] The latter is a challenging undertaking, as the production of base chemicals is capital-intensive and the costly sector transformation needs to start now, even though attractive and rewarding markets for low-emissions products are only just developing. Despite these challenges and the risks they pose to the chemical industry, the industry is stepping up its contribution to the global energy transition by accelerating the development and deployment of low-carbon emitting technologies (LCETs).

Most emissions reductions in the future will result from the use of LCETs that are today at varying levels of readiness; few are ready for deployment at commercial scale, and many are still in an early stage of development.

Considering the size and complexity of the chemical industry on a global level, achieving net-zero emissions requires strong, innovative and strategic collaboration within and beyond the industry and related value chains. To this end, in 2019 the World Economic Forum launched, and is currently hosting, the Low-Carbon Emitting Technology (LCET) initiative, which aims to accelerate the development and upscaling of LCETs through collaborations across the chemical industry and related value chains. In this initiative a group of chemical companies is taking on the challenge of finding a path to net-zero emissions for the industry by developing and implementing technologies such as cracker electrification or the use of biomass as feedstock for olefin production. The ambition of the LCET initiative is to develop collaborations beyond the sector to include a broad range of stakeholders such as partners in the value chain, governments and members of the financial sector, academia and civil society. To achieve net-zero, significant technical, financial and policy challenges will need to be met. Therefore, the initiative will also investigate new financing models and assess policy frameworks to support the deployment of LCETs.

Ultimately, the LCET initiative offers a unique platform for its members to exchange knowledge, initiate partnerships for implementing projects and drive progress towards Net-Zero 2050.

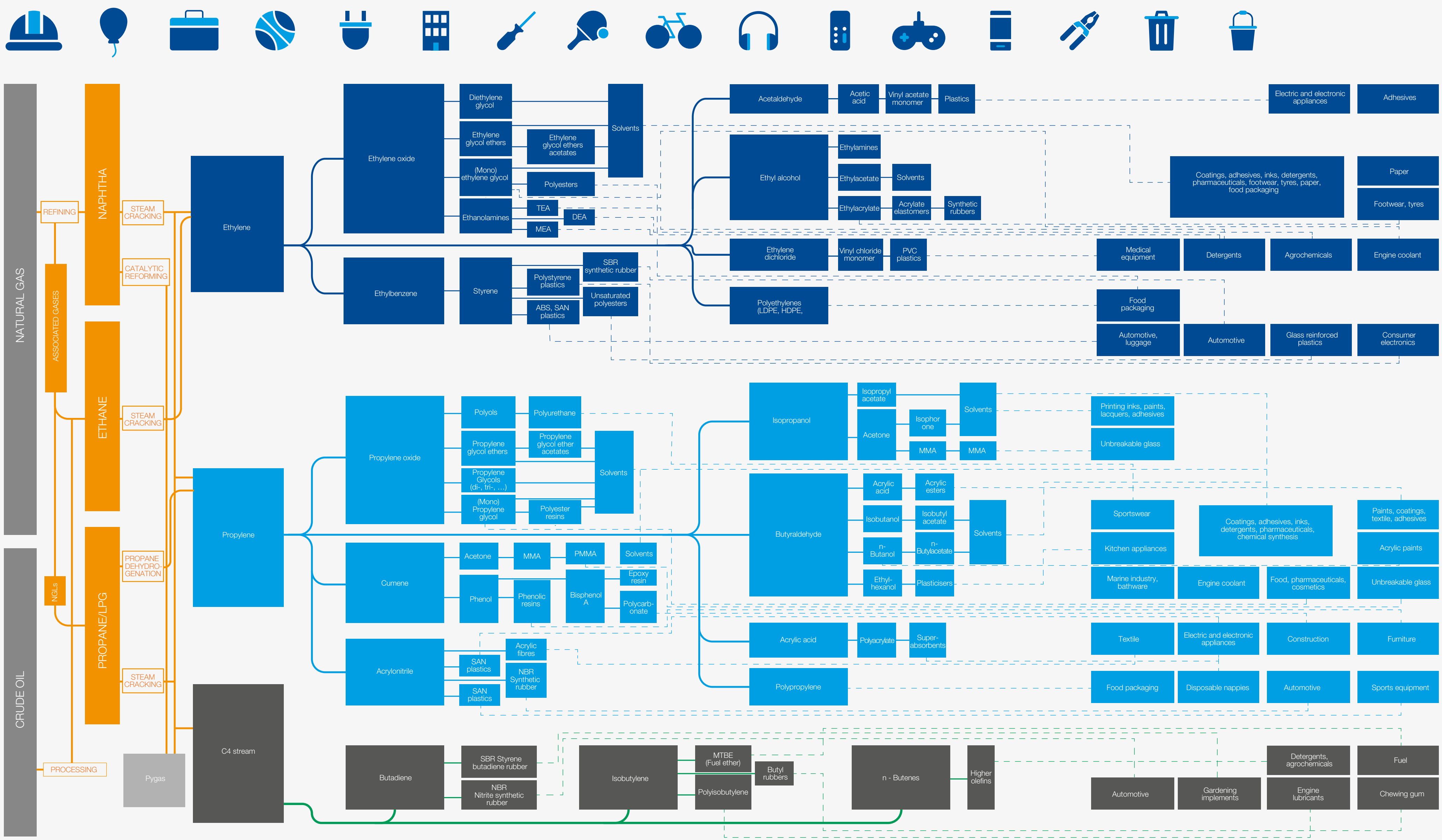
2 Situation and context of the chemical industry

2.1 Sector relevance and complexities

The chemical sector's relevance and complexity are tightly interconnected. Like other process industries such as steel and cement, the chemical industry is a cornerstone of the global economy; however, unlike the more linear value chains and processes of the other industries, the chemical industry is characterized by its value network structure. In chemicals, this network is a web of long value chains leading to refined products – and along which GHGs arise.

The chemical industry comprises companies that produce a broad range of industrial chemicals and customize them to meet the needs of a broad range of applications, i.e. products that nearly always require further processing before reaching the end consumer. Via complex and energy- and capital-intensive manufacturing processes with many tightly interconnected unit operations, raw materials are converted into intermediates and products; many routes lead to the same product; many applications exist for the same product; the number of chemical products reaches tens of thousands.[11] Furthermore, materials – including hazardous ones – are handled in all three physical states of aggregation, and complex relationships exist between raw material variability and operational constraints. In essence, the chemical industry itself is the largest purchaser of chemical products.[12] The market environment is characterized by price volatility of raw materials, strong international competition and increasing regulatory requirements – the European Union Registration, Evaluation, Authorisation and Restriction of Chemicals regulation (REACH) etc. The chemical industry affects most other industries, with more than 95% of all manufactured goods being touched by chemical products (Figure 2).[13, 14]

Figure 2 | **Example of complexity of the chemical industry product flows (from left to right) and involvement in various end product categories (on top)**

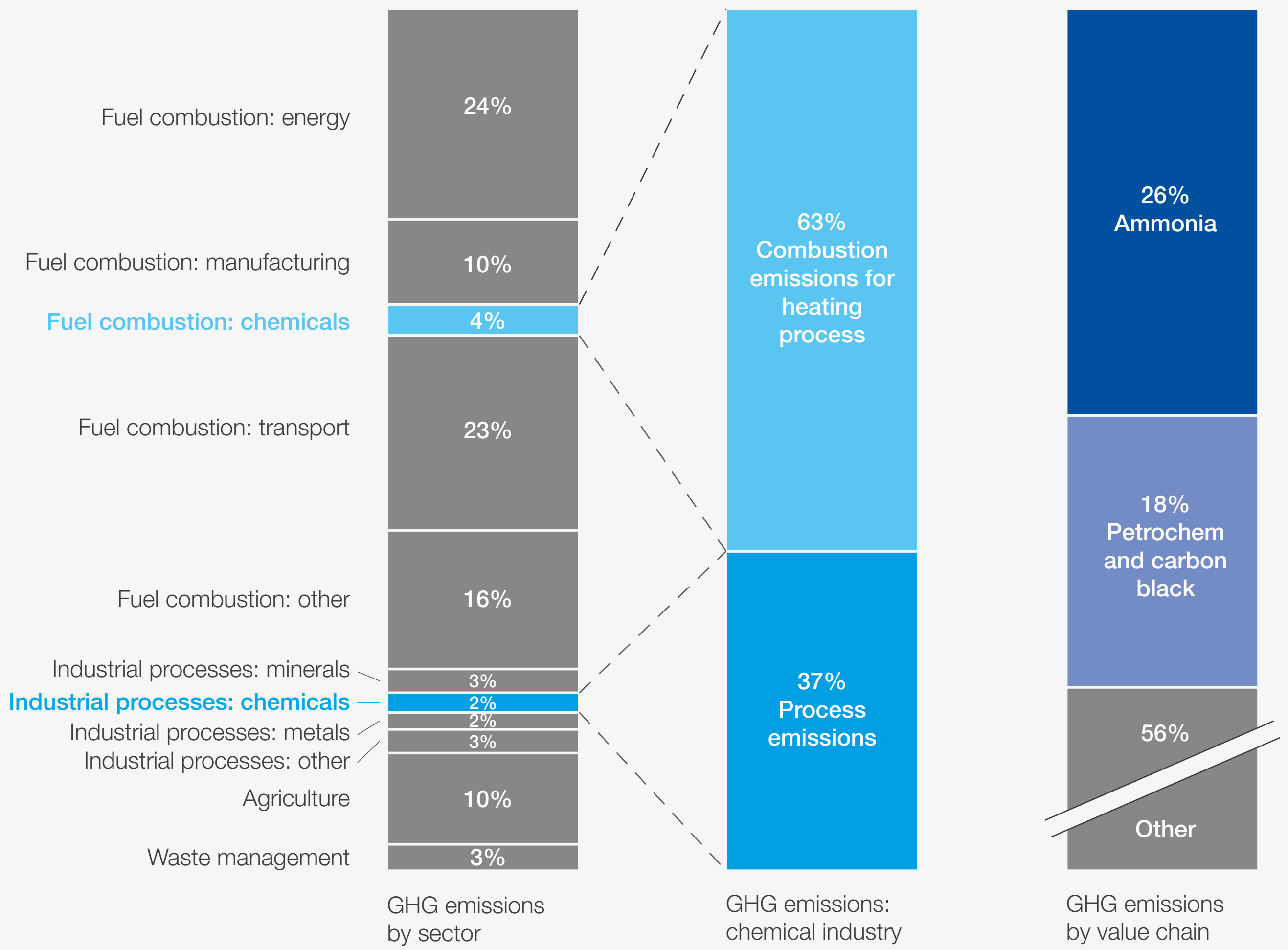


Source: Adapted from Petrochemicals Europe (www.petrochemistry.eu)

2.2 Industry facts and figures

On a global basis, the chemical sector consumes 14% of all oil and 8% of all gas supply as feedstock and fuel and is therefore one of the largest consumers of fossil carbon supply for material use. Globally, 257Mt oil, 114Mt natural gas and 47Mt biomass are being consumed and transformed by the chemical industry to cover its carbon demand.[15] The chemical industry's operations rank behind the cement and steel industries in terms of direct CO_2 emissions. The production of only a small number of chemicals (base chemicals) contributes >44% of the total emissions of the chemical industry; for instance, production of ammonia and petrochemicals (Figure 3).[16, 17, 18, 19]

FIGURE 3: **Direct greenhouse gas emissions of the chemical industry and of ammonia and petrochemical production in detail**



Source: IEA.org, "Chemicals": https://www.iea.org/reports/chemicals; Accenture internal research. Chemical & Natural Resources Strategy Team

Currently, industry efforts focus on lowering Scope 1 and 2 emissions by investing in, for example, energy-efficient technologies and the electrification of processes, as well as procuring renewable energies.

A large part of the consumed carbon supply within the chemical industry is used as feedstock and bound for numerous other industries and various complex value chains geared towards final products. This has profound consequences for Scope 3 emissions accounting and abatement strategies in the life cycles of the sector's goods.

The carbon-accounting complexity warrants more attention in net-zero scenarios, and is amplified by a lack of data transparency and accuracy in the highly intertwined global value and supply chains. Notably, the LCET initiative is currently evaluating various Scope 3 assessment frameworks and will support collaboration on the Scope 3 emissions accounting methodology for the chemical sector.

3 The way forward

3.1 Building blocks towards net-zero: technology innovations

The demand for chemicals and materials will likely quadruple by 2050 compared to 2010 levels.[20] Unfortunately, the established ways of reducing emissions – by continual, incremental process improvements, which are the first choice in CO_2 abatement, or, often, through internal cost optimization toolboxes – will not suffice to achieve net-zero. A holistic approach to emissions reduction using a variety of technologies is required. Immediate actions are needed by the chemical industry to combat climate change. Achieving net-zero by 2050, though, will not be a sudden switch; rather, it will follow a steady pathway of relevant technology development and deployment. New building blocks to be created and implemented along this pathway (not in order of action or significance) are as follows:

- Electrification of existing processes with renewable and carbon-neutral energy
- Use of renewable feedstock by using biomass for feed and/or fuel. The demand for biomass as a renewable source of feed and fuel is increasing in various sectors such as aviation and shipping
- Combination of electrification and renewable feedstock within alternative hydrogen production via electrolysis
- Use of renewable feedstock by increasing circularity via improved waste processing
- Carbon capture use and storage (CCUS)[21] and CO_2 sequestration via reforesting

Some of these technologies, such as carbon capture and storage (CCS) and blue hydrogen (see below), play a critical and very important role for the transition towards long-term carbon-neutral solutions.

To effectively progress on the net-zero journey, new collaborations need to be forged and the technology areas outlined above must be enhanced. Therefore, the contributing partners of the LCET initiative have joined forces to promote the development and upscaling of five low-carbon emitting technology areas that are at different levels of readiness.[22]

Electrification
The bulk of the chemical industry's emissions are energy-related – the burning of fossil fuels to provide energy for chemical processes. Electrifying these processes would therefore contribute significantly to emissions reductions – given that the production of electric energy itself is low in emissions, i.e. based on renewables. Further on in this paper, any reference to electrification refers to renewable or carbon-neutral energy use.

Biomass utilization
Biomass from agricultural waste, side products and forestry can be used as an alternative to fossil fuels and feedstocks in the chemical industry. If the biomass used is sustainably produced, significant reductions in carbon emissions can be achieved due to a closed-loop carbon cycle being formed from biogenic carbon that was previously absorbed by plants during their growth being released. As an example, using biomass waste streams for biofuel production and consequently coupling this with carbon capture and utilization (CCU) or carbon capture and storage (CCS) could serve as a potential temporary carbon sink. Biofuel consequently contributes to decarbonizing the road transport, maritime and aviation sectors. Notably, biomass for feedstock and fuel should not compete with the production of global food supply.

Alternative hydrogen production
Hydrogen could be used as a carbon-neutral fuel for high-energy processes that are difficult to electrify. Conventional hydrogen production is conducted via steam methane reforming or autothermal reforming, in the process of which CO_2 is released and fugitive emissions occur. It is important to avoid these emissions if hydrogen is to be an effective solution in a low-carbon future. There are several demonstrated approaches to doing this, such as blue hydrogen, which combines the conventional method of steam methane reforming with CCS and sufficient measures to address fugitive emissions. Another route for hydrogen production without any process GHG emissions, referred to as green hydrogen, is via electrolysis of water. While the latter technology is considered the most sustainable for the longer term, it remains expensive at the moment and requires abundant renewable energy capacity. Meanwhile, blue hydrogen, which is based on technologies available today, could play a significant role in the transition towards a green hydrogen economy.

Waste processing
Post-launch, the original focus area of the LCET initiative for emissions reduction was emissions reduction processing and recycling of plastic waste. Recycling plastics reduces the required amount of fossil resources needed to produce enough virgin materials to cover demand. It also avoids the incineration of plastics at the end of the life cycle, thus decreasing GHG emissions.

Carbon capture and utilization (CCU)
CCU, while not the easiest technology to implement, complements other technologies

that can directly reduce emissions in working towards net-zero. The potential for CCU to offtake concentrated CO_2 emissions streams from chemical and other operations and consequently transform them into valuable end products or energy/hydrogen carriers such as green methanol is significant.

In the event of CO_2 being converted into valuable end products, it becomes an alternative feedstock for petrochemical production, contributing to the reduction in the use of fossil feedstocks. This leads to CO_2 being stored for the medium to long term in products such as insulation materials for buildings, or plastics to be used for roads and bike paths.

In the event of CO_2 being converted into an energy carrier such as green methanol, it can heavily benefit energy-demanding operations situated inland and without access to affordable renewable energy.

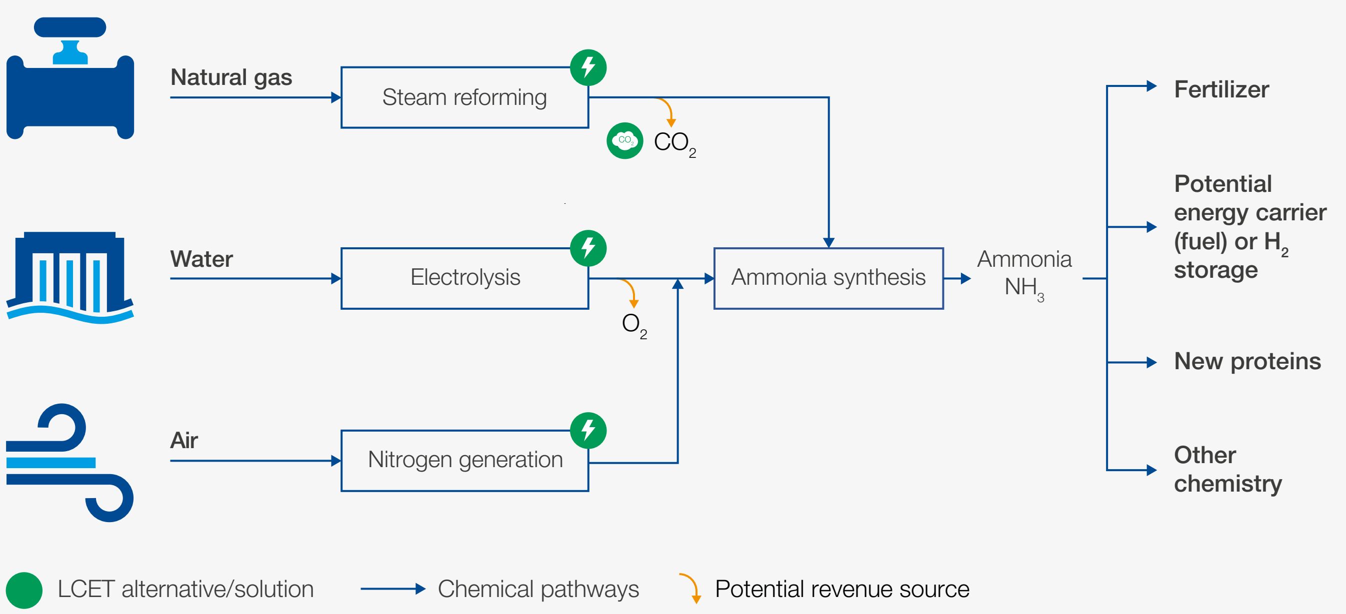
Generally, carbon capture technologies will be crucial to reach net-zero by 2050 – in combination with various storage options in the near term and novel usage routes in the long term. The LCET initiative focuses on the usage route (CCU) rather than storage (CCS), given the great opportunity to transform concentrated CO_2 streams into intermediates, products and/or alternative fuels; however, the chemical industry could benefit from CCS in the transition period.

Currently, all areas in this section, from electrification to CCU, are being investigated by the LCET initiative and are progressing towards project implementation.

3.2 The broader perspective: connecting technologies with a chemical value chain

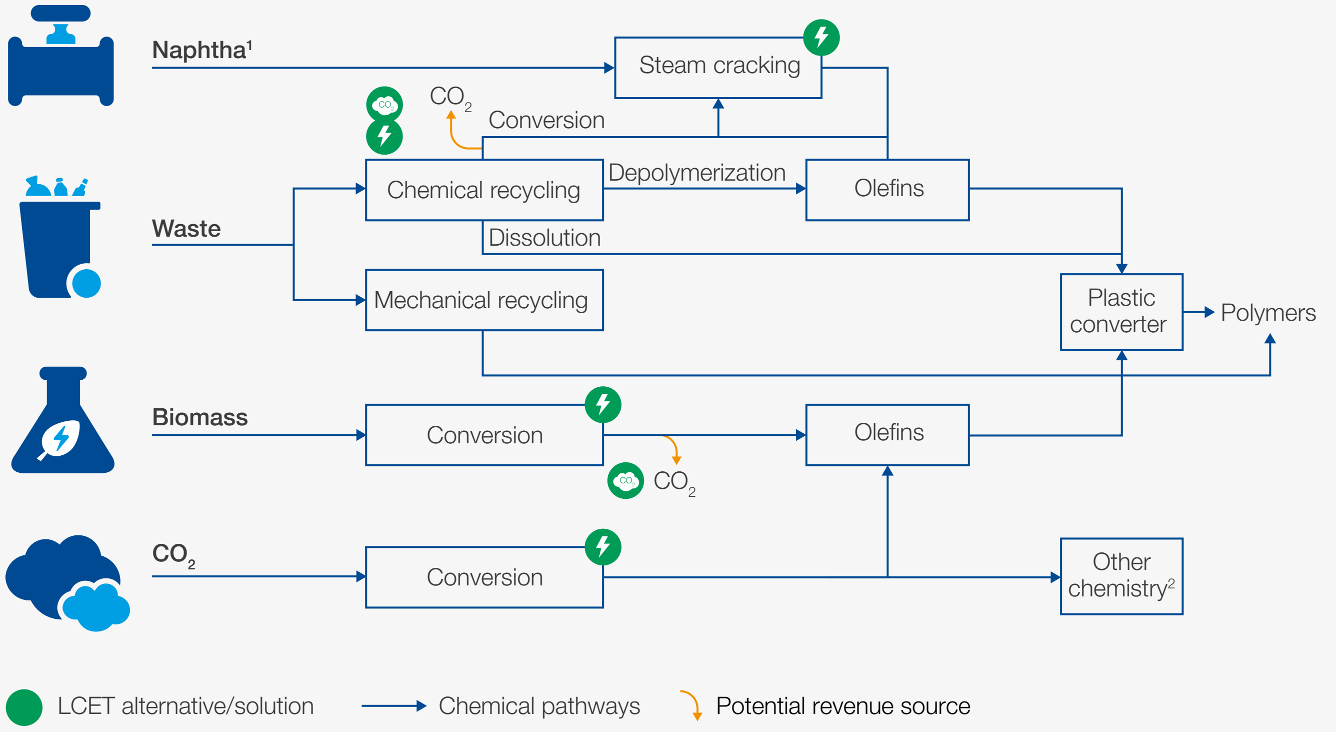
It must be assumed that more capital will be required for chemical production if LCETs are implemented at large scale to maximize the abatement of GHG emissions. Chemical value chains start with a few building blocks, which are typically derived from fossil-based raw materials by applying energy-intensive processes. These form the basis of a wide variety of subsequent value chains that are interconnected to span a complex network that enables the best use of all raw materials. Therefore, the entire value chain network must be considered in order to identify the key backbone value chains that need to be decarbonized to have the biggest impact for the sector. An agreement about the mitigation of associated development risks for these core elements of the network needs to be found *ex ante* within the limits of current antitrust law. At this first level, the two most prominent value chains – ammonia synthesis on the one hand, and olefin production on the other – were identified as backbone elements, each with a high impact on the chemical sector's emissions (Figure 4, Figure 5).

FIGURE 4: **Value chains for ammonia production**



Source: World Economic Forum LCET initiative

FIGURE 5: **Value chains for olefin production**



1. Other fossil fuels being used as feedstock for steam cracking are not shown here
2. Alcohols from CO_2 conversion can e.g. be used as fuels, fuel additives (blending) or as H_2 storage for transport

Source: World Economic Forum LCET initiative

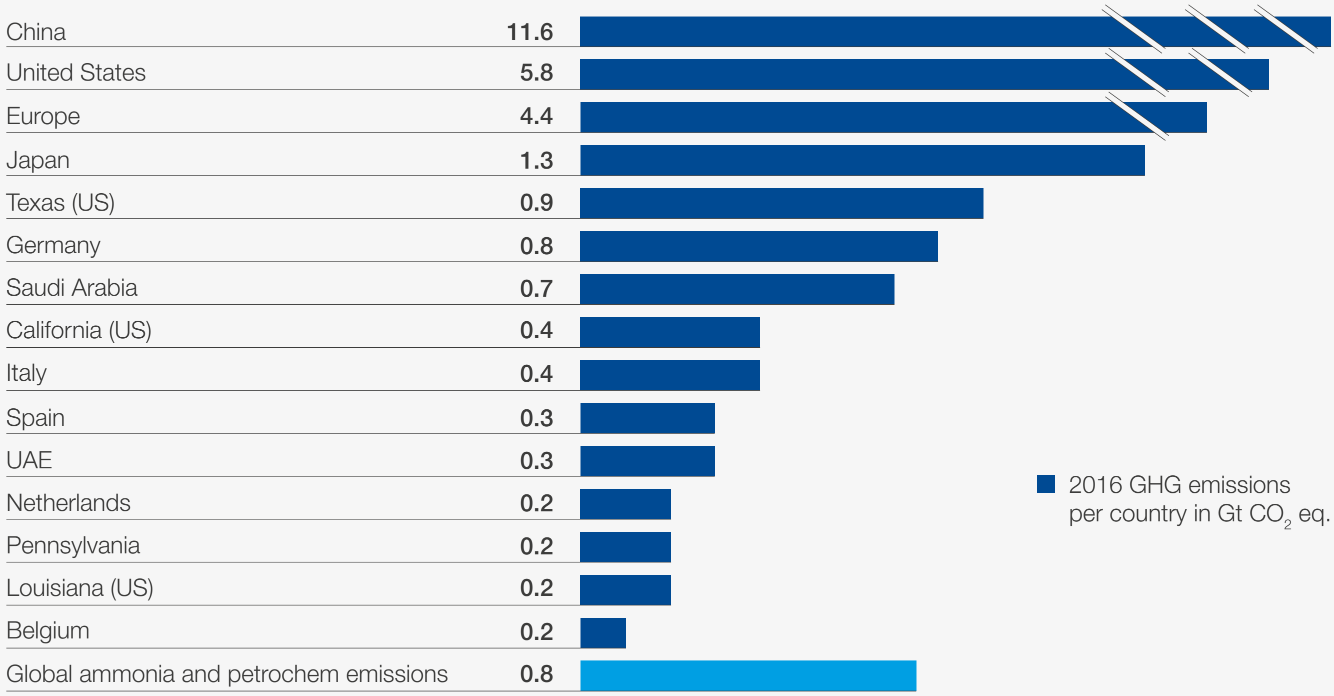
At the second level, within each value chain a nascent product can take various pathways. For both backbone value chains, a small number of the most promising and viable chemical pathways were selected.

At the third level, in terms of investment projects, a mapping of LCETs to the selected chemical pathways was conducted, arriving at value chain archetypes (VCAs); investment and operational costs can then be assigned to these VCAs. For selected VCAs, the optimal financing structure will be defined depending on policy and financing models. A stringent deployment of LCETs will be encouraged through information exchange and collaboration within the value network, acknowledging the legal boundaries of respective jurisdictions.

3.3 LCET deployment: high-level abatement potential

Global CO_2 equivalent emissions amount to ~50Gt per year, of which ~2.9Gt per year are emitted by the chemical industry (total of Scope 1 and 2), indirectly via energy consumption (around 63%) and directly, process-related (around 37%). In comparison, the United States generates 5.8Gt or the European Union 4.4Gt. Among the most important chemical processes for modern human life are ammonia synthesis and petrochemical production; their emissions amount to ~450Mt/a and ~300Mt/a, respectively.[23] Therefore, eliminating the emissions for these two processes would constitute significant contributions to reaching the Net-Zero 2050 target, reducing emissions equivalent to the total GHG emissions of Germany or Saudi Arabia (Figure 6).[24, 25, 26]

FIGURE 6: **Annual GHG emissions (CO_2 eq.) in focus geographies in comparison to global GHG emissions from ammonia and petrochemical productions**



Source: Ritchie and Roser, “CO2 and Greenhouse Gas Emissions”, Our World in Data

Clearly, eliminating all emissions from a value chain is extremely complex. Therefore, the approach needed is one of continuous progress along the net-zero pathway, taking specific process steps in those value chains by, for example, electrifying furnaces, which are the largest emitters of the cracker process, responsible for 90% of emissions of petrochemical production. Other activities will complement the emissions reductions; for instance, CCU or sequestration via reforesting.

Of course, it is pivotal for the success of the net-zero endeavour that sufficient affordable renewable and carbon-neutral energy is available, so that no cross-sectoral transferring of emissions occurs. Achieving the pace of CO_2 emissions reductions in line with the Paris Agreement is already challenging and, as global energy will be increasingly based around electricity, a range of technologies including nuclear power and hydroelectric power will be required, as well as fossil fuels using CCUS. Nuclear and hydroelectric power represent important pillars of low-carbon electricity generation.[27] For example, in advanced economies,[28] nuclear power accounts for 18% of generation and is the largest low-carbon source of electricity.

Currently, in many regions renewable energy is still more expensive than fossil-fuelled energy generation and often less reliable due to strong weather dependencies and day/night cycles. However, the chemical industry requires both an affordable and a reliable power supply. The latter is especially important due to chemical production facilities often requiring continuous operations for financial, safety and energy efficiency reasons. Potential options to mitigate the current reliability complexity of renewable energy could include but are not limited to:

– Adaptation of chemical processes to allow process fluctuations

– Collaborative projects among chemicals, utilities or grid operators to optimize energy storage capacities

3.4 Policy: the force of the normative

The development and upscaling of LCETs depend not only on technological readiness and economic feasibility but also on an enabling regulatory and political environment. All stakeholders must be on board – policy-makers on the one hand, who need to incentivize and enable adoption of LCETs, and industry players on the other, who need to be willing to develop and invest in new technologies.

To facilitate the transition into a low-carbon chemical industry, favourable conditions along six key policy clusters will be vital. Besides incentivizing and enabling legislation, supportive LCET-specific infrastructure, aligned societal trends and a clear industry positioning towards low-carbon technologies are required.

1. Incentives and targets
Setting climate targets and the right incentives is a major driver towards a net-zero chemical industry. While carbon pricing has been established in several jurisdictions as an important lever for low-carbon technologies, increasing carbon prices in some jurisdictions in isolation will incentivize companies to relocate their facilities to areas with less-stringent policies. Avoiding this so-called carbon leakage and creating a level playing field while incentivizing investments in low-carbon technologies is one of the major challenges.

2. Technologies and infrastructure
Incentives and targets will not suffice to change the chemical industry. Two key enablers for low-carbon technologies need to be in place to allow companies to get onto the path to net-zero. On the normative side, policy-makers will be tasked with setting regulations that do not make it virtually impossible to move to a low-carbon alternative; for instance, through restrictions on importing biomass or restrictions regarding the deployment of carbon capture and usage. On the practical side, adequate physical infrastructure – for example, pipeline and power transmission networks or availability of renewable energy supply – will be key enablers for low-carbon technologies.

3. Supporting and enabling
Facilitating operations on a technical level will need to be complemented with enablers on the financial side. Switching from conventional technologies to LCETs requires significant capital expenditures (CAPEX). Furthermore, LCETs will typically also entail operating expenditures (OPEX) above those of current processes, leading to less profitable or competitive products. Higher CAPEX and OPEX make it difficult for LCET projects to act as attractive targets for investors.

For an LCET pilot project still to make an investment case, policy-makers can and should work towards:

– Direct support for LCET projects

– Indirect support for products produced via LCETs (e.g. tax advantages)

– Clear green finance guidelines and GHG emissions-related reporting standards and regulations

A classification scheme defining how activities are considered to be sustainable and/or low-carbon helps with market standardization. Such a scheme could support the scale-up of sustainable investment while enabling transparency for investors and other stakeholders.

A number of direct support mechanisms for emissions reduction activities are emerging and being implemented in different parts of the world. For example, India implemented an energy saving certificate scheme (ESCerts), which is incentivizing investments in energy savings initiatives.[29]

The UK recently released its hydrogen strategy, including a proposal for contracts for difference (CfDs), a support mechanism to help fund hydrogen production.[30] CfDs are designed to overcome the price gap between hydrogen and fossil fuel by guaranteeing a certain price for hydrogen producers. In addition, the UK government is also consulting on the design of a £240 million Net Zero Hydrogen Fund to support the deployment of low-carbon hydrogen production plants.[31]

As part of the new US infrastructure bill, it is proposed that $8 billion will be spent in support of regional clean hydrogen hubs over a five-year period.[32, 33]

4. Markets and demand
Up to now, low-carbon products have typically not been competitive and ultimately could succeed only if there was sufficient demand. Therefore, creating and growing a market for green products is an important part of enabling deployment of LCETs. Procurement actions via private initiatives such as consumer pull for green plastics and via public programmes such as government demand for green materials in car fleets can contribute to driving the growth of this market. Also, policy-makers have a role to play in increasing consumer awareness and direct purchase behaviour towards low-carbon products by introducing relevant and effective regulations.

5. Collaboration and innovation
Development and upscaling of LCETs requires significant efforts, in terms of, for example, research and development (R&D), funding and financing. To this end, clarifying competition-related guidelines by policy-makers, and the facilitation and setting-up of more innovation hubs, whether by local authorities or public-private partnerships, will be pivotal.

6. Caveats and inhibitors
Even with relevant policy enablers in place to enable progress, there may still be some roadblocks that should not be overlooked. Assessing the risks will include identifying putative major court decisions directed against the implementation of LCET projects, and societal opinions and movements that might constitute a hindrance to LCET pilot projects such as CO_2 pipelines or new wind parks.

3.5 Financing: gaps to be addressed

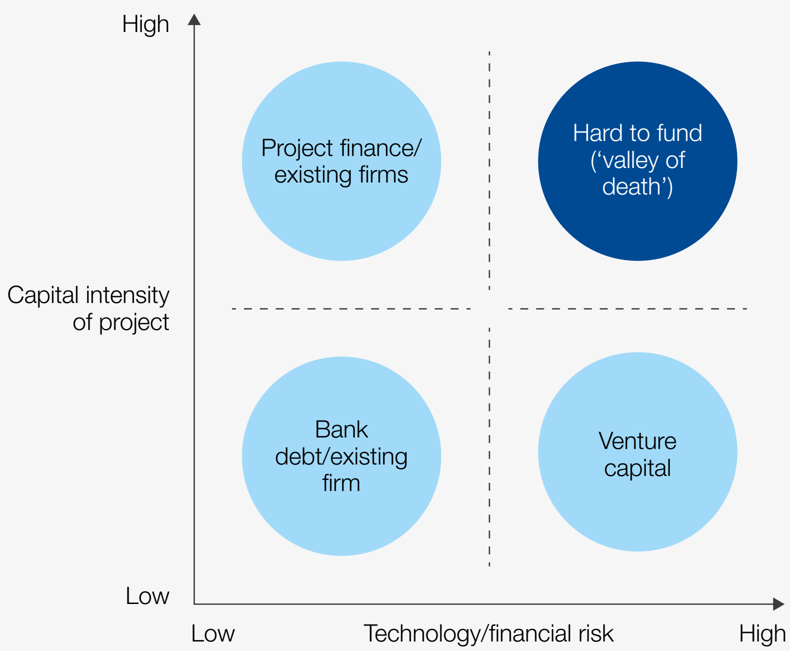
As outlined above, substituting conventional energy sources with green sources, or using low-carbon emitting feeds for olefin production such as biomass or plastics from waste recycling, will temporarily increase the cost base for related chemical products. Similarly, ammonia synthesis requires large quantities of hydrogen, which is conventionally produced via steam methane reforming of natural gas. Natural gas-related production, distribution, equipment and operations costs are currently low due to large economies of scale effects in the production and distribution of natural gas.

To become competitive, the industrial landscape must shift in favour of hydrogen use. The industry therefore requires large investments. As for every investment case, financiers need to understand the potential profitability, initial CAPEX and related risks. However, if current profitability levels make the potential products less competitive than those that already exist, a negative business case will result and financing will be challenging to obtain.

To summarize, moving from established processes and technologies towards LCET-based production processes requires large-scale investments and reduces – at least temporarily – the competitiveness of the products and therefore poses significant risks for potential traditional investors. The ultimate challenge within the net-zero vision for the chemical industry lies not only in developing technological solutions but also in finding investors who are willing to take the risk of financing that transition.

Conventionally, low-risk projects can easily be financed by bank debt or project finance (paid back by project cash flow); however, higher-risk projects and specifically projects with CAPEX requirements as high as those in the net-zero context will have difficulty attracting even risk-prone investors such as venture capital (Figure 7).[34]

FIGURE 7: **The 'valley of death' in financing clean energy technology**



Source: Adapted from Ghosh and Nanda, "Venture Capital Investment in the Clean Energy Sector"

Therefore, a detailed analysis of a set of chosen value chain archetypes must be performed to generate the required understanding of potential operational costs, revenues, initial investment and risks of individual projects.

Ways must be explored to estimate the size of the gap between financing that could be provided by external financiers, the financial extent of public support mechanisms and the companies' own abilities to provide financing on one side and the actual cost of LCET implementation on the other. In a recently published report, the World Economic Forum proposed innovative financing approaches and de-risking solutions to accelerate the deployment of capital towards breakthrough technologies to fight climate change.[35]

Consequently, tailored financing models and structures – as well as the additional support mechanisms required – are currently being developed and evaluated in ongoing expert collaboration with the financing industry. Potential financing models and structures include but are not limited to:

– A public-private partnership as ownership model; for instance, to reduce default risk for financiers

– A mix of financing sources such as ESG (environmental, social, governance) funds

The LCET initiative has a broad perspective on interconnected and cross-sectoral value chains incorporating both upstream partners such as utilities (as outlined above) and downstream partners such as logistics providers. This overall net-zero vision potentially provides financiers with more favourable business cases to evaluate, compared to considering only the individual steps of value creation related to specific investment projects.

3.6 Beyond industry limits: required collaborations

Until now, companies have traditionally undertaken upward or downward intersectoral integration to, for example, increase value capture or reduce costs; such merger and acquisition (M&A) activities were usually driven by the potential benefits for the acting parties. However, considering the net-zero challenge faced by the chemical industry to mitigate and counter climate change, new collaborations and interactions among companies within but also beyond their own sectors will be necessary to increase the possibilities of beneficial outcomes and enable action.

To provide the amounts of renewable and carbon-neutral energy required to electrify many processes that have been established using fossil carbon resources for fuel, the major utility and energy organizations must collaborate with the chemical industry to guarantee a reliable supply of energy. Potential collaborative development of, for instance, new wind parks or solar farms should be a focus for all stakeholders. Furthermore, to create a beneficial system for olefin production using the optimal mix of naphtha, biomass and plastic waste as feedstock, relevant collaborations must be set up to level the playing field for participating stakeholders, justly distributing risks and benefits. Potential collaboration agreements could entail, for example:

– Pricing agreements and revenue-sharing as far as regulations allow

– Guaranteed purchase volumes for plastic waste streams

– Shared renewable and carbon-neutral energy or green hydrogen projects among multiple companies

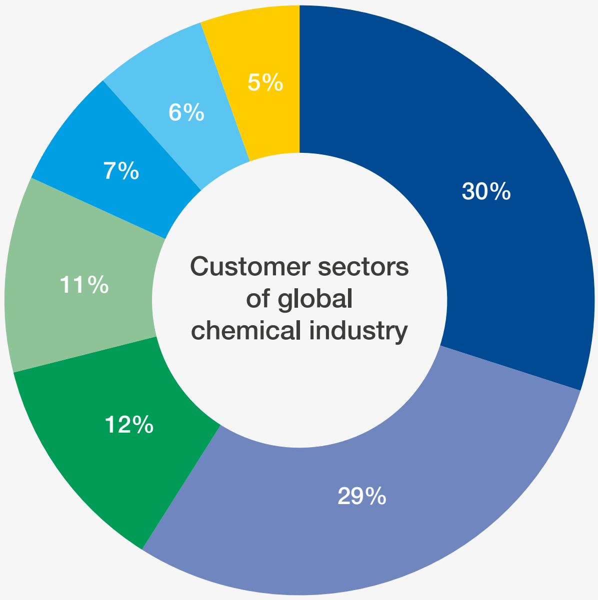
A recent example in this space is the collaboration of Neste, Mitsui Chemicals and Toyota Tsusho, leading an industrial-scale partial replacement of fossil cracker feedstock by 100% biobased hydrocarbons.[36]

Cross-sectoral collaborations in the chemical industry and its value chain are necessary to propel the net-zero vision, reduce individual risks and distribute benefits justly. Construction, fast-moving consumer goods (FMCG) and electronics appear to be predestined collaboration partners, given their tight connection to the chemical sector and their GHG emissions. Recent announcements include, for instance, that companies from the FMCG and chemical sectors (Unilever, Crown Paints and others) will collaborate to develop more sustainable polymers, which hitherto have been fossil-based.[37] This builds on the strengths of the chemical sector as an enabler for a sustainable economy. An example of this is the collaboration between Royal DSM and the agricultural sector to develop a feed additive that, when given to cows and other cattle ruminants such as sheep or goats, reduces enteric methane emissions by 30%.[38] This GHG emissions reduction affects the agricultural sector rather than the chemical sector, but it is still a major contribution to the net-zero vision. And the strong demand for plant-based cultivated meat as sustainable alternatives to products from animal husbandry, ultimately reducing GHG emissions from feed production and sector processes, drives the continued rise of companies such as, for instance, Upside Foods, which strongly rely on chemical innovation and products to sustain their business.[39]

3.7 New markets for green products: the pull effect

Since, as outlined above, deploying LCETs for chemical commodity production will potentially reduce the market competitiveness of the product portfolio, the success of the sector transformation towards net-zero will partially depend on markets accepting price premiums for green products. For example, the price of grey methanol in the market is currently €383/t;[40] green methanol costs are estimated to be between €500/t and €1,400/t, strongly dependent on the price of green hydrogen and, ultimately, renewable electricity. Importantly, the chemical industry is the largest group buyer of its own goods, with a share of 30% (Figure 8).[41] As mentioned above, adequate regulation and policy can push deployment of LCETs and reduce sector emissions, starting at the beginning of value chains; however, efficiently connecting business incentives to deployment of LCETs by creating attractive markets for green products can generate a significant pull effect from the end of value chains. Therefore, public and private procurement initiatives will play important roles in creating attractive markets. For example, in the public domain the legislature could enact laws demanding minimum percentages of green products in public projects or consumption, such as when constructing any kind of public building or using office consumables in administrative offices respectively. In the private domain, retailers, for example, could form interest groups requiring green packaging for their products while effectively reducing conventional packaging in their stores.

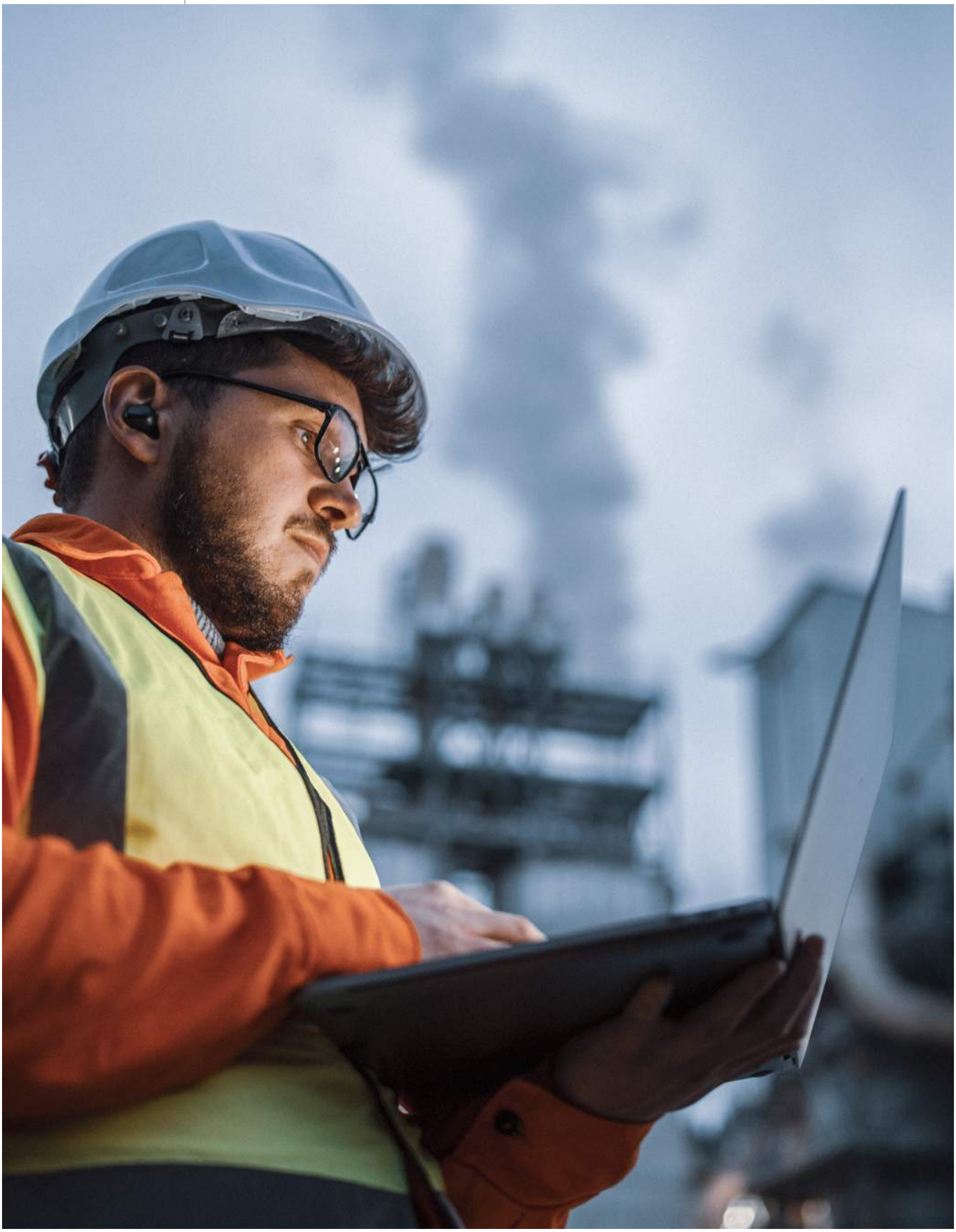
FIGURE 8 **Share of customer sectors of global chemical industry, including chemical manufacturers (chemicals)**



- Chemicals
- Other*
- Rubber and plastics products
- Health and social work
- Agriculture, forestry and fishing
- Services
- Mining, utilities and metals (MU&M)**

* Other includes: textiles, leather and footwear; construction; electronics; pulp and paper; R&D and other business activities; other non-metallic mineral products; electrical machinery and apparatus; beverages and tobacco; coke, refined petroleum and nuclear fuel; other manufacturing; manufacturing necessities, recycling; motor vehicles, trailers and semi-trailers; wholesale and retail trade, repairs; machinery and equipment
** MU&M includes: mining, utilities and metals/fabricated metal products/basic metals

4 Outlook



4.1 Case studies: first established collaborations

Tangible collaborations in the chemical sector, including among members of the LCET initiative, are outlined in the following examples:

Cracker electrification

In the vision of Net-Zero 2050, several collaborations have been launched on electrifying the steam cracking process. This clearly demonstrates that the chemical industry is aware of the need for and the benefit from collaborations on LCET projects.

- BASF, SABIC and Linde have launched a collaboration to pilot the electrification of a steam cracker furnace at BASF's Ludwigshafen site in Germany.[42] Potentially 90% of GHG emissions of the related petrochemical process can be reduced with the development and implementation of this specific LCET based on renewable or carbon-neutral electricity as an alternative to conventional heating by fossil fuel combustion.
- Other collaborations on the electrification of the cracker have been forged; for example, the "Cracker of the Future"[43] and a collaboration between Dow, Shell and the Netherlands Organisation for Applied Scientific Research (TNO) and the Institute for Sustainable Process Technology (ISPT).[44]

Plastic waste processing

SABIC and Plastic Energy have started construction of a commercial unit in the Netherlands that will produce certified recycled polymers made from mixed and used plastics. The project will be realized as part of a 50:50 joint venture called SPEAR (SABIC Plastic Energy Advanced Recycling) and will be implemented with an energy subsidy from The Netherlands Ministry of Economic Affairs.[45]

SIBUR will collaborate with waste operators and regional companies, which will provide post-consumer recycled polyethylene terephthalate (PET) that SIBUR will use to launch "green" PET-granule production in 2022 and thus offer sustainable solutions for packaging.

Mitsubishi Chemical Corporation (MCC) together with ENEOS has decided to construct a commercial chemical recycling plant in Japan. This joint effort will initially focus on using post-industrial plastics. In procuring the feedstock, MCC has entered into a capital and business alliance with Refinverse, a leading waste management and plastics recycling company.

Biomass utilization

Clariant, together with its partner GETEC, announced the completion of the first full-scale commercial sunliquid® plant in Podari, Romania. Sunliquid,® an innovative technology by Clariant, uses agricultural residues, such as straw, as feedstock to be converted into second-generation cellulosic ethanol. Bioethanol offers various opportunities in terms of fuel blending, biobased chemicals (e.g. for bioethylene/polyethylene, bioethylene oxide/ethylene glycol) and sustainable aviation fuel.

Within the World Economic Forum LCET initiative, this provides new project and partner opportunities for biomass-derived low carbon product solutions.

4.2 Call for collaboration

Considering the intrinsic complexity of the chemical industry and its high asset intensity, uncertainties in the regulatory environment pose severe impediments for future investment decisions. This situation is aggravated when it comes to novel technologies at an early stage of the technology life cycle with a low degree of diffusion. Typically, LCETs fall into this category. Hence, cross-sector collaborations will be necessary to mitigate the associated risks by increasing planning reliability with the industrial network and ultimately building bridges to cross the "valley of death" for project financing. Current project collaborations, as outlined above, usually evolve around single assets, clearly lacking the global scale that would be required to successfully take on the net-zero challenge.

To accelerate progress and propel the net-zero vision, new collaborations need to be formed beyond the obvious partners, common business models and traditional value chains, and with significantly bolder goals. To this extent the LCET initiative is aiming to define collaboration models involving multiple stakeholders across a value chain, for which a variety of technologies could be deployed in different regions. This will increase the financial attractiveness and pursue global scalability. Consequently, the LCET will move towards pilot projects once expert subgroups agree on the technology solutions and the necessary connections with relevant stakeholders outside industry limits are forged. Steps will be taken with the global picture in mind to enable efficient upscaling of pilot project findings.

Potential collaboration opportunities could include but are not limited to:

– Cross-sectoral collaborations between chemicals and utilities to increase certainty regarding renewable and carbon-neutral energy

– Cross-sectoral collaborations and interactions between chemicals and the public to strengthen engagement and grow markets for greener products such as greener cement for public procurement or greener materials in all public transport

– Cross-sectoral collaboration in waste management and biomass generation to develop and scale pathways for circular and renewable feedstock

– Other more unusual collaborations such as chemicals and FMCG to establish direct recycling routes for plastics or even biomass

– Cross-sectoral collaborations between chemicals and finance to develop risk-sharing models that enable financing of high-CAPEX/ high-risk projects

– Intrasectoral collaborations in chemicals to generate a common financing vehicle sourcing from combinations of public and private funds for development and implementation

Ideally, such collaborations would be facilitated by means of public-private partnerships to ensure better-informed investment decisions that are "investor-ready". To reach climate goals, action needs to be taken now. The chemical industry is already taking action: associations and individual companies are making commitments to energy efficiency and global climate protection, ultimately targeting net-zero CO_2 emissions.

Contributors

Project Team

World Economic Forum

Fernando Gomez, Head of Industry Communities, Energy, Materials and Infrastructure Platform

Joanna Kolomanska-van Iperen, Platform Curator, Energy, Materials and Infrastructure Platform

Jörgen Sandström, Head of Energy, Materials and Infrastructure Program – Industrial Transformation

Accenture (Knowledge Partner)

Johannes Huber, Strategy Analyst, Chemicals & Natural Resources

Charbel Moussa, Director, Chemicals, Natural Resources & Energy

Catharina Müller-Buschbaum, Managing Director, Industry X

Daniel Sachweh, Analyst, Chemicals & Natural Resources

Felix Schröder, Strategy Consultant, Chemicals & Natural Resources

Holger Vegelan, Managing Director, Chemicals & Natural Resources

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World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland

Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org