International Energy Agency
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The Future of Petrochemicals

Towards more sustainable plastics and fertilisers

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INTERNATIONAL ENERGY AGENCY

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Foreword

We live in a world dependent on petrochemicals. From the cars we drive to the food on our plates, the products and materials we derive from petrochemicals are fundamental to many aspects of modern society. Plastics and fertilisers, the two largest groups of chemical sector products, are indispensable in our everyday lives. Plastics is the fastest-growing group of bulk materials in the world, and synthetic nitrogen fertilisers underpin nearly half the world's food production.

The manufacture of petrochemicals and their derivatives absorbs an increasing proportion of the world's oil and gas – approximately 14% (13 million barrels per day [mb/d]) for oil and 8% (300 billion cubic metres [bcm]) for gas. Because much of this energy enters the petrochemicals sector as feedstock and does not undergo combustion, the sector achieves the seemingly contradictory feat of being both the largest industrial energy consumer and yet only the third-largest industrial carbon dioxide (CO_2) emitter. Even so, with the market for petrochemical products set to expand further as the global economy develops, the future of the petrochemicals industry is of major significance for both global energy security and the environment.

This International Energy Agency (IEA) analysis explains the circumstances of the petrochemicals industry today and projects how it might develop to 2050. Using the IEA Reference Technology Scenario, the projections are first made based on established trends. Then, a path to a sustainable future is drawn for the industry, one consistent with the UN Sustainable Development Goals – the Clean Technology Scenario.

The trajectory of the chemical sector in the Reference Technology Scenario implies a rate of growth in oil demand that is higher than that of any other sector. Of the nearly 10 mb/d growth in total oil demand projected for 2030, the chemical sector is on course to account for more than a third. The sector also plays a significant role in the total growth in gas demand, where it accounts for 7% of the roughly 850 bcm global increase by 2030.

Because of this robust growth in fossil fuel consumption, direct CO_2 emissions from the sector increase by around 20% by 2030 and 30% by 2050. Similar deleterious rises occur in air pollutants and water demand. Perhaps most alarmingly, without drastic improvements in the management of waste stemming from the sector's key material output – plastics – the quantity of plastic waste, including that entering the oceans, continues to rise from today's already unacceptable levels.

An alternative future for petrochemicals – one in which plastics and fertilisers, in particular, are produced more sustainably – is entirely feasible. In this pathway, traced in the Clean Technology Scenario, the petrochemical industry makes the necessary contributions to realising the UN goals. Our analysis concludes by identifying two priority areas for those committed to carrying out this vital transition, along with specific actions to be taken in each.

This is the third book in an IEA series concentrating on what I refer to as "blind spots" in global energy: major areas of energy demand that deserve a greater level of attention from policy makers. Previous studies in the series have focused on energy use in air-conditioning and trucks. There will be more.

Dr. Fatih Birol

Executive Director

International Energy Agency

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Executive summary

Petrochemical products are everywhere …

Petrochemicals, which turn oil and gas into all sorts of daily products – such as plastics, fertilisers, packaging, clothing, digital devices, medical equipment, detergents or tyres – are integral to modern societies. In addition to products critical to our daily lives, petrochemicals are also found in many parts of the modern energy system, including solar panels, wind turbine blades, batteries, thermal insulation for buildings, and electric vehicle parts.

Already a major component of the global energy system, the importance of petrochemicals is growing even more. Demand for plastics – the most familiar of petrochemical products – has outpaced all other bulk materials (such as steel, aluminium or cement), nearly doubling since the start of the millennium. The United States, Europe, and other advanced economies currently use up to 20 times as much plastic and up to 10 times as much fertiliser as India, Indonesia, and other developing economies on a per capita basis, underscoring the huge potential for growth worldwide.

Feedstocks fly under the radar. Chemicals produced from oil and gas make up around 90% of all raw materials, which are known as feedstocks; the rest comes from coal and biomass. About half of the petrochemical sector's energy consumption consists of fuels used as raw materials to provide the molecules to physically construct products.

… and have become the fastest-growing source of oil consumption

The growing role of petrochemicals is one of the key "blind spots" in the global energy debate. The diversity and complexity of this sector means that petrochemicals receive less attention than other sectors, despite their rising importance.

Petrochemicals are rapidly becoming the largest driver of global oil consumption. They are set to account for more than a third of the growth in oil demand to 2030, and nearly half to 2050,[1] ahead of trucks, aviation and shipping. At the same time, currently dominant sources of oil demand, especially passenger vehicles, diminish in importance thanks to a combination of better fuel economy, rising public transport, alternative fuels, and electrification. Petrochemicals are also poised to consume an additional 56 billion cubic metres (bcm) of natural gas by 2030, equivalent to about half of Canada's total gas consumption today.

Countries, including the People's Republic of China[2] and the United States, will see the largest near-term capacity additions; longer-term growth is led by Asia and the Middle East. The United States is expected to increase its global market share for ethylene (steam cracking) to 22% by 2025, up from 20% in 2017. Along with the Middle East, the United States has a feedstock advantage in its access to low-cost ethane owing to its abundant natural gas supplies. This advantage allows both regions to gain the lion's share of ethane-based chemical exports in the short and medium term. Coal-based methanol-to-olefins capacity in China nearly doubles between 2017 and 2025, providing the material inputs for its large domestic manufacturing base. In the longer run, Asia and the Middle East both increase their market share of high-value chemical production by 10 percentage points, while the share coming from Europe and the United States decreases. By 2050, India, Southeast Asia and the Middle East together account for about 30% of global ammonia production.

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[1] Please visit the International Energy Agency (IEA) website for more information on the modelling underlying this publication.

[2] Hereafter, "China".

The combination of a growing global economy, rising population, and technological development will translate into an increasing demand for petrochemical products. Although substantial increases in recycling and efforts to curb single-use plastics take place, especially led by Europe, Japan and Korea, these efforts will be far outweighed by the sharp increase in developing economies of plastic consumption (as well as its disposal). The difficulty in finding alternatives is another factor underpinning the robust overall demand growth for petrochemical products.

An evolving landscape for both petrochemical and oil and gas industries

Increasing global competition in the industry is driven by new supply dynamics for chemical feedstocks. After two decades of stagnation and decline, the United States has returned to prominence as a low-cost region for chemical production thanks to the shale gas revolution. Today, the United States is home to around 40% of the global capacity to produce ethane-based petrochemicals. Led by Saudi Arabia and Iran, the Middle East remains the low-cost champion for key petrochemicals, with a host of new projects announced across the region. China and Europe each account for around a quarter of the global capacity for naphtha-based, high-value chemicals, but they have only very small shares of capacity based on lighter feedstocks because of limited availability. China's burgeoning coal-based chemical industry, once a speculative proposition, now embodies steady technological improvements. India is poised to grow strongly from its current level of only 4% of global capacity to satisfy increasing domestic demand.

Oil companies are increasingly pursuing integration along the petrochemical value chain. Against a backdrop of slower gasoline demand growth, robust growth prospects for chemical products, and attractive margins, oil companies are further strengthening their links with petrochemical markets. New, direct crude-oil-to-chemicals process routes may also come into play, offering alternatives to traditional refining/petrochemical operations although the technology remains challenging for now. For example, Saudi Aramco and SABIC have recently announced a large crude-to-chemicals project of 0.4 mb/d, five times the size of the only existing facility in Singapore.

The production, use and disposal of chemicals take an environmental toll …

Petrochemicals face a number of climate, air quality, and water pollution challenges. Petrochemical products provide substantial benefits to society, including a growing number of applications in various cutting-edge, clean technologies critical to a sustainable energy system. However, the production, use, and disposal of these products pose a variety of sustainability challenges that need to be addressed.

Even though the chemical sector consumes roughly as much energy as the steel and cement sectors combined, it emits less CO_2 than either sector. Still, this amounts to around 1.5 $GtCO_2$, which is 18% of all industrial-sector CO_2 emissions, or 5% of total combustion-related CO_2 emissions. This is in part because the chemical industry consumes more oil and gas than other heavy industries, which tend to rely more on coal. Another contributing factor is that the carbon contained in chemical feedstocks is mostly locked into final products (such as plastics), and it is released only when the products are burned or decompose.

… but solutions are achievable and cost-effective

In our Clean Technology Scenario (CTS), which provides an ambitious but achievable pathway for the chemical sector, environmental impacts decline across the board. In the CTS, air pollutants from primary chemical production decline by almost 90% by 2050; and water demand is nearly 30% lower than in the base scenario. The CTS also emphasises waste management improvements to rapidly increase recycling, thereby laying the groundwork to more than halve cumulative, ocean-bound, plastic waste by 2050, compared to the base scenario – a major step to curb the 10 million tonnes of plastic waste that leak into the world's oceans every year, an environmental problem that is garnering much attention across the globe.

By 2050, cumulative CO_2 emission savings from increased plastic recycling and reuse are equivalent to about half the annual emissions from the chemical sector today. In the CTS, the global average collection rate of plastic waste increases nearly three-fold by 2050. This results in increased production of recycled plastics and a cumulative saving of around 5% in high-value chemical demand, compared to current trends. This outcome poses a significant technical challenge, requiring mature economies to raise average collection rates to the maximum practical level and emerging economies to match the best rates achieved today.

The sector's clean transition is led by carbon capture, utilisation and storage (CCUS), catalytic processes, and a shift from coal to natural gas. Some of the most cost-effective opportunities for CCUS can be found in the chemical sector, which explains its leading role among scalable options for reducing emissions. Catalytic alternatives to traditional process routes can provide more than 15% of energy savings per unit of production. Shifts from coal to natural gas for both ammonia and methanol production, mainly in China, result in decreases in both process emissions and energy intensity. Despite falling investment costs, processes based on electricity and biomass struggle to compete on cost in most regions, due to high prices in a world where these low-carbon energy carriers are in high demand.

The surge in the share of lighter oil products required for petrochemical feedstocks may pose challenges for refining in the CTS. Oil demand related to plastic consumption overtakes that for road passenger transport by 2050. This has important implications for refiners whose processes are currently set up to produce both heavy and light products. The increase in light tight oil (LTO) production in the United States is expected to help address the challenge because LTO is an easier starting point for producing lighter oil products. However, the long-term sustainability of this contribution will also depend on how the resource base, technology, and market conditions of LTO evolve.

Part A: Petrochemicals today

Petrochemicals surround us, yet they constitute one of the key "blind spots" of the energy system. Even among energy professionals, the chemical and petrochemical sector[3] is inadequately understood, which often leads to underestimating it in energy terms. With the sector accounting for 14% (13 million barrels per day) and 8% (300 billion cubic metres) of the total primary demand for oil and natural gas respectively, this deficit of attention deserves redress.

A unique aspect of petrochemical production that helps to account for the lack of attention is the consumption of energy as "feedstock": about half the sector's energy input is not combusted but is consumed as raw material. Understanding the concept of using energy for feedstock is key to understanding petrochemicals.

Part A of this publication, which concentrates on the situation as it stands today,[4] aims to correct the imbalance while exploring the role the sector plays in society (Chapter 1), the energy system (Chapter 2), and the environment (Chapter 3). Future prospects are examined in Part B.

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[3] References to the "chemical and petrochemical sector" and "chemical sector" are used interchangeably, with the latter used where possible for brevity. Both refer to the International Energy Agency's sectoral boundary, which encompasses the sub-sectors included among the United Nations Statistics Division International Standard Industrial Classification Revision 4 Divisions 20 and 21. See also Box 1.1.

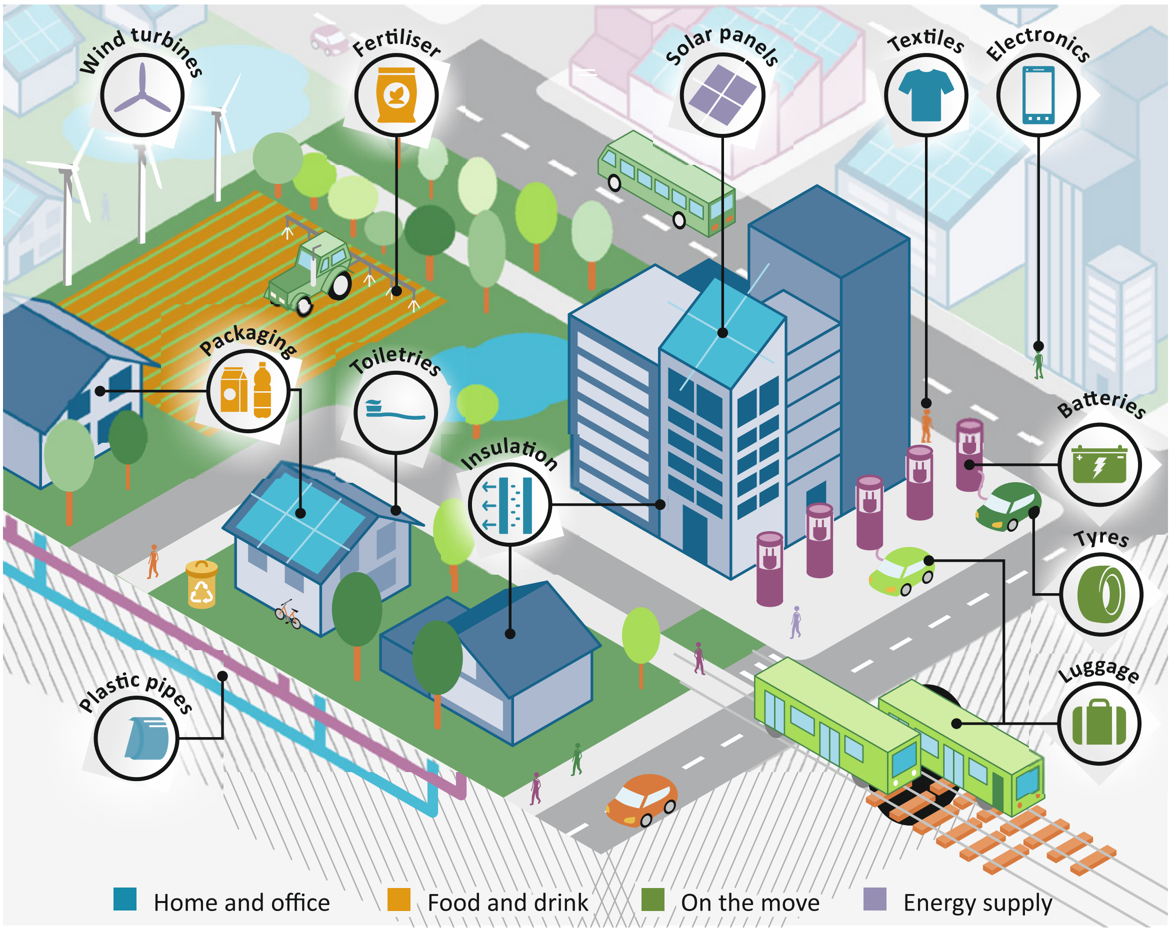
[4] *Today* refers to 2017, which is the estimated base year "2017e" in the modelling. Results are provided for both 2017e and 2015 in the online annex available on the IEA website.

Chapter 1. Chemicals and society

Chemical products are ubiquitous in modern society. It is unusual to find oneself in a building or vehicle unadorned with plastics, rubber or synthetic textiles, and these materials are intimately engrained in our daily routines: toothbrushes, carrier bags, food packaging, mobile phones, computers, carpets, clothes, furniture… and these are just the items we see every day.

Where they are not the main constituent, chemical products often enhance other bulk materials, such as metal and timber, for example by offering protective (e.g. varnish) and decorative (e.g. paint) coatings. Combinations of plastics in electronic equipment are increasingly displacing paper as the medium for conveying information in a digitized world. Modern agricultural systems would struggle to maintain the current level of output without fertilisers and other agrochemicals. The pharmaceutical sector as we know it would not exist. It is no understatement to say we live in a world dependent on chemicals.

Figure 1.1 • The various roles of chemical products in modern society



Key message • Chemical products underpin many aspects of our everyday lives. We live in a world dependent on chemicals.

A world dependent on chemicals

Underlying the demand for chemical products is the demand for the services they provide, such as sustenance, mobility and thermal comfort. These services encompass both universal human needs and the desire of the global population for improved living standards. To take sustenance as an example, fertiliser is used to increase the uptake by plants of vital nutrients, thereby increasing agricultural yields and crop reliability. Plastics are used throughout the global food system in transportation, preservation and consumption. Plastic packaging, much of which is used for food and, increasingly, beverages, is the largest component of single end-use plastic demand, accounting for approximately 36% globally.

As people live longer and enjoy increasing standards of living, they are likely to consume more of the products mentioned above. Furthermore, facilitating a more sustainable future relies increasingly on outputs from the chemical sector. For example, reducing the overall weight of vehicles, a strategy pursued to reduce fuel consumption, is supported through the integration of plastic-based materials. Modern insulation materials that reduce the demand for heating and cooling in buildings also have a strong chemical component.

As with most dependencies, there is an accompanying burden. Chemical products take an environmental toll, both when produced and after use, by ending up where they ought not to. The chemical sector's final energy consumption, which is the highest of any industrial sector, is mainly composed of fossil fuels. In consuming this energy, the sector releases carbon dioxide (CO_2) emissions and air pollutants and contributes to the demand for water for energy.

When deposited in waterways, plastics, fertilisers and other products cause damage to marine ecosystems, each in their own way. When fertilisers are applied to fields in excess quantities – or just before a deluge – they can leach, resulting in high nutrient concentrations in nearby rivers and estuaries. This can result in eutrophication, whereby a surge in algae growth deprives all other life of oxygen, leading to suffocation. With plastics, the pathway is more direct, but no less devastating to marine life. Plastics find their way into the oceans when they are inadequately disposed of, transported and processed. They can then be broken down into particles and be ingested by fish.

The rise of the chemical sector

Society's growing dependence on chemicals has been reflected by a steady period of growth in the output of the chemical and petrochemical sector. The production of plastics – one of the sector's key material outputs – has increased globally by more than tenfold since 1970, faster than the rate of growth of any other group of bulk materials and almost 60% faster than growth of gross domestic product (GDP). Ammonia – a key primary chemical and the chemical base of all nitrogen fertilisers – has seen production increases more in line with those of other energy-intensive sectors, which have each undergone between a three- and sevenfold increase during this period.

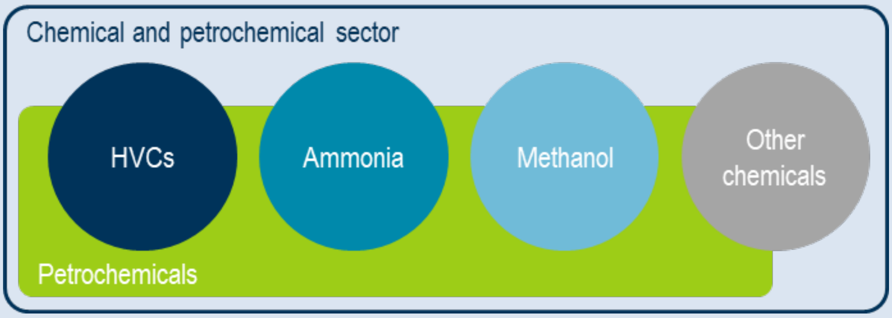
Since the millennium, bulk materials such as cement, crude steel, and primary aluminium have matched and, in some cases, largely exceeded GDP growth rates, particularly to meet new infrastructure needs in rapidly developing economies such as in the People's Republic of China (hereafter, "China"). By contrast, there are initial signs of a decoupling between ammonia production and GDP growth, partly because of increasing efficiency in the use of fertilisers. Overall, this strong trajectory of activity growth reflects the relatively late emergence of petrochemicals as an industrial sector and the continuing advance of its associated technology.

Some key developments in the chemical sector pre-date the period for which activity data are available. For example, some important industrial chemicals can be traced back to the 18th century (notably sulphuric acid); but many of those most relevant to today's consumers were not invented or produced at sufficient scale for more than another century. Ammonia was first produced with a practical level of thermodynamic efficiency after the invention of the Haber-Bosch process in 1909, and nitrogen fertiliser, production of which accounts for 80% of ammonia use today, is still synthesised via the Haber-Bosch process.

Box 1.1 • Chemicals and petrochemicals

Modern petrochemistry has its origins in the oil and gas industry. *Petrochemicals* are a subset of industrial chemicals, hence the full name of the industrial sector that produces them: the "chemical and petrochemical sector". In the context of this report, petrochemicals are defined as chemicals derived from petroleum (oil) products, such as ethane and naphtha, or from natural gas. Using this definition, petrochemicals account for 90% of total feedstock demand in chemical production today. Chemicals such as light olefins (ethylene and propylene) and aromatics (benzene, toluene and mixed xylenes [BTX]), typically called "high-value chemicals" (HVCs), are often co-produced in a process such as steam cracking. Demand for HVCs tends to be driven by the consumption of plastics, synthetic fibres and rubber. Ammonia is an example of a chemical that, though it can be produced from oil, is more commonly produced today from natural gas or coal. Methanol, an important industrial alcohol, is similar to ammonia in this regard. The production of "primary chemicals" (the collective term for HVCs, ammonia, and methanol together), accounts for around -two-thirds of total energy demand in the chemical sector. They are the main focus of this study.

Figure 1.2 • Key chemicals and chemical groups



Notes: *Other chemicals* refers to those not included within the core scope of this modelling. The partial overlap with the petrochemicals boundary indicates the capacity to produce each of these chemicals both from oil and gas, and from other non-"petro" sources.

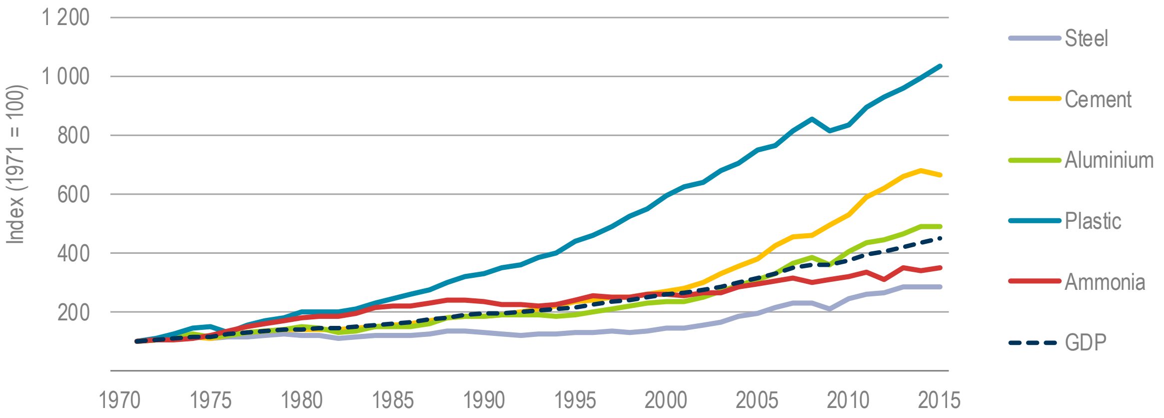
The petrochemicals listed above can all be technically produced today from a variety of different products and substances, including forms of renewable energy such as biomass, water and CO_2 or other carbon sources. This could potentially lead to the "petro" prefix becoming redundant. However, the vast majority of industrial chemicals use oil, natural gas, or coal both as their input materials and as the sources of energy for fuelling the production processes. Not only are these commodities cheap to procure and process relative to the alternatives, but some atomic building blocks required for chemical products such as plastics and fertilisers (primarily carbon and hydrogen) are present in convenient quantities and arrangements.

The first plastic is thought to have been *Parkesine*, invented by Alexander Parkes in 1856; but the explosion of plastics into mainstream applications did not take place until the second half of the 20th century. A key precursor process to large-scale polymer production – steam cracking – was invented in the early 1900s and proved a critical step on the way to achieving large-scale production of what were to be the most transformational set of materials since the invention of steel alloys.

What drives chemical consumption?

It is challenging today to imagine a world without plastics and fertilisers. An example of multiple chemical products playing a fundamental role in society is found in the supply chains that underpin modern food production. Fertilisers and agrochemicals are used extensively to promote crop growth and provide protection against harmful organisms and pathogens. Plastic packaging (the single largest source of plastic demand) plays an instrumental role in delivering food from the pasture to the plate. This and a plethora of other applications result in widespread and persistent demand for these products across most major regions.

Figure 1.3 • Production growth for selected bulk materials and GDP



Notes: Outputs of different industrial sectors are displayed on an indexed basis referred to 1971 levels. *Aluminium* refers to primary aluminium production only. *Steel* refers to crude steel production. *Plastics* includes a subset of the main thermoplastic resins.

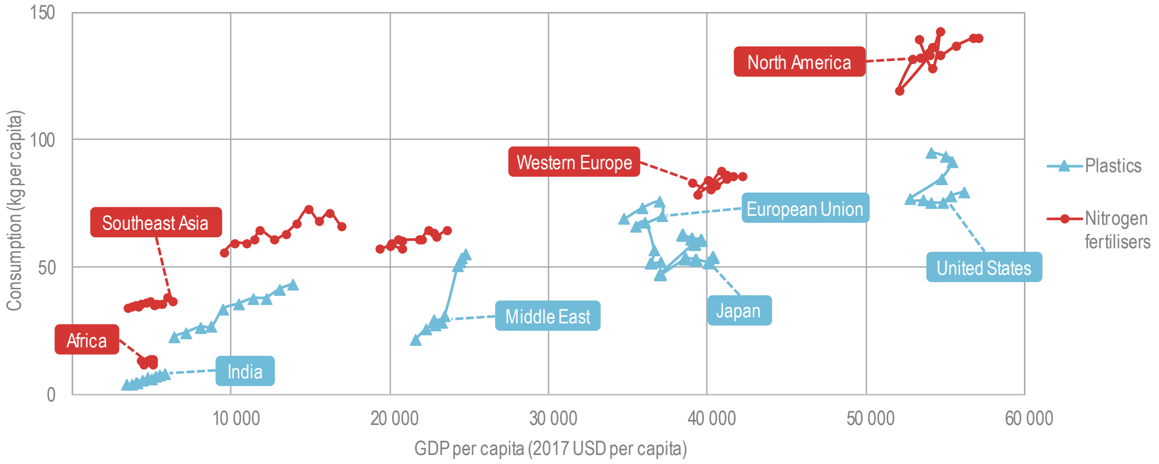
Sources: Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use, and fate of all plastics ever made", https://doi.org/10.1126/sciadv.1700782; Worldsteel (2017), *Steel Statistical Yearbook 2017*, www.worldsteel.org/en/dam/jcr:3e275c73-6f11-4e7f-a5d8-23d9bc5c508f/Steel+Statistical+Yearbook+2017.pdf; IMF (2018), *World Economic Outlook Database*, www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx; USGS (2018a), *2018 Minerals Yearbook: Aluminium*, https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2015-alumi.pdf; USGS (2018b), *2018 Minerals Yearbook: Cement*, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2014-cemen.pdf; USGS (2018c), *2018 Minerals Yearbook: Nitrogen*, https://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2015-nitro.pdf. Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", https://doi.org/10.1021/acs.est.7b04573.

Key message • Demand for plastics has grown faster than that for any other group of bulk materials, whereas demand for ammonia has grown more steadily and even displays some decoupling from economic growth after 2000.

Regional consumption patterns for several important plastics and fertilisers show that as wealth (measured in GDP per capita) increases, so does the consumption of these products. However, in regions with high income per capita, demand saturation appears to emerge for some products, especially fertilisers. In high-income countries such as Japan, the United States, and parts of Western Europe, annual demand for key nitrogen fertilisers has stabilised at around 85-135 kilogrammes per capita (kg/capita), with limited growth per capita having occurred over the last 15-20 years. In lower-income and rapidly developing regions such as India, China and Africa, demand for these products is still on the increase (1-2% annual growth rates are not uncommon), and current consumption ranges from as low as 12 kg/capita to around 60 kg/capita.

Plastic use shows fewer clear signs of saturation, and the range of consumption levels is even wider than that of fertilisers, although both the quality and quantity of data available on plastics consumption tend to be lower than for other bulk materials. Determining consumption patterns is further complicated by the trade in plastic goods that takes place after manufacturing. From the limited data available, it appears that developing regions currently consume as little as 4 kg/capita of key plastic resins, but growth rates are high, sometimes entering double-digit levels. In higher-income countries, consumption levels generally range from 55-80 kg/capita, though most mature economies appear to be exhibiting some signs of saturation around the 60 kg/capita level.

Figure 1.4 • Per capita consumption of plastics and nitrogen fertilisers



Notes: *Plastics* includes the main thermoplastic resins and excludes all thermosets and synthetic fibre. *Nitrogen fertilisers* includes all major ammonia-based fertiliser compounds. The quantities shown reflect the apparent consumption (production less exports plus imports) by the next tier in the manufacturing chain following primary chemical production (e.g. plastic converters for plastics). USD = United States dollars.

Sources: METI (2016), *Future Supply and Demand Trend of Petrochemical Products Worldwide*, Tokyo, www.meti.go.jp/policy/mono_info_service/mono/chemistry/sekkajyukyuudoukou201506.html; IFA (2018), *International Fertilizers Association Database*, http://ifadata.fertilizer.org/ucSearch.aspx.

Key message • High-income countries use up to 10 times as much fertiliser, and up to 20 times as much plastic, per capita as lower-income countries, indicating significant global growth potential.

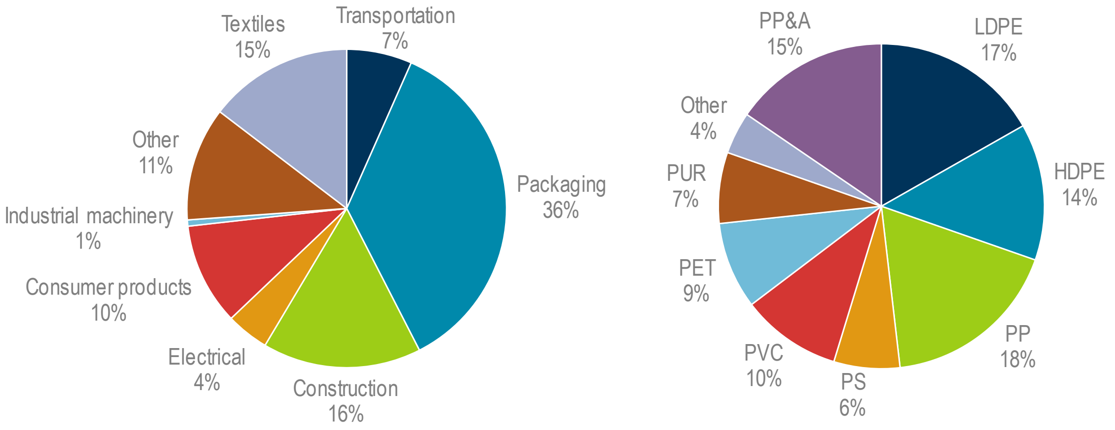
Plastic has a broad set of applications, familiar to many consumers. From carrier bags to cars, plastic is everywhere, making it one of the most versatile materials yet invented. It is, in fact, a group of materials varying in composition. Different types of plastics, or “resins”, are used for different purposes, depending on the specification required in the end-use application. Individual types of plastic are usually distinguished by using their Resin Identification Code (see Box 1.2) or by referring to the name of the dominant polymer in their composition.

Polymers are chains of individual molecules (called monomers): ethylene is the monomer used to make polyethylene. Some polymers contain more than one monomer, such as acrylonitrile butadiene styrene, which is a polymer of the monomers acrylonitrile, butadiene and styrene. Plastics can also be referred to by their trade name: famous examples include Perspex, the trade name for a resin composed of polymethyl methacrylate, and Bakelite, the mercifully shorter name given to the resin of phenol and formaldehyde: polyoxybenzyl methylene glycol anhydride.

Packaging, the largest end-use segment by some margin, accounts for 36% of global plastic demand. This segment includes both consumer packaging, such as drinks bottles made of polyethylene terephthalate (PET), and the packaging used for business-to-business transactions and in industry at large. Synthetic textiles, which together constitute the second-largest end-use segment, are generally considered to be a distinct sub-sector and, thus, are discussed separately below. The construction industry is the second most important non-textile market, accounting for 16% of global consumption, an important plastic for the construction industry being polyvinyl chloride (PVC), which is used for window and door frames, and underground pipes, due to its stiffness and durability.

Consumer products, including toys and utensils, are the next-largest demand segment (10%), with a fairly even utilisation of various resins. Polyethylene, both high-density (HDPE) and low-density (LDPE), polypropylene (PP) and polystyrene (PS) are used evenly across the remaining end-use segments. Polyurethanes are a special case, being reserved for specialty applications, as their properties can be highly "tuned" to suit various purposes, one of which, important from an energy standpoint, is thermal insulation.

Figure 1.5 • Estimated consumption of plastic by end-use sector (left) and resin (right)



Notes: Resins may exclude additives. Estimates based on data are for Europe, the United States, China, and India for 2002-14. Polyester, polyamide and acrylic (PP&A) fibres are assigned exclusively to the textile sector, and the charts excludes synthetic fibres. LDPE = low-density polyethylene; PUR = polyurethane; LDPE includes linear LDPE.

Source: Adapted from Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use, and fate of all plastics ever made", https://doi.org/10.1126/sciadv.1700782.

Key message • Packaging is the leading end-use of plastic consumption globally. The most important types of plastic by volume are polyethylene and polypropylene.

Synthetic textile products are made from fibre that is polymerised from many of the same resins used in the other plastic end-use segments mentioned above (with PET and PP being the most prevalent). Key synthetic fibre products include rope, carpet and clothing, alongside a multitude of specialist applications: Kevlar*,* a type of lightweight and bullet-proof body armour, is made from a synthetic thermoplastic fibre. Polyester fibre (or PET fibre), by far the largest-volume synthetic fibre, recently overtook cotton as the largest-volume fibre produced globally. Today, polyester eclipses demand for all other fibre combined, including natural fibres such as wool and cotton, accounting for about 60% of total global fibre production (Mills, 2011).

Box 1.2 • Key plastics and their typical applications

There are two broad categories of plastics: thermoplastics and thermosets. Thermoplastics are those that constitute the familiar plastic objects around us in everyday life; thermosets tend to be more specialist materials and resins. Whereas thermosets cannot be effectively recycled (except by grinding them down and using them as filler material), most thermoplastics can. Resin Identification Codes 01-07, used to distinguish the main thermoplastics, are often printed on the bottom of plastic packaging and other goods in order to assist their sorting prior to recycling.

Figure 1.6 • Key thermoplastics

01 – PET. PET is mainly used to make polyester fibre, but its other key end-use is food and beverage packaging. Its key properties are its high crystallinity and strength.

02 – HDPE. HDPE is one of the most versatile plastics, used in anything from shampoo bottles to hard hats. It is made entirely of ethylene and is among the most recycled plastics.

03 – PVC. PVC is a tough resin that is most frequently used in construction. PVC windows, doors and pipes are commonplace on construction sites and in buildings throughout the world.

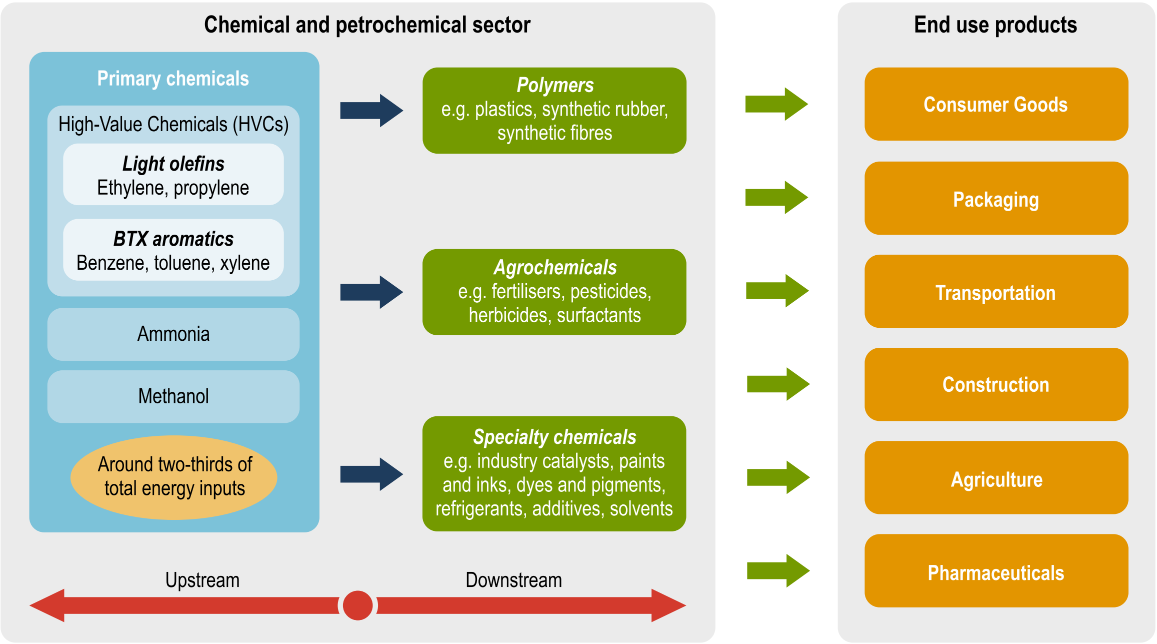
04 – LDPE. LDPE was the first polyethylene plastic to be invented and is another key plastic used for packaging. It is the key constituent of most plastic carrier bags.

05 – PP. PP is a versatile plastic with many end-uses. Because it has a higher melting point than some other key polymers, it is often used in automotive applications, where high temperatures can be encountered.

06 – PS. PS comes in three main forms: "general purpose" "high impact" and "expandable". The latter is used in packaging applications to protect goods during transport and storage.

07 – O. Other thermoplastics include polycarbonate, acrylonitrile butadiene styrene, styrene acrylonitrile, polymethyl methacrylate, polyacrylonitrile, polyvinyl acetate, and many others. They have a wide range of uses, but each is produced in much smaller volumes than 01-06 above.

Figure 1.7 • Primary chemicals in context



Key message • While most energy consumption in the chemical sector takes place upstream, a host of transformations, intermediates, and end-use sectors lie downstream from primary chemicals.

Can chemicals be used more efficiently?

Several strategies can be pursued to improve the efficiency with which chemicals are used throughout the value chain, thereby providing the same final services while consuming fewer chemicals and chemical products. Widespread deployment of such strategies can reduce overall demand for material. These approaches are often collectively referred to as "material efficiency" strategies. Although many chemicals are gases and liquids (as opposed to durable materials like plastic and steel), the same principles apply (Allwood et al., 2013; Allwood and Cullen, 2012). Examples of relevant measures are:

- **Re-using products.** For example, using a plastic bottle twice halves the amount of material demanded relative to the purchase of a new bottle. This is an especially important strategy for products with a short lifetime, as multiple tranches of savings can be achieved rapidly.
- **Recycling.** Providing secondary input materials, so consuming less virgin material and less energy. Plastic recycling is the key example in the chemical sector, but other pockets of recycling exist, such as recovery and recycling of the solvent, acetic acid.
- **Using products more intensively.** Structural materials, such as reinforced composites (e.g. for wind turbine blades), can be designed to a tighter specification, thereby reducing the amount of material required relative to thicker or over-designed components.
- **Reducing material losses along supply chains.** In plastic manufacturing, an array of moulding and extrusion processes provides an efficient way to deploy material exactly where and how it is needed, and many can recycle and utilise “in-house” scrap.
- **Increasing product lifetimes.** This reduces the rate at which products need replacing and, therefore, the cumulative material demand over a given time period. This strategy overlaps to some extent with the re-use of products.
- **Other strategies**, including material substitution and achieving significant behavioural and/or lifestyle changes so as to reduce absolute demand – consuming, moving, and using less.

In the chemical sector, plastics constitute the main group of material outputs, although many material efficiency strategies also apply to rubber, synthetic fibre, and other durable products. For chemical products that decompose, dilute or otherwise disperse during use, it is more difficult to intervene to effect material savings. Examples are applying fertiliser to managed soils or using cosmetic and hygiene products delivered as aerosols. Especially in these cases, but also for durable products, material efficiency strategies that reduce the need to replace the product are often the most effective starting point. Refilling plastic containers, repairing rubber tyres, and deploying fertilisers efficiently are all examples of strategies that limit the need for recycling.

The potential of plastic recycling to reduce the demand for primary chemicals is dependent on the amount and quality of available scrap and on the level of recycling achieved. For several bulk materials in other sectors, recycling rates[5] are already high: steel and aluminium around 80% and paper around 60%. The rate of non-fibre plastic recycling is much lower (though the data are much poorer). It is estimated that some 18% of available plastic waste (excluding synthetic fibre) is currently recycled in some form, although the rate of displacement of virgin resins is much lower since much recycling is currently “open loop” (see Box 1.3). The upside of this low recycling rate is, of course, that the potential for increasing plastic recycling is much greater than for several other materials.

Today there are two main categories of plastic recycling: mechanical and chemical recycling, with the former being much more widespread.

Mechanical, or “back to polymer”, recycling offers a simpler and generally lower cost source of secondary plastic production, in which the chemical structure of the polymers remains intact. Collected and sorted plastic waste is the feed material, which is then cleaned, cut up into chips, and re-melted ready for moulding. Some impurities often remain after cleaning, including various additives used in virgin plastics to yield certain properties. For instance, isophthalic acid is often used as an additive in PET bottles to reduce their crystallinity, thereby improving the clarity and transparency. If the PET resin in the bottle is to be recycled and used for other purposes where this characteristic is no longer required, the additive – often deeply embedded in the chemical

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[5] The recycling rate is defined here as the collection rate for recycling after initial use.

structure of the product – can become an inhibiting impurity, rather than a helpful additive. These impurities can result in lower-performance in recycled materials, relative to their virgin counterparts. The colouring used in virgin plastics presents a further – but mainly aesthetic – challenge. Two plastics of the same chemical composition, but differing colours, are very difficult to separate using existing industrial sorting processes. In mixed waste streams, where thousands of colours of plastics are encountered, the consequence tends to be that resins of multiple colours are recycled together. This often limits the choice of the colour of the final product to black. This sounds trivial, but it has a significant impact on the extent to which recycled material can displace virgin production.

Chemical, or "back to monomer", recycling describes a group of processes in which the plastic waste is converted back to the chemical building blocks that produced the original virgin material. This involves chemical transformations, calling for complex industrial processing equipment, and thus is generally more capital-intensive than is mechanical recycling. The key advantage of chemical recycling is that the quality obtained in secondary plastic production is often equal to that of virgin production, enabling the same product to be recycled many times. The difficulty, though, is that the process economics tend to be less favourable relative to the virgin production routes for the same plastic. As a result this route is not yet followed at an industrial scale globally (Rahimi and García, 2017).

Box 1.3 • Material cycles: Circular, open and closed loops

A product or material is said to be recycled or reused in a closed loop if it is returned at the end of its initial lifetime in a fit state to fulfil the service for which it was originally produced. Open-loop recycling describes that which enables a second lifetime for the material used in the original product, but at least some is used to produce a different product from the original. A material or product is described as circular (or exhibiting circularity) if it completes the closed loop without loss. Technically, most products can be returned to their original chemical components. However, few materials or products are circular in today's supply chains, due to material losses during use and disposal.

PET drinks bottles for water and soft drinks are an example of a chemical product that is reused and recycled, but in varying degrees of open and closed loops. To take three of many possible pathways:

1) A drinks bottle can be purchased and re-used multiple times, either directly by the consumer or after return to the vendor for cleaning and re-filling, forming an entirely closed loop on a material basis. Several countries and states (e.g. Germany and California) have incentives in place to encourage consumers to collect and return plastic bottles. These schemes are even more common for glass bottles.

2) The bottle can be sent to a chemical recycling facility where it is broken down into its key chemical building blocks and re-manufactured to form a new bottle from the basic monomers. So-called "bottle-to-bottle" recycling is a form of back-to-monomer recycling.

3) Again, the bottle can be returned to a recycling facility, chipped, melted and re-manufactured to form polyester fibre. Fibre is a lower grade end-use of PET, where slightly lower grades of polymer purity can be tolerated relative to food- or bottle-grade resin. This means the recycled product cannot be re-used in its original application. Because of this and the fact that there is no large-scale outlet for recycling PET fibre, even this imperfect recycle loop occurs only once. This type of recycling is often referred to as "downcycling" and is an example of open-loop recycling.

Beyond recycling and reuse, other material efficiency strategies are thought to have limited potential when it comes to plastics. Conversion losses in the major chemical production processes are close to their theoretical minimums. With energy accounting for a significant portion of operating costs, there is a long history of continuous technological progress in catalysis and process design to improve the conversion and selectivity of chemical processes, thereby minimising production costs and improving competitiveness.

Light-weighting of plastic products is often already carried out to its practical limit. Thinner plastic bottles and carrier bags serve to reduce the amount of plastic required for containing and transporting consumer goods, but further gains are limited by material properties and practicalities. Underpinning the successful deployment of these strategies are effective design principles (e.g. design for disassembly), often supported by regulations. Illustrating the application of a necessary environmental constraint, however, in many countries, there is a minimum requirement for the thickness of a plastic bag (typically 40-50 microns), without which they become fragmented in waste streams and difficult to sort and collect.

Fertilisers are integral to our modern agricultural systems, improving yields and limiting diseases. But there can be too much of a good thing. "Fertiliser efficiency" is usually defined as increase in yield achieved per unit of fertiliser applied. Because soil conditions and desired crops vary considerably with climate and location, there is no single optimal target value for the amount of fertiliser to be applied.

In Western Europe, with respect to nitrogen fertilisers specifically (the most energy-intensive to produce), country studies from the 1990s found that fertiliser application could be reduced by 44%, without nutritional loss, when applied more efficiently (Worrell, Meuleman and Blok, 1995). Between 1987 and 2007, nitrogen fertiliser use per hectare in the European Union declined by more than half; and in China it is estimated that a reduction of 30-50% could take place without reducing crop yields (Good and Beatty, 2011).

Seven chemical building blocks underpin a vast industry

Despite the substantial complexity of the chemical sector, only seven primary chemicals – ammonia, methanol, ethylene, propylene, benzene, toluene, and mixed xylenes – provide the key building blocks on which the bulk of the chemical industry is based. These primary chemicals account for approximately two-thirds of the sector's total consumption of final energy products.

Ammonia (NH_3) is the starting compound for all nitrogen-containing fertilisers. At ambient conditions, it is a toxic colourless gas with a pungent smell; but in water solutions, it can be treated without much difficulty. Globally, more than half of ammonia is converted to urea, which is in turn mainly used as a fertiliser, but it also has industrial applications. Ammonia and urea are often produced in integrated or co-located facilities since the large quantity of concentrated CO_2 released during the manufacture of ammonia is used as an input to urea production. In aggregate, agricultural uses account for approximately 80% of total ammonia demand, but ammonia also serves as a chemical building block in several industrial applications, explosives, and cleaning products. Global ammonia production is approximately 185 million tonnes per year (Mt/yr).

Methanol (CH_3OH) is a light, colourless and odourless liquid that is highly flammable. Methanol is most commonly used to make other chemicals. About 40% is converted to formaldehyde and further processed into plastics, plywood, paints, explosives and textiles. It is also used in anti-freeze, solvents and fuels for vehicles, and it can serve as an energy carrier. Methanol can also be converted to other primary chemicals. Global methanol production is approximately 100 Mt/yr.

Ethylene (C_2H_4) and **propylene** (C_3H_6) – collectively referred to as **light olefins** – are reactive compounds widely used, for example, in the production of polymers to manufacture plastics. The largest derivative of each of these olefins is their simplest polymer derivative: polyethylene and polypropylene. Combined global ethylene and propylene production is approximately 255 Mt/yr.

Benzene (C_6H_6), **toluene** (C_7H_8) and **mixed xylenes** (C_8H_{10}) – collectively referred to as **BTX aromatics** – can be also easily modified, and have a specific smell that prompted the use of "aromatics" as a name. They are used in health and hygiene, food production and processing, transportation, information technology and other sectors. Global production of BTX aromatics is approximately 110 Mt/yr.

Light olefins and aromatics are referred to collectively as **HVCs**. The market prices of HVCs are typically a multiple of those of methanol or ammonia. This is, in large part, because they are mainly made from oil, which tends to be more expensive than the gas and coal used for ammonia and methanol production, an aspect that is explored further in the discussion of feedstocks in Chapter 2.

Key production processes

HVCs are produced either in multi- or single-product processes in the chemical sector; alternatively, they are sourced as by-products from refinery operations. Ethylene, propylene and BTX aromatics are co-produced in **steam crackers**. Whereas ethylene is produced almost exclusively in the chemical sector in steam crackers, propylene is sourced in large quantities as a by-product of refining operations, specifically, of **fluid catalytic cracking**. The majority of BTX aromatics are sourced from FCC and **continuous catalytic reforming** units in refineries. The dominant processes for producing propylene as a single product are **propane dehydrogenation** and **olefin metathesis**. Olefins can also be produced from methanol using the **methanol-to-olefins** process although this is done only in China, where abundant access to coal sufficiently lowers the cost of producing methanol. Aromatics can also be produced via a similar route, although this process is still at the demonstration phase.

The key process for producing both ammonia and methanol is **steam reforming** of natural gas. Although the synthesis step that takes place after this process differs for each chemical – Haber Bosch synthesis for ammonia and methanol synthesis at various pressures – the need for hydrogen-containing synthesis gas is common to both. Oil feedstocks, such as naphtha, liquefied petroleum gas and fuel oil, can also be used, either with steam reforming or via a similar route to synthesis gas – **partial oxidation**. Again, China uniquely uses coal as a feedstock for producing both methanol and ammonia. Coal must first undergo **gasification** before synthesis gas can be obtained, which is highly energy-intensive.

References

Allwood, J.M. and J.M. Cullen (2012), *Sustainable Materials - With Both Eyes Open*, UIT Cambridge, Cambridge, United Kingdom.

Allwood, J.M. et al. (2013), “Material efficiency: providing material services with less material production”, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 371/1986, 20120496, https://doi.org/10.1098/rsta.2012.0496.

Geyer, R., J.R. Jambeck and K.L. Law (2017), “Production, use, and fate of all plastics ever made”, Science Advances, Vol. 3/7, e1700782, https://doi.org/10.1126/sciadv.1700782.

Good, A.G. and P.H. Beatty (2011), “Fertilizing nature: A tragedy of excess in the commons”, PLoS Biology, Vol. 9/8, p. 1-12 https://doi.org/10.1371/journal.pbio.1001124.

IFA (International Fertilizer Association) (2018), *International Fertilizer Association Database*, http://ifadata.fertilizer.org/ucSearch.aspx (accessed 6 June 2018).

IMF (International Monetary Fund) (2018), *World Economic Outlook Database*, www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx (accessed 6 June 2018).

Levi, P.G. and J.M. Cullen (2018), “Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products”, *Environmental Science and Technology*, Vol. 52/4, p. 1725-1734, https://doi.org/10.1021/acs.est.7b04573.

METI (Ministry of Economy, Trade and Industry) (2016), *Future Supply and Demand Trend of Petrochemical Products Worldwide*, Tokyo, www.meti.go.jp/policy/mono_info_service/mono/chemistry/sekkajyukyuudoukou201506.html (accessed 6 June 2018).

Mills, J. (2011), *Polyester & Cotton: Unequal Competitors*, Tecnon Orbichem, www.coton-acp.org/modules/docpool/files/atelierspolyester-coton.pdf.

Rahimi, A. and J.M. García (2017), “Chemical recycling of waste plastics for new materials production”, *Nature Reviews Chemistry*, Vol. 1/6, p. 1-11, https://doi.org/10.1038/s41570-017-0046.

USGS (United States Geological Survey) (2018a), *2018 Minerals Yearbook: Aluminium*, https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2015-alumi.pdf.

USGS (2018b), *2018 Minerals Yearbook: Cement*, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2014-cemen.pdf.

USGS (2018c), *2018 Minerals Yearbook: Nitrogen*, https://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2015-nitro.pdf.

Worldsteel (2017), *Steel Statistical Yearbook 2017*, www.worldsteel.org/en/dam/jcr:3e275c73-6f11-4e7f-a5d8-23d9bc5c508f/Steel+Statistical+Yearbook+2017.pdf.

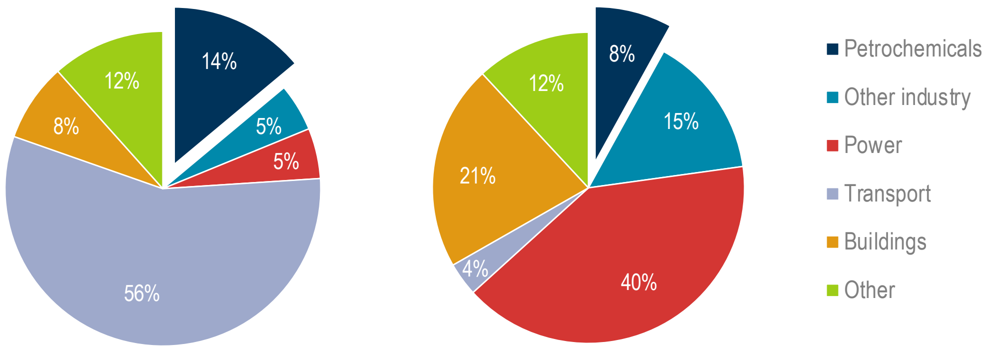
Worrell, E., B. Meuleman and K. Blok (1995), “Energy savings by efficient application of fertilizer”, *Resources, Conservation and Recycling*, Vol. 13/3–4, p. 233-250, https://doi.org/10.1016/0921-3449(94)00045-7.

Chapter 2. Chemicals and the energy system

As in society, chemicals play an important role in the energy system. The chemical sector is the largest industrial energy consumer, ahead of iron and steel, and cement. It accounts for approximately 10% of total final energy consumption and almost 30% of industrial final energy consumption. The chemical sector is also the largest industrial consumer of both oil and gas, accounting for 14% and 8% of total primary demand for each fuel respectively. Within the chemical sector, primary chemicals account for almost 90% of the consumption of oil and gas.

Total primary demand for oil is dominated by the demand for liquid fuels in transport for fuelling cars, trucks, ships and planes, which accounts for almost 60% globally. The chemical sector is the next-largest source of oil demand, accounting for 14% of primary demand. By contrast, power generation dominates primary demand for natural gas (40%), followed by demand for space and water heating in buildings (21%). The chemical sector, accounting for 8% of total demand for natural gas, uses twice as much as the entire transport sector.

Figure 2.1 • Primary oil (left) and natural gas (right) demand in 2017 by sector



Note: *Petrochemicals* includes process energy and feedstock.

Key message • Petrochemicals account for 14% and 8% of total primary demand for oil and gas respectively.

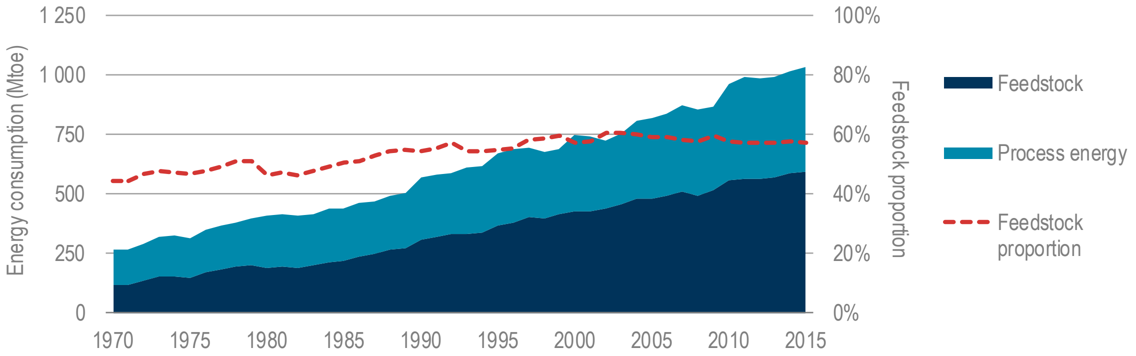
From feedstock to chemical products

As noted earlier, fuels are consumed in two ways in the chemical sector: as energy to drive processes and as "feedstock". Process energy consumption in the chemical sector is similar to that in other industrial sectors: fuels are consumed to provide direct heat, steam and electricity to drive the sector's processes, equipment and facilities. The use of fuels as feedstock is unique to the chemical sector and is integral to understanding how the sector performs its role.

"Feedstock" describes the use of various fuels as a material input. Akin to iron ore inputs to the iron and steel industry or alumina inputs to the aluminium industry, chemical feedstock is the source of the carbon and hydrogen used physically to constitute chemical products. Feedstock is quantified in energy units because, before use, it is indistinguishable from the same energy products used as fuels. But, once feedstock undergoes transformation in the chemical sector, it is easier to think of it as a material, with its carbon and hydrogen atoms rearranged physically to constitute the plastics and other chemical products manufactured within the sector.

Chemical feedstock accounts for more than half the total energy inputs to the chemical sector globally. The vast majority of feedstock consumed from 1970 until today has been in the form of fossil fuels, with oil, natural gas and coal contributing cumulative shares of approximately 74%, 25% and 1% respectively. The gradual upward trend in feedstock as a share of total energy inputs suggests a steady increase in process energy efficiency and integration, relative to feedstock requirements. Reductions in feedstock requirements are limited by chemistry. However, there may be other influencing factors, such as the complexities involved in reporting on feedstock use.

Figure 2.2 • Feedstock and process energy consumption in the chemical sector



Source: IEA (2017), *World Energy Balances*.

Key message • Today, feedstock accounts for just over half of the sector's energy inputs.

Box 2.1 • Chemical feedstock: Energy or material?

Whereas the main inputs and outputs to say, the iron and steel sector (iron ore in, steel out) are unequivocally recognised as materials, the same cannot be said of the chemical sector. Chemicals form a bridge between the energy system and consumers' vehicles, homes and plates. Chemical feedstock consists of molecules of oil, natural gas and other carbon- and hydrogen-containing minerals, which are extracted from the ground and processed to end up physically constituting, for example, the million or so plastic bottles the world currently produced every minute (Laville and Taylor, 2017). Feedstock is also embedded in the synthetic fibre, rubber, detergents and other chemical products we use every day to manufacture packaging, carpets, cars, cutlery, electronic goods, toothbrushes, clothes and a plethora of other consumer goods. We are surrounded by chemical products and, therefore, also by chemical feedstock.

At first glance, it appears that feedstock can be consigned to the "material" category. Alas, the picture is more complex. When entering the chemical sector as a fuel, feedstock is measured in energy units and accounted for in energy statistics. This is because, at that point, it is indistinguishable on a molecular level from its process energy counterparts. In other words, it could still be burned to release energy, just like any other fuel. A further complication arises, in that the feedstock can also play a role in the process energy requirements. Some unconverted feedstock in by-products is recirculated and used as fuel inputs. Molecules of feedstock often release energy as they are rearranged and reassembled in the chemical supply chain.

To complete the circle, feedstock embedded in chemical products can often return to something more like a store of energy. Plastic and other chemical product waste is frequently burned in waste-to-energy facilities in order to generate electricity and heat. Perhaps the easiest way to consider feedstock is to think of it as akin to wood. Like the oil and gas used for chemical feedstock, wood can be used both as a material and as a fuel. Charcoal and other forms of biomass made from wood appear in energy statistics and are measured in energy units. Conversely, and again like feedstock, timber – a wood product, analogous to plastic – is used to construct buildings and other end-use products, which it would be strange to quantify in energy units (this house contains "x gigajoules" of timber, as opposed to "x tonnes"). Feedstock is to the chemical industry what wood is to carpentry.

Approximately 12 million barrels per day (mb/d) of oil products, 105 billion cubic metres (bcm) of natural gas and 80 million tonnes (Mt) of coal enter the sector as feedstock and undergo a complex series of chemical transformations, eventually leaving the sector embedded in chemical products.

- More than 90% of the oil – mostly in the form of ethane or naphtha – entering the chemical sector as feedstock is transformed into high-value chemicals (HVCs). Very small amounts are used for methanol and ammonia production, with the rest being used for other chemicals, notably, carbon black.
- About 25% of gas demand for chemical feedstock is used to produce methanol, with the majority of the rest used to produce ammonia.
- Coal feedstock usage is split in fairly even proportions across methanol and ammonia.

Approximately 190 Mt of chemicals, two-thirds of which are HVCs, are also produced as by-products in the refining sector, making their way into the chemical sector for further processing. The remainder of these refinery chemicals, butylene – also produced as a co-product in steam cracking within the chemical sector – is used for various fuel applications and forms the base of most synthetic rubber.

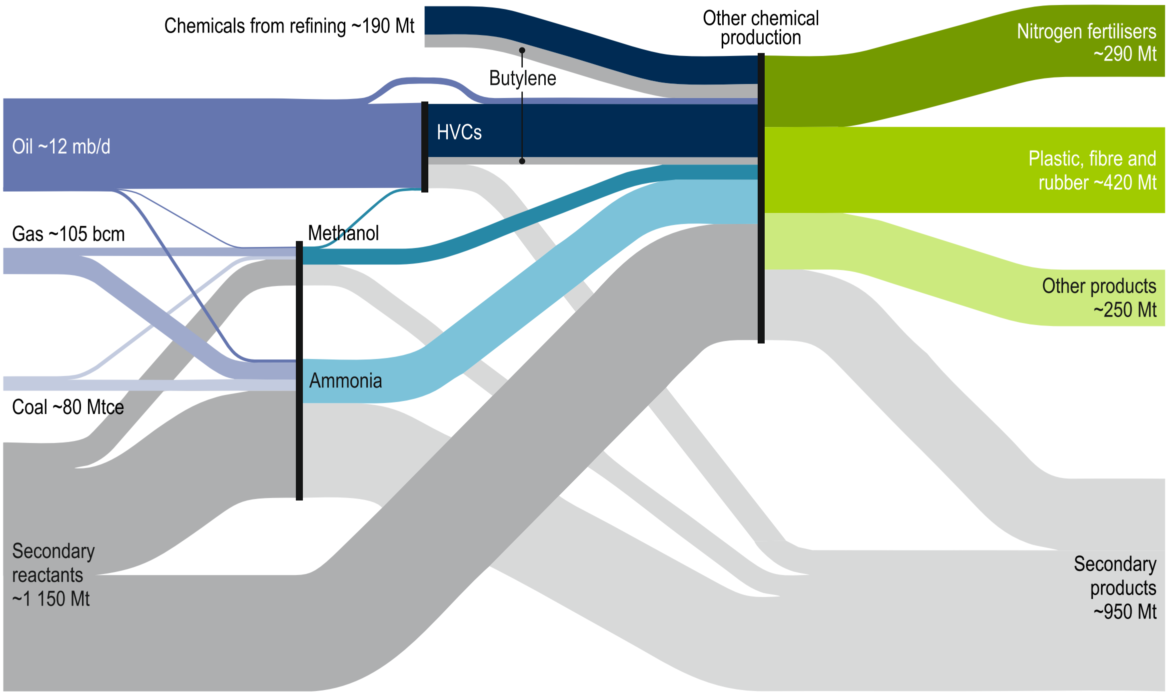
Nitrogen fertilisers, plastics, synthetic fibres and rubber account for more than 70% of the total mass production of chemicals. The remainder of the products consist of a host of monomers and other intermediate chemicals that go on to be transformed into thousands of small volume downstream chemicals and products. The complexity at the margins in the chemical sector is hard to overstate. The European Chemicals Agency (a regulatory body) tracks more than 100 000 unique substances. Many of these substances are produced using primary chemicals and their derivatives.

The total mass of chemical products leaving the chemical sector is larger than the mass of feedstock entering it. This is because in addition to feedstock (mainly composed of carbon and hydrogen), many chemical products contain other elements (mainly oxygen, nitrogen and chlorine) that are added at various points in the supply chain. In mass terms, these other compounds comprise around a billion tonnes, although their exact quantity is uncertain. The magnitude of these secondary material flows is a key reason why the sector is so energy-intensive. Heating, cooling, moving and separating these substances, in addition to the feedstock and the primary chemicals, consumes large amounts of process energy.

Another question is the extent to which these secondary material flows can be re-absorbed in the production of other chemicals, although it is known that this practice is already widespread in some parts of the supply chain. For example, the carbon dioxide (CO_2) by-product from ammonia manufacture (process emissions) is used as a raw material input to urea manufacture on a large scale. Although many chemical operations are integrated to achieve a high degree of efficiency in resource use within an individual facility, the full potential for the use of by-products from one process as inputs to another across the industry as a whole is difficult to ascertain.

In addition to the principal chemical production pathways shown in Figure 2.3, there are others that play a marginal role today, globally. For instance, recycling thermoplastics can reduce demand for primary chemicals and, thus, save energy and CO_2 emissions. For each tonne of polyethylene recycled (the most common plastic used in packaging), more than 1 tonne of ethylene demand can be eliminated, saving at least 1.5 tonnes of oil-equivalent (toe). Bio-based feedstock can also displace fossil fuel feedstock or replace derivative chemicals further down the value chain. These alternatives offer promising potential to support the decoupling of chemicals production from CO_2 emissions, in part due to their relatively low current levels of penetration.

Figure 2.3 • Passage of fossil fuel feedstock through the chemical industry in 2017



Notes: All flows in the diagram are sized on a mass basis. Secondary reactants and products are the compounds specified within chemical reactions that do not form part of the feedstock or main products. Key examples include water, CO_2, oxygen, nitrogen and chlorine. Some of the secondary products entering the sector on the left of the figure may well coincide with those leaving it on the right – CO_2 emitted from ammonia facilities and utilised in urea production is a key example. Mtce = Million tonnes of coal-equivalent.

Source: Adapted from Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", https://doi.org/10.1021/acs.est.7b04573.

Key message • More than 500 million tonnes of oil-equivalent (Mtoe) of feedstock is consumed per year to make nearly 1 billion tonnes of chemical products. Oil is the dominant feedstock for HVCs, whereas gas and coal are used for ammonia and methanol.

Globally in 2017, recycling of major plastic resins is estimated to have reached 16% of available waste, while global production capacity of bio-plastics stood at just over 2 Mt (European Bioplastics, 2018) (the latter equivalent to less than 1% of annual global plastic demand, if fully utilised). Theoretically, the chemical sector could do without fossil fuels altogether, but feedstock containing carbon and hydrogen will remain a requirement.

What determines the selection of feedstock?

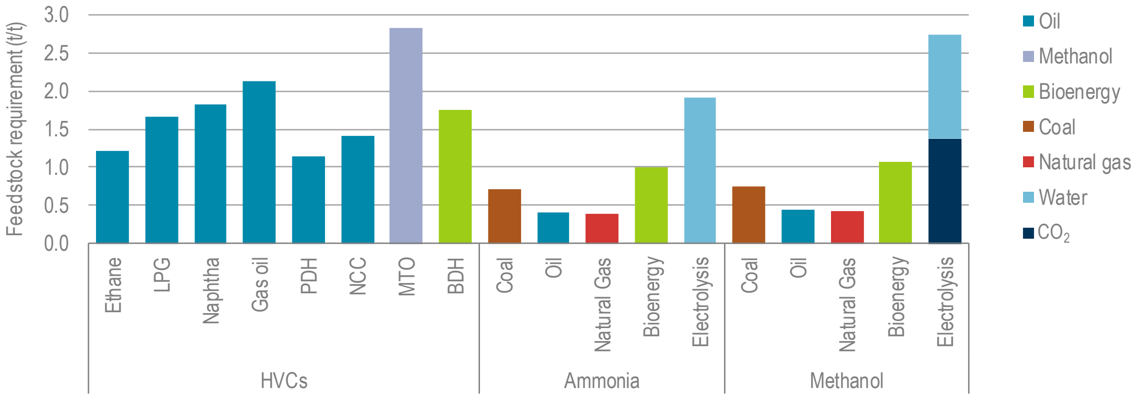
For much of the history of the chemical industry, primary chemicals could be made only from oil and natural gas. Modern chemistry and industrial processing permits most energy products to be converted into most primary chemicals, either directly or via secondary processing. Ammonia and methanol can be made directly from oil, natural gas, coal, bio-energy, and even water (by splitting water molecules to make hydrogen, although methanol requires a separate source of carbon because none is available in the water molecules). HVCs can be made from oil directly, but also from all the other fuels listed above via methanol. This last element of flexibility in the supply chain is a relatively recent development, following the commercialisation of methanol conversion processes. Methanol-to-olefins (MTO) is now commercial, whereas the more challenging transformation from methanol-to-aromatics is still at the pilot plant stage (Bazzanella and Ausfelder, 2017).

Despite this innovation and flexibility, not all routes are equally competitive, which explains the dominance of fossil fuels in today's demand for chemical feedstock. Ethane (North America and the Middle East) and naphtha (Europe and Asia) are the principal feedstocks used to make HVCs, whereas natural gas is the key input for producing methanol and ammonia globally, except in the People's Republic of China,[6] where coal is dominant for both. The overarching consideration in the selection of feedstock and process routes is the production cost, allowing for equipment costs and process yields, though there are also other factors at play, some of which are regional, including feedstock availability, labour costs and the regulatory environment.

Process equipment costs, excluding engineering and installation costs, tend to be fairly uniform regionally for a given technology because there are relatively few vendors available and therefore little variation among offerings. However, overall costs vary significantly between the process routes available, which are distinguished, primarily, by the feedstock they utilise. Equipment for producing chemicals from solid feedstock, primarily coal and biomass, tends to be more capital-intensive than equipment for producing the same product from natural gas. Using ammonia as an example, for a unit of production, equipment costs using coal are more than twice as high as natural gas, whereas biomass equipment costs are nearly sevenfold higher.

Process yields refer to the amount of product that can be obtained per unit of feedstock consumed, and are one of the most important determinants of the choice of route because they directly affect both feedstock and process energy consumption. For the simultaneous production of HVCs from the same process run ("co-production" or "multi-product processes"), ethane as a feedstock offers the highest yields, using only 1.2 tonnes of feedstock per tonne (t/t) of HVCs produced. The introduction of catalysts in steam cracking can deliver yield gains of about 20% when using naphtha as feedstock.

Figure 2.4 • Feedstock options by chemical product



Notes: BDH = bioethanol dehydration; LPG = liquefied petroleum gas; NCC = naphtha catalytic cracking. The quantity pertaining to BDH is in terms of bioethanol.

Key message • Multiple feedstocks can be utilised to make the same product, but with significant variations between the amount of input required.

Routes that produce selected HVCs individually can consume relatively low amounts of feedstock per unit of product, especially when using a feedstock of similar chemical structure

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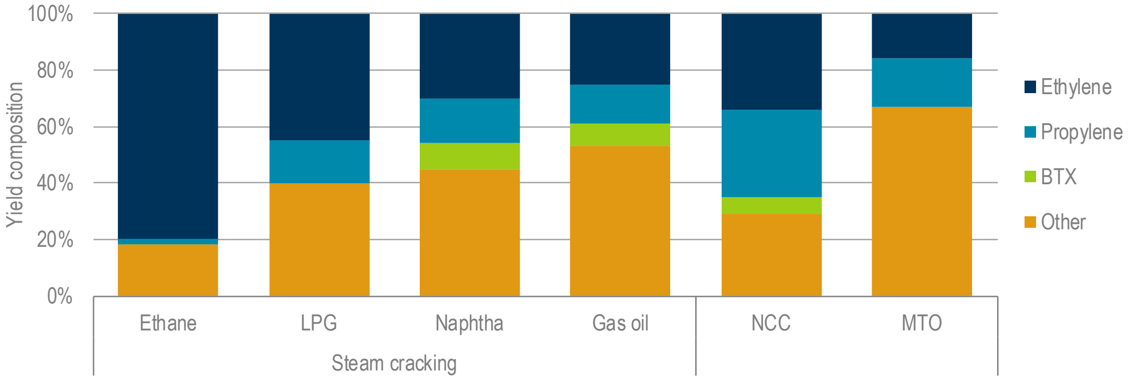
[6] Hereafter, "China".

to the product, such as the case of propane dehydrogenation (PDH) to produce propylene. To produce both ammonia and methanol, natural gas offers the highest yields. Bioenergy-based routes are typically more feedstock-intensive compared to their fossil-based counterparts due to their lower carbon and energy content.

In co-production processes, there is typically a compromise between the overall amount of HVCs produced (process yield) and the diversity of products (ethylene, propylene and benzene, toluene and mixed xylenes (BTX) aromatics) obtained. For example, while an ethane steam cracker yields about 50% more HVCs than a naphtha-based one, the mix of HVCs produced is predominantly composed of ethylene. In contrast, naphtha steam cracking delivers a more balanced portfolio of ethylene, propylene and BTX aromatics, but at a lower yield rate than the ethane-based route. The differences are mainly due to the degree of similarity between the chemical structure of the feedstock and the final product. The relative level of demand for the different HVCs can, therefore, be an important factor in feedstock selection. Single-product processes can be used to fill the gaps left by the use of relatively cheap, locally available feedstock.

Figure 2.5 • Yield of individual HVCs in multi-product processes



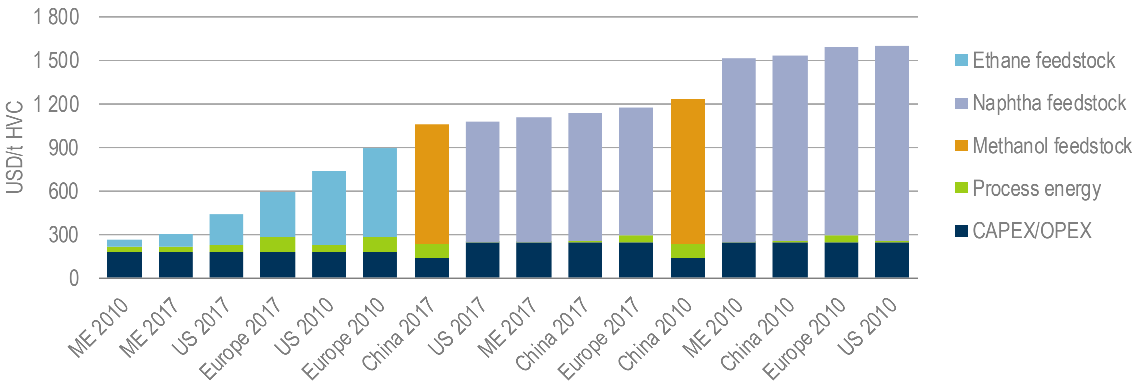
Key message • Higher overall yields are often obtained at the expense of a balanced product profile.

The main determinant for the choice of route to produce a particular product is the availability (and therefore, cost) of feedstocks, which varies substantially between regions. Whereas crude oil has a similar price across the globe, natural gas prices can vary by a factor of 4. Furthermore, despite the global market for oil, many of the lighter products – ethane and LPG, in particular – are either unavailable in some regions or are imported at significant additional cost. Natural gas tends to be more expensive than coal and oil products more costly than natural gas.

Feedstock costs can represent anywhere between 15% and 85% of the levelised production costs of HVCs, depending on the feedstock choice. The prices of feedstocks and process energy inputs vary over time, according to the market dynamics of supply and demand. The surge in supply of ethane in the United States as the shale gas revolution picked up momentum led to a fall in ethane prices after 2011, to the extent that "ethane rejection" (ethane being left un-extracted from natural gas streams) became commonplace.

For the production of HVCs, ethane crackers offer the consistently cheapest route from a simplified levelised cost perspective; but these units yield few products aside from ethylene, whereas naphtha and MTO units provide a more balanced slate of propylene, ethylene and aromatics. In both 2010 and 2017 – before and after the US shale gas revolution upended oil and gas markets – ethane steam crackers in the Middle East were offering the most competitive route to a unit of HVCs, although the differential in production costs of ethane-based steam cracking between the Middle East and the United States decreased more than threefold between 2010 and 2017 as a result of the shale revolution. Before the slump in oil prices in 2014, Chinese MTO plants (using methanol as feedstock) offered a substantial discount, relative to the cheapest naphtha cracker (nearly USD 300 per tonne of high value chemical (tHVC)), whereas in 2017 this discount decreased almost to zero.

Figure 2.6 • Simplified levelised cost of HVCs for selected feedstocks and regions



Notes: Fuel and feedstock costs are calculated based on average prices during both 2010 and 2017, whereas capital expenditure (CAPEX) and fixed operational expenditure (OPEX) are assumed to remain constant both over time and between regions, for a given technology. CAPEX assumptions: USD 1 500 /tHVC for ethane steam cracking; USD 1 000/t HVC for MTO; USD 2 050/tHVC for naphtha steam cracking. Fixed OPEX: 2.5-5.0% of CAPEX. Discount rate is 8%. A 25 year design life is assumed for all equipment. Energy performance ranges: 12-19 gigajoules (GJ)/tHVC for naphtha steam cracking; 14-17 GJ/tHVC for naphtha steam cracking; 11 GJ/tHVC for MTO. Feedstock requirements correspond to those shown in Figure 2.4. Process energy requirements include fuel, steam and electricity, are calculated on a net basis, assuming full utilisation of available fuel gas in the product stream. ME = Middle East, US = United States.

Sources: Feedstock prices from Argus Media (2018), *Key Prices*, www2.argusmedia.com/en/methodology/key-prices.

Key message • Among the main costs of production, feedstock is the most influential factor in determining regional production advantages.

These cost dynamics determine, to some extent, where primary chemical production takes place around the world. Regions with an advantageous feedstock position (e.g. Middle East and United States for HVCs) tend to contribute large volumes to the global production of primary chemicals. Asia Pacific accounts for half of global primary chemical production (326 Mt per year), with China as by far the largest chemicals producer in Asia, accounting for 20%, 33% and 55% of HVCs, ammonia and methanol global capacity, respectively. Because of the very limited availability of feedstock from natural gas liquids in China – the country's natural gas output not being rich in these substances -- China depends heavily on naphtha feedstock (more than 90%) for HVCs.

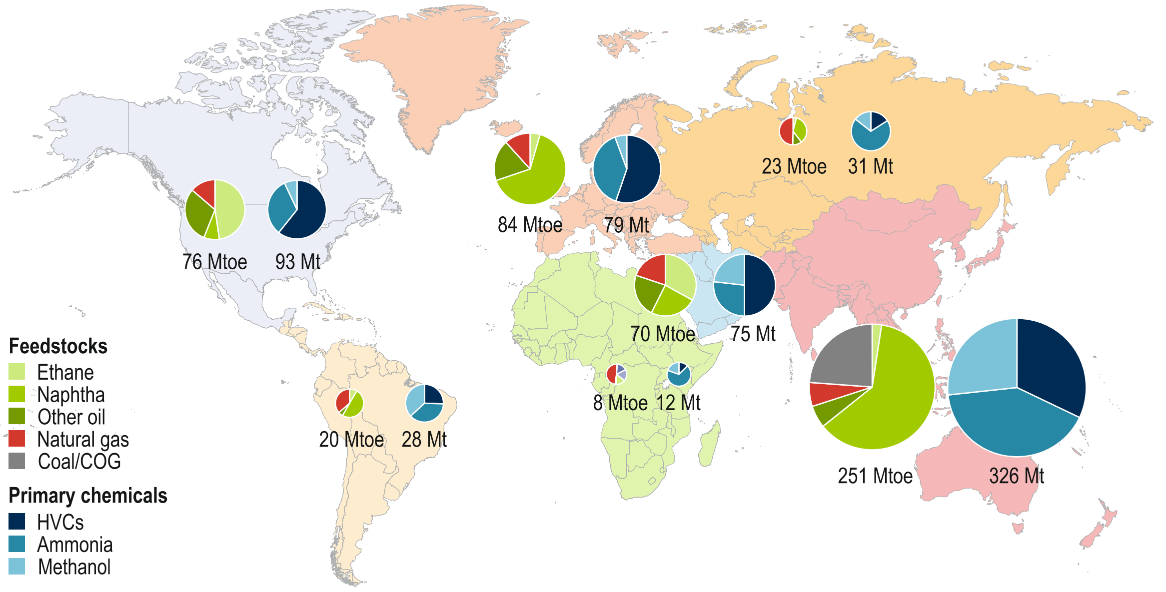
This also explains why Chinese refinery LPG yields are some of the highest in the world – close to 10%. Despite this, China has significantly ramped up LPG imports to feed PDH plants dedicated to propylene production in recent years. China's feedstock deficit from indigenous petroleum sources has incentivised coal-to-olefin project developments, which has increasingly brought coal companies into petrochemical operations. Interestingly, the Saudi petrochemical holding, SABIC, has announced a joint venture plan with Shenhua, the largest coal producer in China, in the coal-to-chemicals field. The abundance and low price of coal in China means that, despite higher equipment costs and lower selectivity compared to natural gas, it is also advantageous in terms of production cost to obtain ammonia and methanol from coal. The development of a coal-based chemical industry in China has helped lower production costs for some chemicals, although capacity utilisation rates tend to be quite low, indicating over-capacity and some sub-optimal deployment of assets.

The Middle East is generally at the lower end of the cost curve among producing regions for primary chemical production. Currently, the region has 12%, 9% and 15% of the world's production capacity for HVCs, ammonia and methanol, respectively. The region is thought to have strong potential growth. Of the region's total crude oil production (about 28 mb/d), only about 7 mb/d is refined locally, with the rest exported to global markets. Over 90% of naphtha output is also exported rather than being used locally as feedstock, partly as a result of the ample availability of far cheaper alternatives, such as ethane and LPG, which together make up more than half of regional HVC feedstock.

Europe holds a large, but declining, segment of global production capacity for primary chemicals. Once the largest region for chemical production, it now accounts for more modest shares of the world's production capacity: 15% for HVCs, 12% for ammonia and 3% for methanol. However, the region retains a strong position in high-value market segments further downstream (cosmetics, consumer chemicals, etc.), which sustains several upstream assets, despite the region being high up the cost curve for most primary chemicals.

The United States remains a key source of primary chemicals among developed countries, and it is expected to remain competitive across many segments in future. It hosts 16% of the world's HVC production capacity, 7% of ammonia and 5% of methanol. The United States is rapidly expanding its petrochemical capacity, thanks to the shale revolution, which has led to natural gas liquids (NGLs) production doubling to nearly 4 mb/d in five years. Unsurprisingly, ethane and LPG dominate the feedstock mix for HVCs, accounting for 55% and 34%, respectively, with naphtha holding less than a 10% share.

Figure 2.7 • Primary feedstock use and chemical production by region



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Notes: The left pie chart of the pair for each region displays feedstock usage, while the right pie chart displays primary chemical production. The pie charts are sized in proportion to the total quantity (Mtoe or Mt) in each case.

Source: IFA (2018), *International Fertilizer Association Database*, http://ifadata.fertilizer.org/ ucSearch.aspx; expert elicitation.

Key message • Asia dominates both global primary chemical and naphtha feedstock demand. North America is the leader in ethane-based HVC production.

Chemicals: Traded commodities

Trade in chemical products takes place at several points along the value chain, enabling producers to focus on aspects in which they can maintain a competitive advantage. Trade in primary chemicals tends to be modest relative to that of the downstream derivatives, mainly because of high transportation costs and low margins. A step along the derivative chain (e.g. from ethylene to polyethylene) not only adds value but often results in easier transportation.

Where the equipment and capital are accessible, producers tend to add value by moving down the derivative chain. Trade data in the two largest-volume primary chemicals and their largest-volume derivatives show a relatively similar pattern over the last ten years. Global ammonia production in 2016 was 180 Mt, of which the globally traded volume was roughly 10-15 Mt, or about 7%. Over the previous decade trade volumes declined slightly, both in absolute terms and as a share of production, which stood at about 10% in 2006 but, overall, have remained relatively flat. The pattern of trade has also remained relatively consistent, with three of the top five exporters, and four of the top five importers, maintaining similar positions.

Urea is the largest-volume derivative of ammonia, consuming more than half of the annual production of ammonia. It is more expensive than ammonia because it offers greater nutrient value (nitrogen) per tonne as a fertiliser, creating an additional margin for urea producers. Because ammonia is a gas at ambient conditions and urea is a solid, urea is also easier to transport, giving urea export a cost advantage relative to exporting ammonia.[7] This is reflected in global trade volumes of urea, which, in absolute terms, were approximately 60% higher than those of ammonia in 2006 and more than 300% higher in 2016. Ethylene and its largest-volume derivative, polyethylene, tell a similar story.

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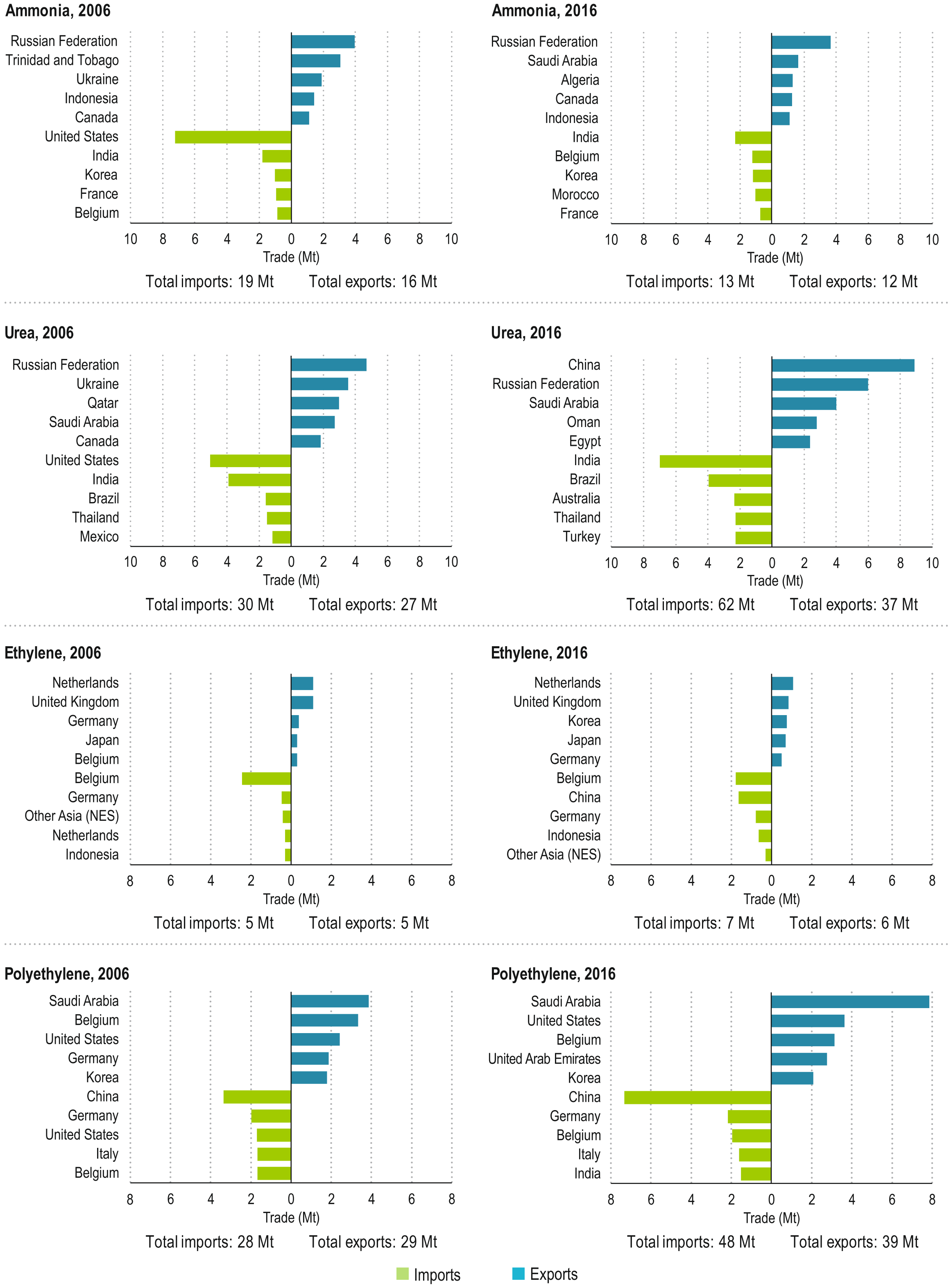
[7] Ammonia can be stored in solution. But the overwhelming bulk of its global trade is in anhydrous (without water) form, indicating the inefficiency incurred in dilution.

Figure 2.8 • Trade in key primary chemicals and some important derivatives



Notes: Exports and imports do not include re-exports and re-imports. NES = not elsewhere specified.

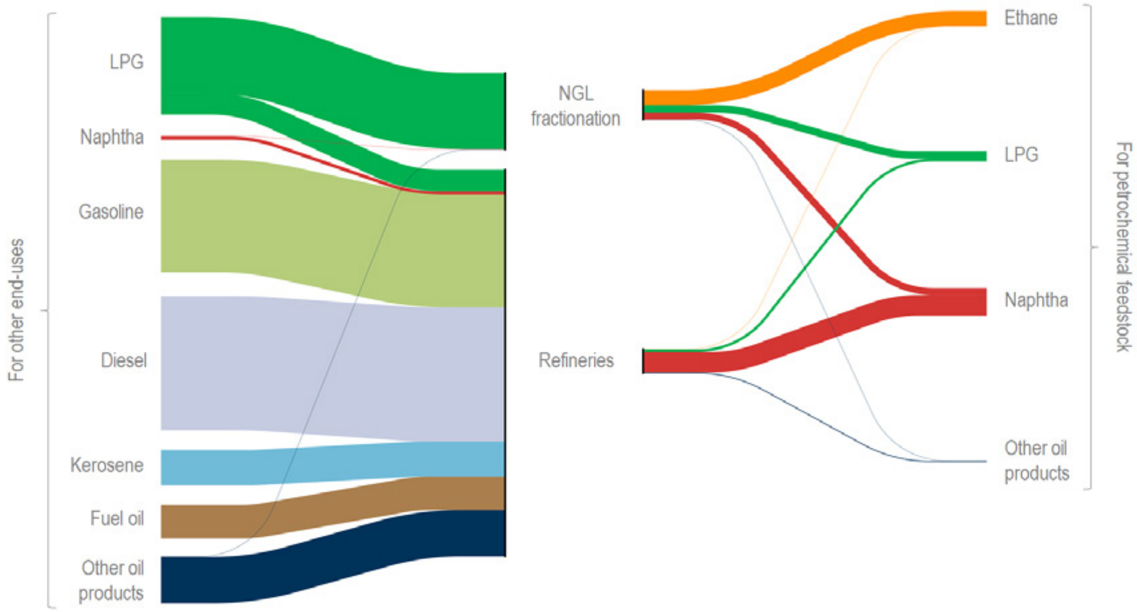
Source: United Nations (2018), *UN Comtrade Database*, https://comtrade.un.org/.

Key message • Trade patterns have remained relatively consistent over the period 2006-16. Derivative chemicals (urea and polyethylene) are traded in larger volumes than their parent primary chemicals (ammonia and ethylene).

Supply of oil feedstock for chemicals and integration opportunities

Oil products used as chemical feedstock may come from refinery operations or NGL fractionation. In volume terms, oil demand for chemical feedstock is dominated globally by the fractionation products of NGLs. Refineries do not produce ethane to any meaningful extent, and their LPG yields are typically below 5%. Thus, ethane, which accounts for almost a third of all chemical feedstock, and most of the LPG used as chemical feedstock, are supplied by NGL fractionation plants. In contrast, refineries provide the bulk of heavier feedstocks, including naphtha, which is the most popular feedstock, and other distillates. Average refinery naphtha yields are around 7%.

Figure 2.9 • Destinations of oil products from NGL fractionation and refineries



Notes: The line thicknesses in the diagram are sized according to volume, and are indicative. Biofuels are excluded. Other sources of liquid fuels, such as coal liquefaction and gas to liquids are excluded.

Key message • Refineries are only a secondary source of feedstock to the petrochemical sector, with most feedstock coming from NGL fractionation.

The proportion of chemical feedstocks sourced from refineries is limited, not only because an average barrel of crude oil contains only a limited amount of light fractions (LPG), but also because of competition for straight-run yields of light distillates (naphtha) for gasoline blendstocks, to supplement that part coming from the upgrading of residual oils. Moreover, LPG and naphtha usually have negative margins (i.e. priced lower than crude oil), discouraging refineries from increasing their yields. In other words, these products are essentially by-products of a process that is geared to producing the transport fuels, gasoline, and middle distillates (diesel and kerosene) that dominate the refinery output product slate. It is their processing margins that determine the economic case for refineries to operate.

However, global averages mask significant regional variations. Refinery yields of both LPG and naphtha are higher in regions where local supplies of NGLs are relatively low. In Asia, for example, NGL output is only 1 mb/d, just 6% of the global total, while total demand for ethane, LPG and naphtha is more than 8 mb/d. This means that Asian petrochemical manufacture is more reliant on naphtha, which can be supplied by refineries in higher volumes than LPG or ethane. This is one reason why Asia accounts for about 60% of global naphtha consumption as petrochemical feedstock. But, despite higher naphtha yields, the region is still a large net importer of naphtha and LPG from the Middle East and Europe.

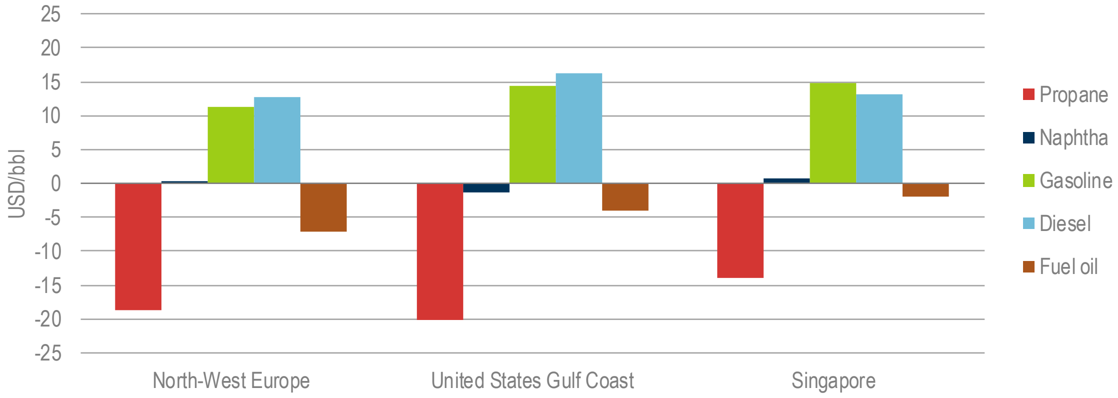
Asian operators have also started importing LPG and ethane for feedstock use in PDH plants and steam crackers, respectively. The bulk of incremental imports have come from the United States, due to the attractive prices available at the US export hubs. Such seaborne ethane shipments are a very recent phenomenon, initially going from the United States to European and Indian steam crackers. The intention to import US ethane has also been announced by several Chinese companies. Even so, the use of naphtha in Asian petrochemical feedstock is not expected to decline significantly, because of the sheer scale of feedstock demand growth.

Asian refineries' intake of US light tight oil is also growing. After the US ban on crude oil exports was lifted in late 2015, US crude oil exports skyrocketed to 1.1 mb/d in 2017. Of these, more than one-third has arrived at Asian refineries, many of which are integrated with petrochemical facilities. In several months during the course of 2017, China surpassed Canada as the largest buyer of US crude oil. Echoing this dynamic, a growing supply of condensate is triggering investments in condensate splitters in the United States and Asia, enabling higher naphtha yields.

Upstream integration

Chemical production can be integrated with the sourcing of its feedstock: either with refineries or NGL fractionation plants. Refineries are the more complex case and, therefore, the focus of this section. In any event, no single factor explains why chemical producers would choose to opt for upstream[8] integration, and what works well in one region may not be a good recipe for another.

Figure 2.10 • Selected average oil product price differentials in 2017



Notes: USD/bbl = United States dollars per barrel; Details of cost data used for comparison: North-West Europe product prices vs North Sea dated; US Gulf Coast prices versus average of Argus Sour and Light Louisiana Sweet, Singapore versus Dubai.

Source: Price data from Argus Media (2018), *Key Prices*, www2.argusmedia.com/en/methodology/key-prices.

Key message • Production of petrochemical feedstock alone is not profitable for refineries.

For refineries with integrated petrochemical operations, the commercial and economic conditions are different. One obvious benefit is the reduction in the transport costs for feedstock. As a result, steam crackers are often located in the same industrial hub as refinery sites, even when the ownership differs. Combining these assets within a single entity's portfolio saves corporate overheads and staff costs, as well as providing potential synergies in utility supply and logistics infrastructure. The most important benefit comes from matching the complementarities in energy supply and demand requirements.

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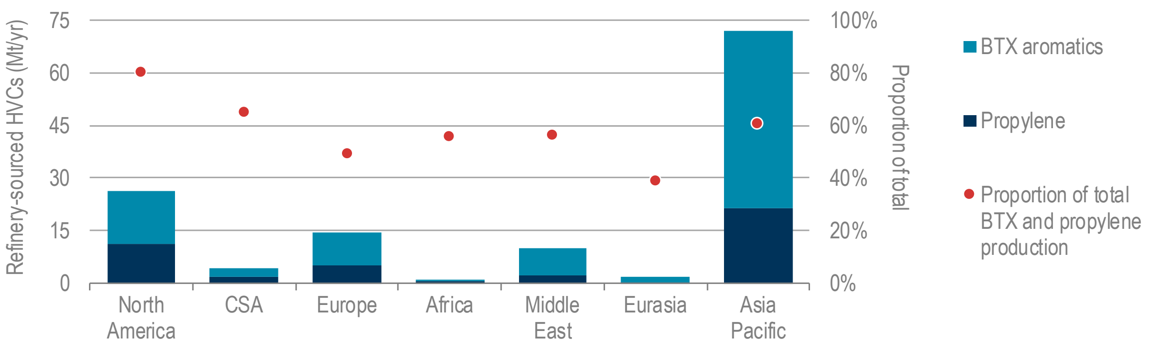
[8] *Upstream* describes the refining and exploration industries from a chemical sector vantage point.

Not only is low-value refinery output, such as naphtha, a valuable feedstock for petrochemical processes (e.g. steam cracking), but a by-product of steam cracking, hydrogen, is a vital input into a refinery's desulphurisation units: the higher the sulphur content in the crude oil being processed, the bigger the hydrogen requirement to meet increasingly stringent sulphur content limits in transport fuels. Refineries extract some hydrogen from naphtha reforming, but usually this is not sufficient. In these instances hydrogen is purchased to fill the gap. Other by-products of steam cracking, such as pyrolysis gasoline, can be further processed in refineries for use as gasoline components. In addition, integrated refinery-petrochemical processing may allow increased flexibility in the choice of crude oil feedstock, thus expanding the range of crude oil qualities that can be profitably processed in the refinery in different market conditions.

Figure 2.11 • Propylene and BTX aromatics production in the refining sector



Note: CSA = Central and South America.

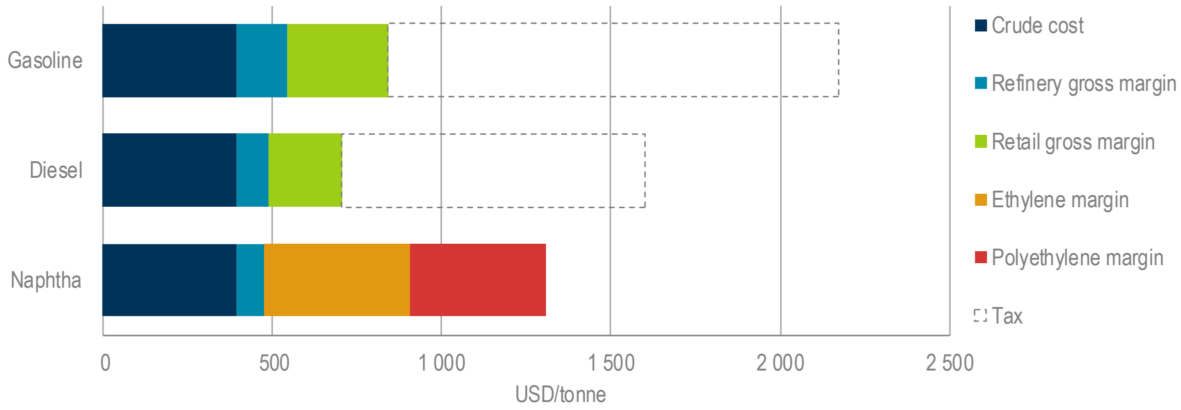
Key message • Regions with lighter feedstocks tend to source more of their propylene and BTX from refineries.

Refineries also produce certain amounts of HVCs, such as propylene and BTX aromatics, directly from catalytic cracking and reforming processes. These can account for 1-2% of a refinery's yield. More than 40% of propylene and around 80% of BTX aromatics are estimated to be sourced from refineries globally. Given the relationship between the feedstock used and product yields, where the share of heavier feedstock (e.g. naphtha) used in the petrochemical industry in a given region is large, the proportion of propylene and BTX aromatics produced in refineries tends to be lower. The demand for these HVCs does not usually dictate the operating regime of the refining processes in which they are co-produced, which are normally geared towards maximising gasoline and middle distillate outputs.

A trend is emerging for oil companies to expand their business portfolio into petrochemicals, in search of higher and more resilient sources of income. This may involve co-located or integrated facilities or investment in standalone NGL feedstock crackers. Different levels of operational integration can be achieved, up to a full integration aiming to maximise chemical yields across the operation. New direct crude-oil-to-chemicals technologies expand the opportunities for deep operational integration.

The level and type of integration between refining and petrochemical operations varies by region. Europe and Asia both depend on crude oil feedstock imports and have limited local availability of NGLs. Under these circumstances, the case for operational integration is strong. In the United States and the Middle East, ready availability of low-cost NGL, especially ethane, means that the direct upstream-to-petrochemical route is the prevailing option.

Figure 2.12 • Indicative economics for fuels and petrochemicals in Europe



Notes: Composition of 2017 average German retail prices for diesel and gasoline are used and average taxes. Refinery gross margin calculation based on North-West Europe quotes. Ethylene and polyethylene margins calculated based on average prices in Europe.

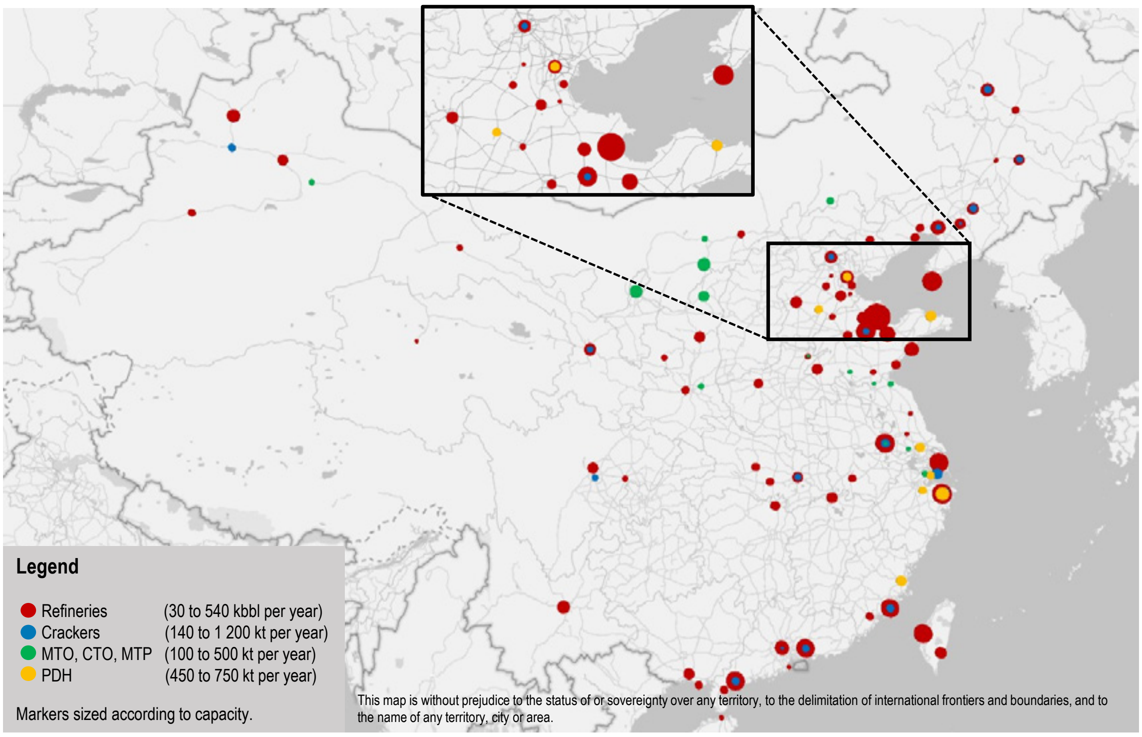
Source: Price data from Argus Media (2018), *Key Prices*, www2.argusmedia.com/en/methodology/key-prices.

Key message • For integrated refiners, the petrochemical path can offer higher margins than fuels.

China has the highest level of refining and petrochemical integration globally. More than three-quarters of the production capacity of HVCs is owned by and takes place in the vicinity of refineries. Sinopec, a Chinese oil and gas company that is the world's largest refiner, accounts for half on its own. Facilities tend to be located in the coastal provinces. A notable exception arises in the case of methanol-based routes to HVCs, which rely indirectly on coal as feedstock. The larger among these plants are located inland, close to coal reserves. One indicator of the general tendency for integration is the fact that the names of most Chinese refineries, whether independent or owned by state-owned oil companies, are more correctly translated into English using the word "petrochemical" rather than "refinery".

China also provides interesting examples of so-called "reverse integration". In these instances, it is the petrochemical company that is moving upstream, rather than the refinery moving downstream. A major fabric company in China, Hengli Group, which is a supplier to global apparel brands, is not only building a petrochemical-oriented 400 kb/d refinery in Dalian, Liaoning province, but has been looking to purchase stakes in Abu Dhabi oil fields. HengYi Petrochemical is another striking example. Initially a synthetic textile company, it expanded into synthetic fibre manufacturing and then moved further upstream. Currently the company is building a refinery in Brunei, geared towards producing petrochemical feedstock for export to China. The choice of an overseas location reflects, in part, the regulated crude oil import quota system in China. Brunei is close to the oil shipping routes through the straits of Malacca.

Figure 2.13 • Major refineries and HVC plants in China



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Notes: Plant locations are not all precisely known. Where the exact location of a plant is unknown, it is placed in the centre of the closest settlement, province or region. CTO = coal to olefins; kbbl = thousand barrels; kt = kilotonne; MTP = methanol to propylene.

Source: Plant locations from Oil & Gas Journal (2017), *Annual Refining Survey*, www.ogj.com/articles/print/volume-88/issue-13/in-this-issue/general-interest/annual-refining-survey.html; expert elicitation.

Key message • China's petrochemical capacity follows refinery placement, with naphtha crackers concentrated in the 11 coastal provinces, while methanol-based output tends to be located in coal-producing regions.

While the Middle East ranks as the third-largest petrochemical producer, its level of petrochemical/refinery integration is low compared to other regions. This may change. In recent years, the largest Middle Eastern oil companies have announced ambitious expansion programmes. The United Arab Emirates' Abu Dhabi National Oil Corporation (ADNOC) announced a USD-45-billion downstream investment plan aiming to create the world's largest refining and petrochemical facility by 2025. The company is also exploring downstream opportunities in India and other growing Asian markets. Such programmes are at least in part explained by the desire to create a more balanced revenue stream, including refining margins. Many of the refinery projects announced include integrated petrochemical units and the continued abundance of ethane and LPG supplies may result in expansion of more direct upstream integrated projects, bypassing refineries.

The direct crude oil-to-chemicals route may soon come to challenge the current model of upstream integration. Saudi Aramco and SABIC have announced a large crude-oil-to-chemicals project of 400 thousand barrels per day capacity, five times the size of the only similar facility operating now, ExxonMobil's plant in Singapore. The Saudi project is expected to come on stream in the mid-2020s. Saudi Aramco is also developing a proprietary technology, based on thermal cracking of crude oil to produce chemicals, which promises a 70-80% yield of chemicals. A commercial design is expected to emerge by 2019. Whether such technology will spread to other regions is uncertain. In oil-importing regions, the margins from direct crude-oil-to-chemicals processes will be lower, due to inherently higher energy requirements (relative to standard technologies) and transport costs for the feedstock. Concurrently, Saudi Aramco is also pursuing other avenues for growth in its petrochemical operations. The company has announced plans to purchase a controlling stake in SABIC, one of the largest petrochemical companies in the world.

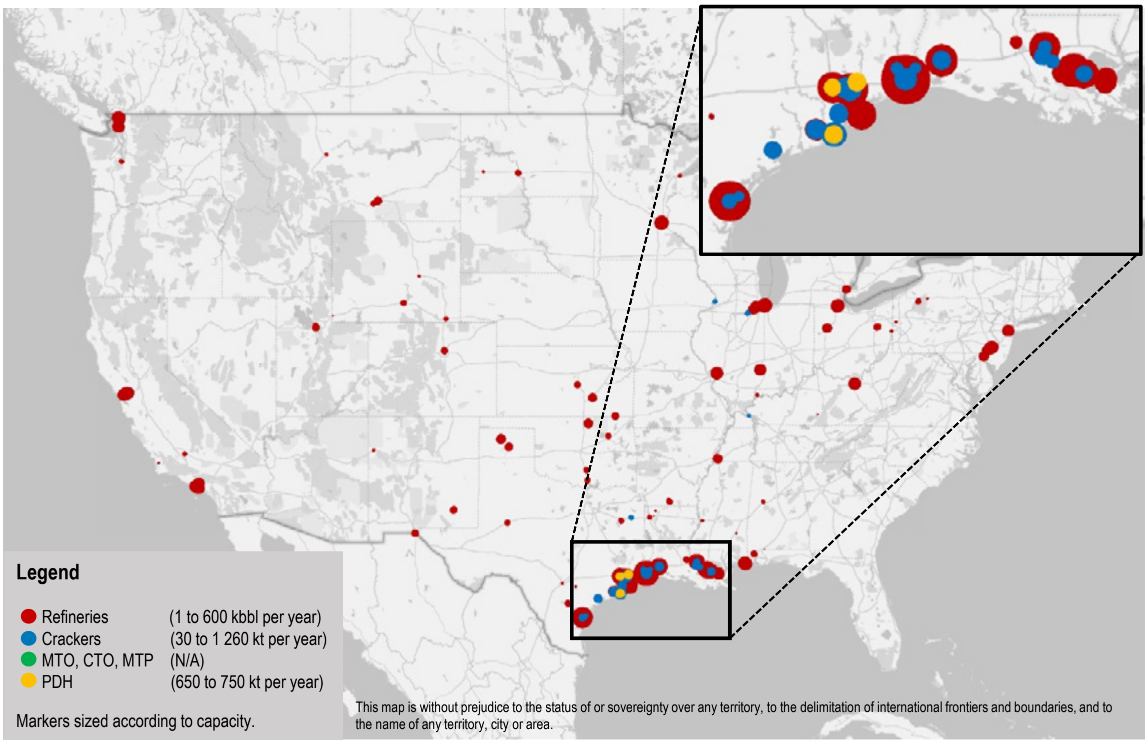
Until recently, Europe was the largest producer of HVCs globally with naphtha providing close to 75% of this feedstock. Despite this, the combined share of gasoline and naphtha in total oil demand in Europe is just above one fifth, while middle distillates account for more than half. Gasoline demand has decreased by a third in Europe in the last decade, due to the switch *o*f the passenger vehicle fleet to diesel. There is an excess of naphtha in Europe, which is exported as gasoline blendstock. Historically, the largest market for it has been in the northeast of the United States, but with higher refinery throughput in the United States, the region is being increasingly supplied by US refiners. Given the expected developments in supply-demand balances for oil products, the gasoline export market opportunities open to European refiners will diminish. Directing naphtha to petrochemical operations would seem an obvious solution; however, there are complex factors at play.

About 40% of European naphtha steam cracking capacity is located within integrated refinery-petrochemical complexes, with non-integrated petrochemical companies accounting for the rest. Increasing integrated share even further would require new investment, either in green-field projects or in the acquisition of assets, similar to the recently announced Saudi Aramco-SABIC deal. Somewhat counter-intuitively, the opposite trend has been observed in Europe.

First, a major petrochemical enterprise, Ineos, was formed on the basis of the petrochemical assets that BP divested in the early 1990s. Later, Ineos purchased two BP refineries, (in the United Kingdom and France), moving up the value chain. A similar transaction by LyondellBasell, however, was not successful, as the former Shell refinery in France purchased in 2008 was closed in 2011, although the petrochemical units have remained in operation. Ineos considered closing down refining operations at the Grangemouth site in the United Kingdom in 2013 when margins dropped, but met strong opposition from the local employees and the refining operations were maintained. The company has turned to US ethane imports to replace falling supplies from the North Sea, becoming the first long-haul importer of ethane in the world. Its two refineries and associated petrochemical plants are now operated in a joint venture with PetroChina, which is the international arm of the China National Petroleum Corporation.

Naphtha steam crackers integrated within refineries in the United States account for less than 20% of total US naphtha cracking capacity. Naphtha is not well placed to compete with much cheaper ethane. Naphtha molecules have been traditionally redirected to the gasoline pool, which makes up about half of US oil product demand. US oil companies have expanded petrochemical operations. Half of US ethane steam crackers are now owned by oil companies and several new projects are in the pipeline. Despite this, there is still greater separation of ownership of refining and petrochemical operations in the United States, relative to other regions. Chemical production still tends to take place in the vicinity of refining operations, primarily on the Gulf Coast. This reflects the fact that the region is a landing point for natural gas and crude oil, attracting both petrochemical producers and refiners to the same region.

Figure 2.14 • Major refineries and HVC plants in the United States



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Note: N/A = not applicable.

Source: Plant locations from Oil & Gas Journal (2017), *Annual Refining Survey*, www.ogj.com/articles/print/volume-88/issue-13/in-this-issue/general-interest/annual-refining-survey.html; expert elicitation.

Key message • The bulk of the petrochemical capacity in the United States is located on the Gulf Coast, coinciding with substantial refining capacity. This is because the region is a hotspot for both natural gas (NGLs for petrochemicals) and crude oil (for refineries) processing.

In short, the regional idiosyncrasies of oil production and demand are an important factor in determining the extent of integration of refining and petrochemical operations. This is especially true for countries that depend on imported feedstocks. In feedstock-surplus regions, gasoline demand can influence the attractiveness of naphtha, both positively and negatively. Conversely, the availability of inexpensive feedstocks from NGL fractionation has a significant impact on the feedstock choice. The role of oil companies in the petrochemical sector seems set to increase, both through operational refining/petrochemical integration and via the more direct avenue of upstream/ petrochemical integration.

A new wave of alternative feedstocks?

A variety of carbon- and hydrogen-containing materials can replace oil, natural gas and coal as chemical feedstocks. Key among these are bioenergy products, which are a source of both carbon and hydrogen. Alternatively, each element can be sourced separately, for instance from gases arising from the iron and steel industry (e.g. coke oven gas (COG)) or from CO_2 and water. The main advantage of alternative feedstocks is that they can offer a net reduction in CO_2 emissions – process emissions during production and end-of-life emissions – relative to traditional feedstocks. The reductions stem from the fact that these substances would have otherwise gone unutilised (even if originally sourced from fossil fuels), or because they are renewable and therefore do not contribute to accumulation of CO_2 in the atmosphere (on a long-term basis).

Ethylene – the most important HVC – is produced on an industrial scale from bioethanol derived from sugarcane and other bioenergy crops. So-called bioethylene is produced by dehydrating (removing water) from the ethanol in a well-established process reaction. This route tends to be competitive only in areas in which bioethanol can be produced at a competitive cost, based on good local availability of bio-based raw materials. Brazil, which derives large quantities of ethanol from the fermentation of abundant sugarcane, hosts 50% of the world's bioethylene capacity. VärmlandsMetanol AB and ThyssenKrupp Industrial Solutions plan to commission the first commercial-scale demonstration plant to produce methanol through biomass gasification in Sweden (VärmlandsMetanol AB, 2017). The process will use similar equipment to coal-based methanol production.

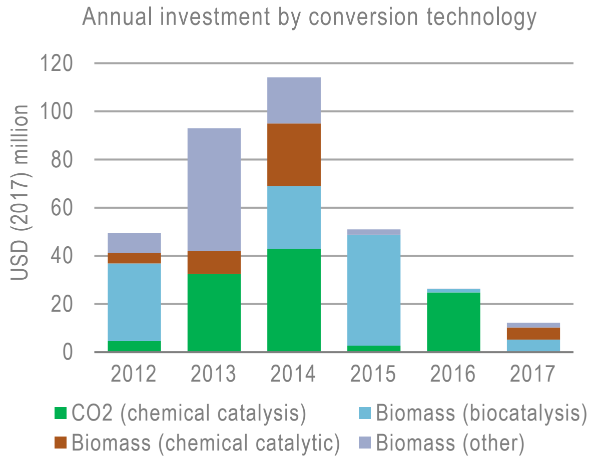
Hydrogen can be produced using water and electricity through electrolysis, as an alternative to using fossil fuel feedstocks. Electrolysis is already widely deployed in industry to produce metals, such as aluminium and lithium. Electrolysis-derived hydrogen can be used in the chemical industry as a building block for all primary chemicals. Combined with nitrogen, carbon and oxygen, hydrogen is used directly to produce methanol and ammonia, and indirectly (via methanol-to-olefins/aromatics) to produce the starting materials for the entire range of plastics and other chemical products. Electrolysers – the key piece of equipment required for electrolysis – operate by passing an electrical current between an anode and a cathode via an electrolyte. Catalysts are used to reduce the amount of electricity required.

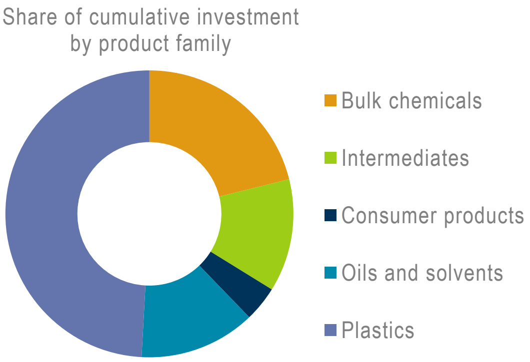
The largest electrolysers ever constructed operated in Norway between 1927 and 1991, fuelled by low-cost and abundant hydropower (Szymanski, 2017). The plants consumed 135 megawatts (MW) of electricity from adjacent hydropower facilities, and each produced 30 000 cubic metres of hydrogen per hour of operation. More recent water electrolysis projects for industrial-scale clean-energy applications have been much smaller, with the average size of a plant installed in 2017 being 0.75 MW (IEA, 2018). Plans have been announced to build a solar-powered ammonia demonstration plant, to be commissioned in 2019 in Australia by Yara, the world's largest ammonia producer (Brown, 2017). Efforts continue in Iowa in the United States to produce solar-ammonia for use both as a fertiliser and as a fuel (Schmuecker Pinehurst Farm LLC, 2017).

The iron and steel sector generates several gases containing valuable components that make them suitable for use as fuels, reducing agents or even feedstock. About 20% of the methanol produced in China today uses COG as feedstock, employing the same technology as coal-based methanol production (without the gasification step). COG contains mainly hydrogen, methane, carbon monoxide and CO_2, and it is generated as a by-product in coke oven plants.

There are various initiatives to explore the use of the gases arising from iron and steel works as chemical feedstock, even where the hydrogen to carbon balance is not as advantageous as in COG. The Carbon2Chem project in Europe aims to demonstrate ways to convert such gases into ammonia and methanol, with production rates fluctuating to support electricity grid balancing needs (Thyssenkrupp, 2017). Processes that biologically convert these gases to ethanol have already been tested in an industrial context in China by LanzaTech and there are further plans to demonstrate this technology at commercial scale in Europe and China (LanzaTech, 2017). Although such gases often have a fossil fuel origin – primarily coal – their use as chemical feedstock can have a positive environmental impact, relative to the use of additional fossil fuel feedstock in their place.

Figure 2.15 • Venture capital investment in alternative feedstocks





Notes: Left-hand graph shows annual value of deals conducted across technology categories. Right-hand graph shows cumulative investment over the same time period subdivided by product category.

Source: Cleantech Group (2018), *i3 Database: The Innovation Network that Drives Sustainability*, www.cleantech.com/i3/.

Key message • CO_2 utilisation and biocatalytic biomass-based processes for the production of plastics have attracted most of the investments.

By-products and waste from other smaller industries and even from domestic food waste can also be used as chemical feedstock. Akzo Nobel, a European chemical producer, plans to build a facility in the Netherlands that will create methanol via the gasification of residual waste (AkzoNobel, 2018). Similar processes exist for producing the hydrogen required for ammonia in Japan (Showa Denko, 2015).

The use of alternative feedstock is at an embryonic stage of development further downstream in the chemical sector. In the absence of mature industrial processes, it is instructive to look at the investments being made in technology start-ups as an indication of where investors see potential for growth in such technologies.

During the five years preceding 2012, when investment in the clean technology sector was buoyant, more than USD 80 million per year was invested in alternative chemical feedstock start-ups, reflecting a trend of rising investment in the biotechnology sector in general. Since the end of the first clean technology surge in 2011, alternative chemical feedstock start-ups, using biocatalytic technologies, have struggled to attract the same levels of funding. One reason for this is the difficulty experienced in scaling up enzymatic conversion technologies from the laboratory to the market in the short time periods that are acceptable to venture capital investors (usually under five years). Enzymatic processes can be highly sensitive to the precise condition of the feedstock and yields can be hard to replicate at scale.

Other biomass conversion technologies, including chemical catalysis, have received attention in recent years, as have technologies promising to convert CO_2 to chemicals. However, since 2015 the value of the deals reported in this sector has fallen significantly, to just USD 10-20 million per year. Despite the promise of alternative feedstocks and the need to achieve sustainability in the chemical sector, the implications are either that investors do not think the near-term market opportunity is significant (or that the market value will be sustained in the long-term), or that there is a lack of new technologies being spun out of laboratories into start-ups. Both trends are of concern to policy makers hoping to guide the world towards more sustainable chemical feedstocks and economic valorisation of sustainable biomass.

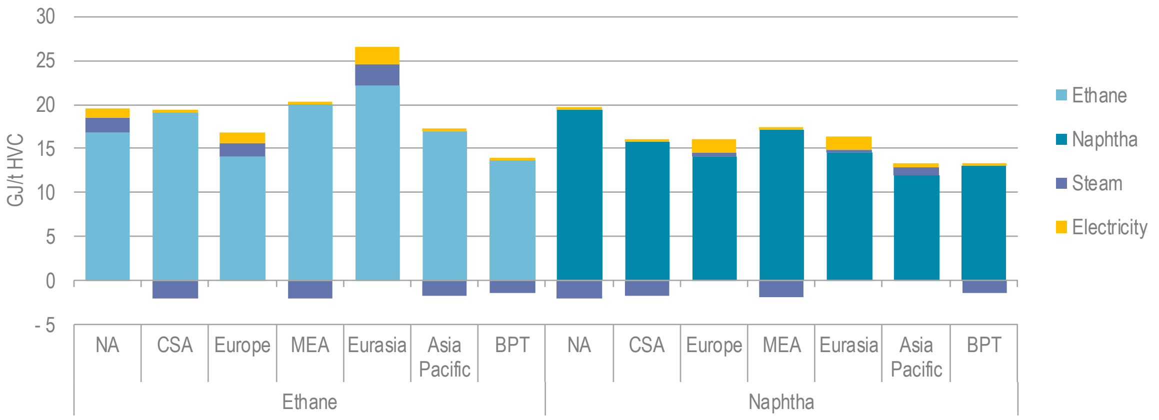
Bio-based plastics, especially for packaging, have attracted the largest share of cumulative investments in alternative chemical feedstock start-ups over the last ten years. This likely reflects that there is significant and growing consumer awareness of the environmental impacts of petroleum-based plastics. The ability to develop a complete plastic product that can be sold to consumer products firms without needing extensive further chemical processing or integration with other value chains is another factor. Furthermore, plastics are a large and rapidly growing market worldwide that is highly differentiated by performance. The implication is that plastics could offer a promising route to the scale up of alternative feedstock.

The energy driving chemical processes

Process energy accounts for just under half of the total energy consumed for primary chemical production. Process energy requirements consist of fuel, steam and electricity. The specific process energy demand per unit of product output (specific energy consumption (SEC)) depends not only on the feedstock used but also on local factors, such as the amount of thermal integration at the site, the age of the plant, and the operating and maintenance practices.

The greatest gains in terms of SEC reductions result from a change in feedstock, from solid to gas or liquid feeds. For coal-based ammonia or methanol, even the best-performing SEC is around twice as high as the SEC related to production from natural gas. By contrast, feedstock changes within the gas or liquid range yield only incremental gains in process energy performance – the differential between the best performing SEC for naphtha and for ethane steam cracking is less than 5%, with the latter typically requiring the greater amount of process energy.

Figure 2.16 • Regional SEC for ethane and naphtha steam cracking



Notes: NA = North America, MEA = Middle East and Africa, BPT = Best Performing Technology, and describes the lowest specific energy consumption currently in commercial use. Regional figures are average values for performance in that region. Fuel requirement is shown on a gross basis, irrespective of the fuel type and the extent of off-gas utilisation for fuel. Negative quantities for steam indicate net steam production.

Key message • Local factors can matter more than the choice of feedstock for process energy consumption in steam cracking.

Local characteristics matter for process energy demand. Heat can be transferred from one gas or fluid to another within a process. This enables, for example, the preheating by hot exhaust gases of tepid input gases, resulting in fuel savings. The net level of steam required in a process can be negative, meaning that the process produces steam in excess of its own demand, as is often the case with steam crackers. This excess steam can be exported to neighbouring processes. Taking the dominant route globally for producing HVCs as an example, the performance of the average Asian naphtha steam cracker is only 10% higher than that of the best performing plant. In other regions, consumption can be up to 50% above the optimum. Whether this results in an overall cost disadvantage depends on fuel prices.

Generally the contribution of electricity to SEC in primary chemical production is relatively small, and it tends not to vary as much between plants as the thermal components. This is because electrical equipment for chemical processes, such as motors, pumps and fans, tends to be relatively uniform and close to maximum efficiency, if sized and maintained correctly.

References

AkzoNobel (2018), *Waste to Chemicals*, https://industrialchemicals.akzonobel.com/sustainable-innovation/waste-to-chemicals/ (accessed 6 June 2018).

Argus Media (2018), *Key Prices*, www2.argusmedia.com/en/methodology/key-prices (accessed 6 June 2018).

Bazzanella, A.M. and F. Ausfelder (2017), *Low Carbon Energy and Feedstock for the European Chemical Industry*, DECHEMA: Gesellschaft für Chemische Technik und Biotechnologie e.V., https://dechema.de/dechema_media/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf.

Brown, T. (2017), *Yara: Solar Ammonia Pilot Plant, for Start-up in 2019*, https://ammoniaindustry.com/yara-solar-ammonia-pilot-plant-for-start-up-in-2019/ (accessed 6 June 2018).

Cleantech Group (2018), *i3 Database: The Innovation Network that Drives Sustainability*, www.cleantech.com/i3/ (accessed 6 June 2018).

European Bioplastics (2018), *Bioplastics Market Data*, www.european-bioplastics.org/market/ (accessed 6 June 2018).

Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use, and fate of all plastics ever made", *Science Advances*, Vol. 3/7, e1700782, https://doi.org/10.1126/sciadv.1700782.

IEA (International Energy Agency) (2017), *World Energy Balances*, OECD/IEA, Paris.

IEA (2018), *World Energy Investment 2018*, OECD/IEA, Paris.

IFA (International Fertilizer Association) (2018), *International Fertilizer Association Database*, http://ifadata.fertilizer.org/ucSearch.aspx (accessed 6 June 2018).

LanzaTech (2017), *LanzaTech Scale-Up and Commercialization*, www.bio.org/sites/default/files/0145PM-Nick Bourdakos.pdf.

Laville, S. and M. Taylor (2017), "A million bottles a minute: World's plastic binge 'as dangerous as climate change'", *The Guardian*, www.theguardian.com/environment/2017/jun/28/a-million-a-minute-worlds-plastic-bottle-binge-as-dangerous-as-climate-change (accessed 6 June 2018).

Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", *Environmental Science and Technology*, Vol. 52/4, p. 1725-1734, https://doi.org/10.1021/acs.est.7b04573.

Oil & Gas Journal (2017), *Annual Refining Survey*, www.ogj.com/articles/print/volume-88/issue-13/in-this-issue/general-interest/annual-refining-survey.html (accessed 6 June 2018).

Schmuecker Pinehurst Farm LLC (2017), *Carbon Emission Free Renewable Energy*, http://solarhydrogensystem.com/ (accessed 6 June 2018).

Showa Denko (2015), *Showa Denko Expands Utilization of Used Plastic to Produce Ammonia*, www.sdk.co.jp/english/news/2015/14469.html (accessed 6 June 2018).

Szymanski, S. (2017), *Green Ammonia and H2@Scale: An Industry Perspective*, www.energy.gov/sites/prod/files/2017/05/f34/fcto_may_2017_h2_scale_wkshp_szymanski.pdf.

Thyssenkrupp (2017), *Research Project "Carbon2Chem" Now Part of KlimaExpo*, www.thyssenkrupp.com/en/newsroom/press-releases/press-release-120288.html (accessed 6 June 2018).

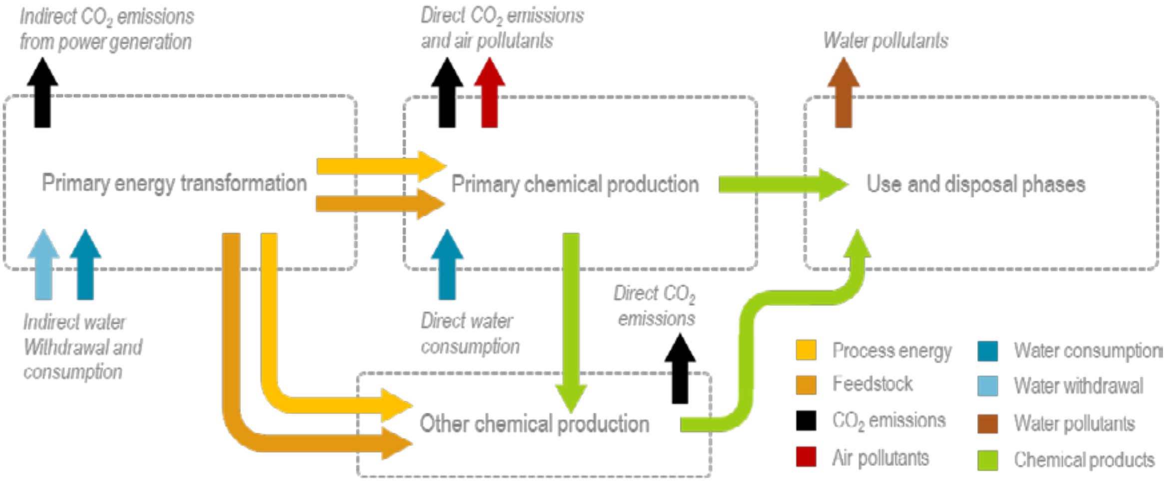
United Nations (2018), *UN Comtrade Database*, https://comtrade.un.org/ (accessed 6 June 2018).

VärmlandsMetanol AB (2017), *World´s First Commercial Scale Biomethanol Plant in Hagfors Sweden*, www.varmlandsmetanol.se/dokument/History_2017.pdf.

Chapter 3. Chemicals and the environment

The environmental impact associated with chemical products is as multi-faceted as their role in society. Among other environmental ills, the production of chemicals leads to carbon dioxide (CO_2) emissions, air pollutants and water demand. But chemical products can also facilitate environmental progress in other sectors. Any boundary drawn around the environmental impact of a product or industrial sector is imperfect. The key environmental constraint considered in this work is direct CO_2 emissions from the chemical and petrochemical sector. This, along with investments and fuel costs, are the key drivers of the technology selections and other results presented in later chapters.

Figure 3.1 • Scope of environmental considerations



Note: The environmental impacts indicated in the figure do not provide an exhaustive account of the environmental burdens associated with the chemical sector and its products, nor does the figure provide an account of the environmental benefits facilitated by chemical products, which are discussed later in this chapter.

Key message • Beyond CO_2 emissions, the chemical sector places a multi-faceted burden on the environment: air pollutants, water demand and water pollutants are key elements to consider.

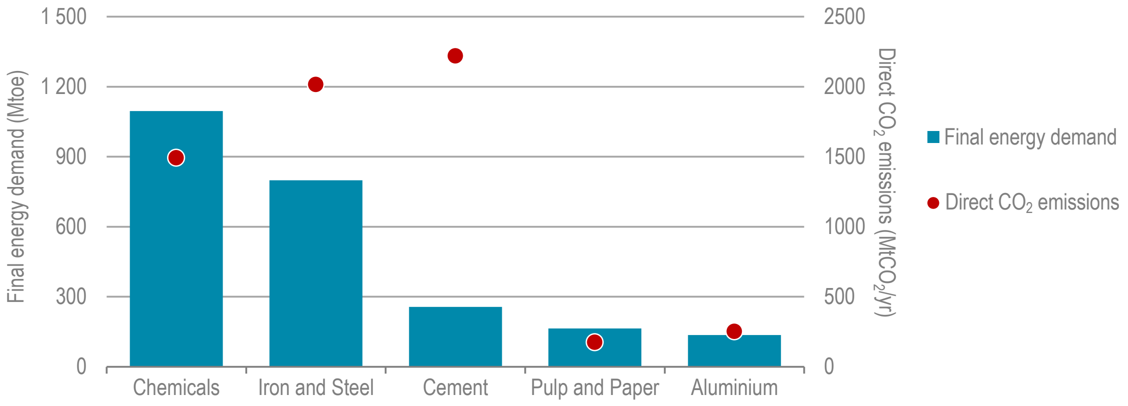
As noted earlier, chemical production, despite being the largest industrial energy consumer, is only the third largest source of industrial CO_2 emissions, followed by the iron and steel, and cement sectors, because more than half of its energy input is used as feedstock and leaves the sector locked into products. Further CO_2 emissions and air pollutants are released during the use of certain chemical products, such as fertilisers and cleaning products. Without effective management of waste and agricultural practices, plastics and fertilisers can cause devastation to marine life when they leak into bodies of water. This chapter explores some key facets of these burdens, concentrating on CO_2 emissions, air and water pollution, and water demand.

CO_2 emissions from the chemical sector

Today, CO_2 emissions from the chemical sector are approximately 1.5 gigatonnes of carbon dioxide ($GtCO_2$) per year globally, or 18% of industrial CO_2 emissions. The sector's emissions stem from two key sources. First, energy-related emissions (1.3 $GtCO_2$ or 85%) are released, as in any other industrial sector, when fuel is combusted to generate heat, both directly and for the production of steam on-site. Second, process CO_2 emissions (0.2 $GtCO_2$ or 15%) reflect the difference in carbon content between the feedstock and the product. For example, if roughly 0.4 tonnes of methane feedstock (75% carbon) is required to make a tonne of ammonia (0% carbon), the process CO_2 emissions per tonne of ammonia product would be approximately

1.1 tonnes of carbon dioxide (tCO_2). Non-CO_2 greenhouse gas emissions from the chemical sector are estimated to be the equivalent of a further 350-400 million tonnes of carbon dioxide equivalent ($MtCO_2$-eq) (Fischedick et al., 2014),[9] but they are not further analysed in this publication.

Figure 3.2 • Global final energy demand and direct CO_2 emissions by sector in 2017



Notes: *Final energy demand* for chemicals includes feedstock, and, for iron and steel, it includes energy use in blast furnaces and coke ovens. *Direct CO_2 emissions* includes energy and process emissions in the industry sector. Mtoe = million tonnes of oil-equivalent.

Key message • Despite being the largest industrial energy consumer, the chemical sector ranks third among industrial CO_2 emitters.

Primary chemicals account for around 60% of the total CO_2 emissions in the chemical sector. Ammonia is the single largest source, contributing 49% of the primary chemicals' CO_2 emissions, followed by high-value chemicals (HVCs) (27%) and methanol (24%). The CO_2 intensity of coal-based ammonia and methanol is, respectively, more than two and half times and almost five times that based on natural gas-based routes.

As might be expected, the regional shares of CO_2 emissions relating to primary chemical production follow regional shares of production, particularly ammonia. Asia Pacific accounts for a particularly large share of process emissions, due to the People's Republic of China[10] using coal as feedstock. The relative proportions of process and energy-related emissions in other regions are similar, with regions utilising lighter feedstocks (e.g. the Middle East) showing lower proportions of process emissions.

As in other industrial sectors, CO_2 generated by the sector has only three possible pathways: it can be released to the atmosphere, utilised or stored. The concept of carbon capture, utilisation and storage (CCUS) encompasses a range of technologies and strategies for mitigating CO_2 emissions. Some of the "lowest hanging fruit" among CCUS applications are to be found in the chemical sector. This is because CO_2 is separated from the process stream, in both ammonia and methanol production facilities, in order to meet the chemical process requirements.

The cost of CO_2 captured from concentrated process emissions from ammonia production can be as little as USD 25 (United States dollars)/tCO_2 (Irlam, 2017). These cheaper opportunities for CO_2 capture from ammonia production are limited by the availability of concentrated emissions

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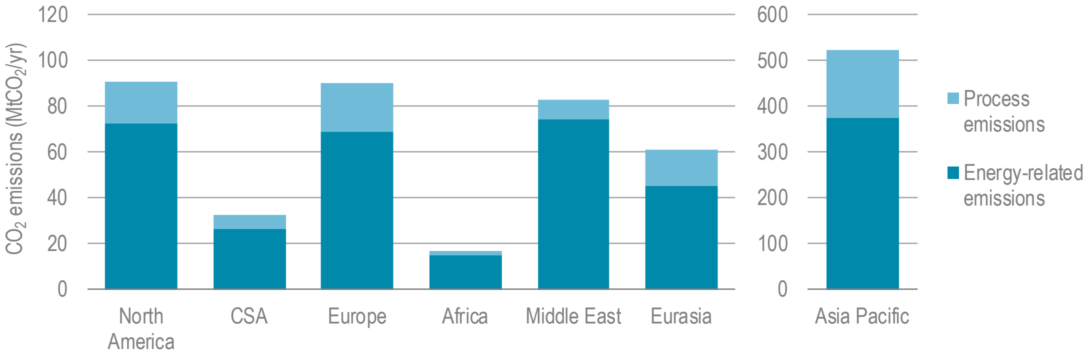
[9] Including hydrofluorocarbons, nitrous oxide, sulphur hexafluoride and methane. Range provided based on a figure of 363 $MtCO_2$-eq provided for 2010.

[10] Hereafter, "China".

streams. Some 1.7 million tonnes of carbon dioxide per year ($MtCO_2$/yr) is captured globally from fertiliser production facilities, beyond that utilised for urea production (Global CCS Institute, 2018). All of this 1.7 $MtCO_2$/yr capture capacity is located in the United States, with the captured CO_2 used for enhanced oil recovery. The volume captured is equivalent to 7% of the country's CO_2 emissions from producing ammonia.

Figure 3.3 • Direct CO_2 emissions of primary chemicals by region in 2017



Note: CSA = Central and South America.

Key message • Regions with high levels of production, particularly of ammonia, generate correspondingly high levels of CO_2 emissions.

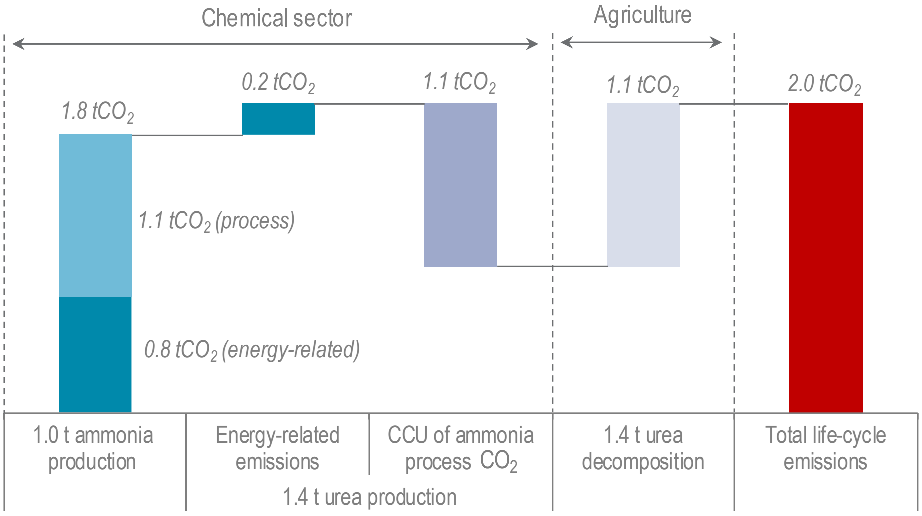
The political climate surrounding CCUS varies among regions, particularly the "S" – storage – component. Encouraging signs can be seen in the United States' recent moves to increase incentives for the storage and use of CO_2 through the so-called "45Q" legislation, which contains a provision to raise the tax credit for the permanent geological storage of a tonne of CO_2 from USD 22 to USD 50 in 2026 (Bennett and Stanley, 2018). It is estimated this could increase CO_2 capture by 10-30 $MtCO_2$/yr over the next six years in the United States, with most of the CO_2 used for enhanced oil recovery.

In some parts of Europe, the outlook is less encouraging. Germany has effectively banned large-scale storage of CO_2 gas (German Government, 2012). The "*Speicherung von Kohlendioxid*" (CO_2 storage act) was signed into German law in 2012, restricting total annual storage to 4 $MtCO_2$. By contrast, the Netherlands has ambitious plans, including funding to store 18 $MtCO_2$ from industrial sources annually by 2030 (Dutch Government Parties Coalition, 2017). This is equivalent to one-third of the Netherlands' targeted industrial CO_2 emissions savings.

The use of CO_2 for specialised purposes, such as the production of urea and carbonated beverages is widespread, but these particular avenues lead to limited – if any – permanent reductions in CO_2 over the full life cycle. As soon as the carbonated beverage is opened or the urea-based fertiliser is applied to the soil, release of the CO_2 to the atmosphere begins again. Additional potential pathways exist for the utilisation of CO_2 as a feedstock elsewhere in the chemical sector, such as forming the carbon content of plastics.

Producing a tonne of urea requires a minimum of 0.73 tCO_2. In rare cases, CO_2 is manufactured or sourced from naturally occurring underground deposits, but in the majority of cases it is provided by an adjacent ammonia plant. Nearly half of all process CO_2 generated during ammonia production globally (almost 130 $MtCO_2$/yr) is used in this way as a raw material input for urea production, with a further 140 $MtCO_2$ being released. Most CO_2 generated during ammonia production is combustion related, totalling nearly 300 $MtCO_2$. It is not so easy to capture the more dilute – and therefore more expensive to separate – CO_2 streams generated in combustion processes.

Figure 3.4 • Indicative life cycle pathway for CO_2 utilisation in urea manufacture and use



Notes: Figures may not sum due to rounding. Emissions quantities indicative of current best practice energy performance, and take no account of the (small) losses that take place along the supply chain. Ammonia production based on natural gas. Energy-related CO_2 emissions do not include any credit for net steam generation. CCU = carbon capture and utilisation.

Key message • Nearly 130 $MtCO_2$ is utilised for urea production annually, but the bulk of this is released downstream in the agriculture sector, sometimes only days later.

CO_2 utilisation for urea production is, by a considerable margin, the largest carbon capture and utilisation application globally. But it is really only a rest stop on the road to emissions release. After the urea leaves the production plant, it is sold, stored, and then applied to the soil in order to fulfil its primary purpose – delivering the nitrogen it contains (46% by weight) to the roots of plants and crops. The CO_2 that was embedded in the urea is then released to the soil and, as the urea decomposes, to the atmosphere.

Air pollutants from primary chemical production

Air pollution is a public health crisis and the fourth-largest overall risk factor for human health worldwide, after high blood pressure, dietary risks, and smoking (IEA, 2016a). More than eight-out-of-ten of the world's urban population live in areas where concentrations of air pollutants exceed the standards laid out in the World Health Organization's Air Quality Guidelines (WHO, 2005). Energy production and use is the main contributor to air pollution, with the key source being combustion of fossil fuels and biomass.

Box 3.1 • What is air pollution?

Air pollution consists of the concentrations in the air of solids, liquids or gases that have a negative impact on the surrounding environment and people. There are many such pollutants and they may occur naturally (from dust, wildfires and volcanoes) or as a result of human activity, be visible or invisible, emit an odour or be odourless. Air pollutants can stay in the atmosphere from minutes to years, depending on their characteristics, and, while often considered a local issue, may actually have a range that is local, national, regional or global. Primary pollutants are those emitted directly as a result of human activity or natural processes, while secondary pollutants are created by the reaction together of primary pollutants, sunlight and other components of the atmosphere. Examples of air pollutants from human activity include:

Sulphur oxides (SO_x), in particular sulphur dioxide (SO_2): fossil fuels, coal and oil contain sulphur to differing degrees. If the sulphur is not removed beforehand, SO_x are released at combustion and enter the atmosphere, if not captured.

Nitrogen oxides (NO_x), nitrogen oxide (NO) and nitrogen dioxide (NO_2): NO_x stem from high-temperature combustion or the oxidation of NO to NO_2 in the atmosphere. NO_2 is a toxic gas that can lead to the formation of particulate matter and ozone.

PM is a mix of solid/liquid organic and inorganic substances that may be a primary or secondary pollutant. PM can have major detrimental health impacts. Size is an important factor in determining these impacts: – "coarse particles" (PM_{10}) are between 2.5 and 10 micrometres (µm) in diameter and "fine particles" ($PM_{2.5}$) are smaller than 2.5 µm. The adverse health impacts of PM_{10} are less severe than those of the fine particles. However, there is a longer history of data collection on PM_{10} and, even today, many cities lack the equipment to monitor outdoor concentrations of $PM_{2.5}$. Black carbon, a particular type of fine PM that is formed by the incomplete combustion of fossil fuels and bioenergy, is a short-lived climate pollutant (SLCP).

Carbon monoxide is a colourless, odourless, toxic gas that comes from the incomplete combustion of fuels.

Volatile organic compounds (VOCs) are released from chemicals, solvents or fuels (as well as natural sources) as they evaporate or sublimate into the surrounding air. They are associated with a range of negative health effects. Methane, the main component of natural gas (also a SLCP), is often considered separately from other VOCs as its characteristics differ.

Ammonia is released from agricultural and waste management activities. Once in the atmosphere, ammonia reacts with oxides of nitrogen and sulphur to form secondary particles.

Ground-level ozone is formed from NO_x and VOCs in the presence of sunlight. At high concentrations, ozone is a pollutant and a SLCP.

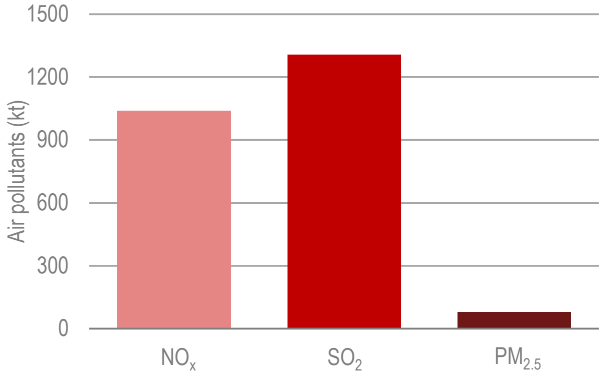
Other pollutants include heavy metals, such as lead (emitted from industry, power generation, waste incineration and, in some countries, from transport fuels) and mercury (mainly from coal combustion). In line with previous analysis by the International Energy Agency (IEA), the range of air pollutants covered in this report is limited to the anthropogenic emissions of SO_2, NO_x and $PM_{2.5}$ (IEA, 2016a).

The energy sector is the largest contributor to annual global anthropogenic emissions of three key air pollutants. This annual contribution is estimated to be around 80 million tonnes (Mt) for SO_2, about 107 Mt for NO_x and 30 Mt for $PM_{2.5}$. The main sources of air pollutants arising from fuel combustion are coal (for SO_2), oil (for NO_X) and biomass (for $PM_{2.5}$). The industrial sector is the largest source of SO_2 (over 45%) and NO_x (26%) within the energy sector, whereas cooking and heating stoves are the largest source of $PM_{2.5}$, contributing more than half (IEA, 2016a).

Among industrial activities, the chemical sector is the second largest source of SO_2 (about one-third) and of NO_x (almost 20%), behind the iron and steel sector. It also contributes to $PM_{2.5}$ (20%). Like most heavy industry, chemical sector activity tends to take place outside urban centres, but emissions from this activity can still have a significant impact on human health. One encouraging factor is that the source of emissions from chemical production is stationary (unlike vehicles, for example). This means several can be taken to mitigate emissions, such as installing specialised combustion and end-of-pipe capture equipment. These options are discussed further in Chapters 4 and 5.

While 2.5 kilogrammes (kg) of SO_2 and 2.0 kg of NO_x are estimated to be emitted per tonne of primary chemical produced globally on average, just 0.2 kg of $PM_{2.5}$ is emitted on the same basis. Combustion-related pollutants from primary chemical production account for almost 50% of the chemical sector's NO_x and around 30% of its SO_2, but around just 20% of its $PM_{2.5}$ emissions. Asia Pacific suffers from substantially higher SO_2 and $PM_{2.5}$ emissions than other regions, due to its widespread use of coal as a source of process energy. NO_x emissions do not follow a consistent pattern between regions, linked to the dominant fuel, as factors affecting its release tend to have more to do with the characteristics of the combustion equipment used.

Figure 3.5 • Air pollutants relating to primary chemical production in 2017



Notes: kt = kilotonne. Estimates of air pollutant emission levels refer to combustion-related sources in primary chemical production. The main non-combustion sources of these air pollutants tend to be located downstream of primary chemical production, e.g. NO_x from nitric acid production. International Institute for Applied Systems Analysis/IEA joint analysis.

Key message • NO_x emissions from primary chemical production tend to exceed those of SO_2, apart from in Asia Pacific where coal use for chemical production takes place on a large scale.

Water demand for primary chemicals

Water is essential for economic activity, life and wellbeing. It is also a critical input for the production of energy. Water is required at each stage of energy production, for fossil-fuel extraction, transport and processing, power production and irrigation for biofuels. Water can also be extracted as a by-product of fossil fuel extraction. Water is used in the chemical industry for a variety of purposes, including the cleaning and flushing of process units, steam generation and for use as feedstock.

Though water is ubiquitous, freshwater makes up just 2.5% of the global water resources, with less than 1% available for human consumption. The amount of water available varies by country and annual averages often hide the variability that occurs by season. While pockets of water stress[11] occur in most countries, recent estimates indicate that more than a third of the global population is affected by water scarcity[12] (United Nations, 2018b).

Population increase, economic growth and the associated rise in water demand, coupled with uncertainty about the impact that climate change will have on water resources, could lead to a more water-constrained future. However, it is not just quantity that impacts availability – the quality of water also matters. While potable water is not needed for all purposes, where it is necessary, the water treatment processes can be costly and energy-intensive. Nonetheless, in areas that experience water scarcity, alternative non-freshwater sources, such as wastewater, brackish water or seawater, might offer the best option to meet growing water demand.

Water use is commonly assessed using two measures: withdrawal and consumption. Withdrawal is the volume of water removed form a source, while consumption is the volume withdrawn that is not returned to the source (i.e. evaporated or transported to another location) and is no longer available. Withdrawals are always greater than or equal to consumption and represent a first limit when water availability is constrained.[13] Water

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[11] Defined as when renewable annual freshwater supplies fall below 1 700 cubic metres (m^3) per person.

[12] Defined as when renewable annual freshwater supplies fall below 1 000 (m^3) per person.

[13] Overdrawing groundwater resources faster than the recharge rate can also be problematic as it lowers the water table and can lead to increased salinity of water supply.

consumption reduces the amount of water available to satisfy demand and is an important criterion in areas where water resources are already strained.

Today, the agricultural sector is the largest water user, accounting for roughly 70% of water withdrawals and the bulk of water consumption. The industrial and energy sectors together account for roughly 20% of global water withdrawals and around 12% of global consumption (IEA, 2016b).[14] Water availability[15] is increasingly an important measure for assessing the viability of industrial and energy projects.

The water used for primary chemicals accounts for about 1% of the water withdrawn and 4% of the water consumed in industry. Direct water demand estimates for primary chemical production include water uses as feedstock (e.g. steam cracking). Water demand for process heating is excluded due to the wide range of possible configurations for steam systems across chemical sites.

In primary chemical production, water and energy intersect in two main ways. Most of the water used is needed indirectly, for producing primary energy (i.e. oil, gas, bioenergy) and generating the electricity that is demanded by the chemical processes. Today, about 45% of water withdrawn for primary chemical production is consumed, with around three-quarters in indirect use. The remainder is used directly as feedstock in chemical processes such as steam reformers and steam crackers. As some of these processes occur at high temperature and pressure, high-purity freshwater is a necessity. Among primary chemicals, ammonia is the most water-intensive, with around 1.3 cubic metres per tonne (m^3/t) on a global, average, direct-consumption basis, followed by HVCs (0.8 m^3/t) and methanol (0.6 m^3/t). Water intensities for each primary chemical vary regionally depending on the share of each process technology and fuel.

While the risks for water-scarce regions are obvious, even regions that have ample water resources may face constraints related to drought, seasonal variation, climate change, floods, water pollution, and regulations. Global aggregates give some overall guidance, but assessment of the impact of water stress and competition between users associated with water withdrawals and consumption, needs to be location-specific.

Asia Pacific accounts for about half of total water withdrawals and consumption in primary chemical production globally. China accounts for about 80% of water withdrawals in Asia Pacific (primarily indirect), due to the presence of coal-fired power using once-through cooling technologies.[16] While once-through cooling technologies are generally more efficient and have lower capital costs compared to wet-tower and dry cooling, they require the highest water withdrawal rate. A high level of coal demand for primary chemical production also contributes to water withdrawals, with China accounting for the bulk of global use of coal as feedstock for ammonia and methanol production. Coal-fired power generation (commonplace in China) that uses wet-tower cooling systems withdraws less water, but *consumes* more relative to other cooling technologies.

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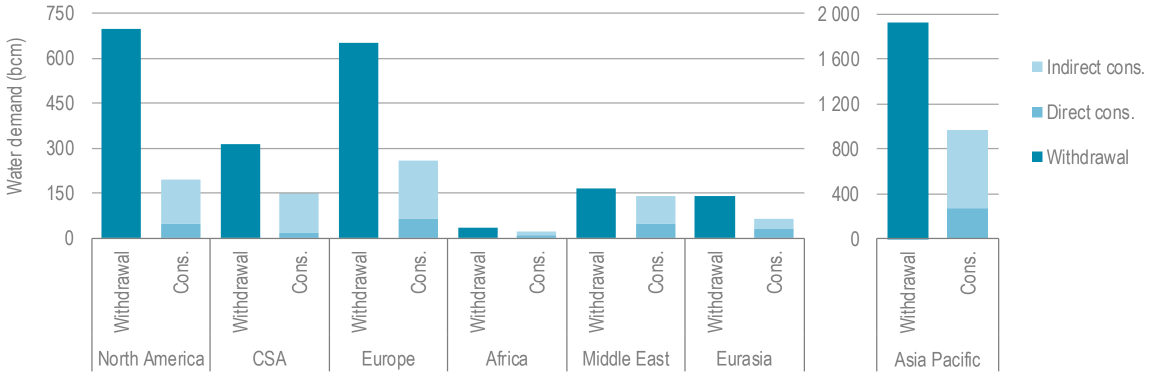
[14] Many analyses report only industrial water withdrawals and consumption, including for energy use. The IEA, which disaggregated this in 2016, found that the energy sector accounts for 10% of total global water withdrawals and 3% of total global consumption.

[15] Analysis in this report focuses on freshwater use. While non-freshwater sources are already being used, either to replace or complement freshwater, in many places the use of alternative sources is at a nascent stage or is not yet economic, relative to freshwater.

[16] *Once-through* is also referred to as *open loop cooling*.

Figure 3.6 • Water demand for primary chemical production by region in 2017



Notes: bcm = billion cubic meters; cons. = consumption. Direct water demand estimates for primary chemical production include water uses are feedstock (e.g. steam cracking). Water demand for process heating is excluded because of the wide range of possible configurations for steam systems across chemical sites.

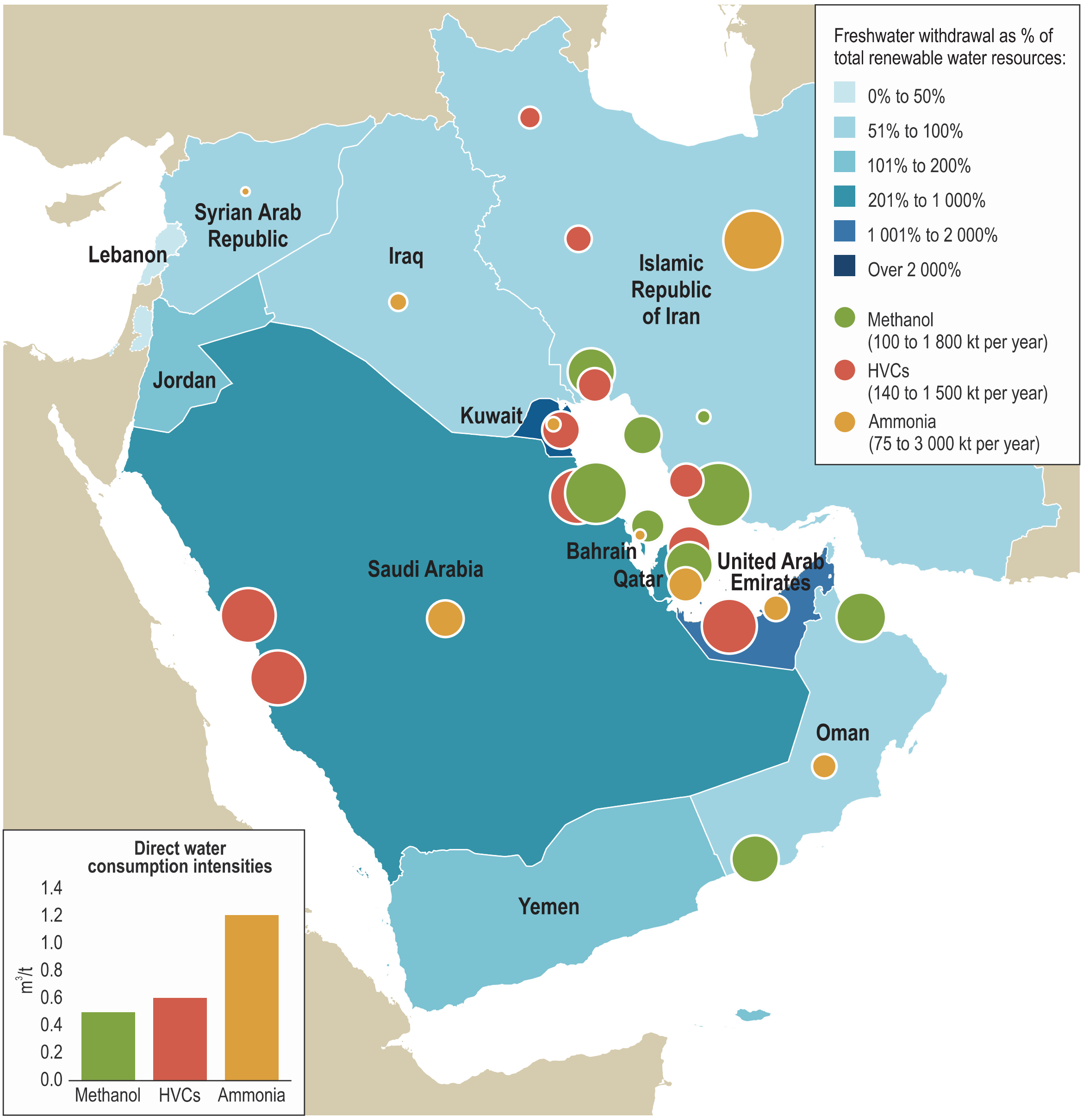
Key message • Asia Pacific accounts for more than half of total water withdrawals and consumption in primary chemical production globally.

Both North America and Europe each account for roughly 15-20% of total global water withdrawals for primary chemical production and for around 10% and 15%, respectively, of total water consumption. Nuclear power – which on average withdraws more water per unit of energy than coal or natural gas plants – plays a greater role in electricity generation in these regions than in Asia Pacific and the Middle East. Direct water use per unit of primary chemical produced is about 30% lower in North America compared to Europe. This is because Europe has a high share of total ammonia production, the most direct water-intensive primary chemical.

While the Middle East's share of global primary chemical production is similar to that of Europe and North America, the region's water withdrawals for this activity represent only 4% globally, and only 8% of water consumed. Indirect water demand for primary chemical production in the Middle East is low relative to other regions, owing to the use of oil and gas for fuel and feedstock. However, it is worth noting that the sector consumes much of what it withdraws. In contrast, the direct use of water per tonne of primary chemical is similar to that in North America because a similar range of primary chemicals is produced. This, in combination with relatively low indirect consumption, leads to a greater share of direct water use in total consumption than in most other regions.

The majority of the primary chemical production capacity in the Middle East is located on the coastline of the Persian Gulf, to facilitate trade. Unfortunately, this area includes some of the most water-stressed countries in this part of the world, including Kuwait, Saudi Arabia, Qatar and United Arab Emirates, where water scarcity is already a major concern. Rising demand for water for increased primary chemical production may cause the region to rely more on costly and energy-intensive forms of water supply such as desalination.

Figure 3.7 • Primary chemical production capacity and water stress in the Middle East



Notes: The direct water consumption intensities displayed are the average for the Middle East region. Direct water demand estimates for primary chemical production include water uses as feedstock (e.g. steam cracking). Water demand for process heating is excluded because of the wide range of possible configurations for steam systems across chemical sites. Ammonia plant capacity is shown for each country as a whole since specific plant locations were not available.

Source: WRI (2018), *Aqueduct Database*, www.wri.org/our-work/project/aqueduct.

Key message • Primary chemical production is concentrated along the coastal Persian Gulf increasing concerns over water stress in these regions.

Environmental impacts of chemical products

Chemical products are one of the key materials used in a multitude of end-use sectors. A "late bloomer" among industrial sectors, the chemical sector has increased its market size by producing substitutes for other materials such as wood and metals. As discussed in Chapter 1, these are now the first choices among materials for many end-use applications. Consumer goods and packaging materials rely extensively on plastics, but plastics are also making inroads into the sectors traditionally dominated by other materials, such as buildings and transport, partly because of increasing attention paid to energy savings and emissions reduction in these sectors. Conversely, chemical sector outputs can also be deployed to make inefficient or wasteful devices and products, leading to emissions in other sectors. They can even become pollutants themselves.

Chemical products can help reduce emissions in other sectors

Improving the thermal performance of buildings, using efficient construction practices, and renovations targeted at improving energy efficiency have the potential to save the equivalent of the annual energy usage of all the Group of 20 major world countries in 2015 (UNEP and IEA, 2017). Enhanced insulation materials are required to capture this energy saving potential. Because of their enhanced engineering properties, synthetic insulation materials (most of which are plastic-based) make up 90-95% of all thermal insulation material production (Bozsaky, 2011). For example, the thermal resistance of polyurethane is among the highest in its class of insulation materials. Low-pressure expandable foams can also significantly reduce air leakages and thermal bridges (i.e. paths for heat transfer within the building envelope). Reflective roof coatings, made of plastics, are known to help cool buildings in warmer climates.

However, using chemical-based insulating materials has broader environmental impacts. For instance, the embodied CO_2 (the emissions released during its manufacture) of polyurethane and polystyrene is higher than that in naturally occurring insulation materials, and they are also more difficult to recycle. The buildings and construction sector is the second-largest user of plastics after packaging. This sector needs to seize the opportunities for energy efficiency that are offered by chemical-based products while also considering potential externalities, especially at the production and end-of-life phases. A key enabling action is to provide better information to designers and specifiers during the design process.

The material mix of vehicles in the transport sector is dominated by conventional steel alloys. However, the ever-growing pressure for fuel efficiency improvement and the rapid uptake of electric vehicles are gradually changing the picture. At present, fuel efficiency policies cover 80% of global passenger car sales and 50% of global truck sales, and the coverage (and stringency) of efficiency regulations seems set to increase.

The use of lightweight materials – plastic-based materials, as well as other materials, such as high strength steel and aluminium – is an important pathway to a significant improvement in the fuel efficiency of vehicles. The trend is already visible. In the United States over the period 1995-2014, the share of plastics, plastic composites, and rubber in the material composition of light-duty vehicles has grown on average from 10.5% to 13.2% (Dai, Kelly and Elgowainy, 2016).

Resins that are reinforced with carbon fibre are one of the most common plastic-based materials used in lightweight vehicle design, but, on an industrial scale, recycling options for this material remain elusive, mainly because of the tendency to damage the fibres during the recycling process. Moreover, some characteristics of recycled carbon fibres are not well controlled, including their origin, which diminishes confidence in the performance of recycled carbon fibre material. This means the recycling of plastic composites is typically open loop, because recycled carbon fibres cannot be used again for the same application (Oliveux, Dandy and Leeke, 2015).

The share of lighter materials in vehicles is likely to continue to increase, as countries introduce specific targets for light-weighting. For example, based on a 2010 baseline the United States has set targets for reducing vehicle weight by 30% and 50% by 2025 and 2050, respectively (US DOE, 2013). The growing adoption of electric vehicles, where the challenge of weight reduction to increase driving range is acute, could also translate into greater use of plastic and plastic-based composites. The widespread deployment of autonomous, connected, electric and shared vehicles could also increase the potential for the use of plastics in cars, if confidence in the prospect of fewer and less-severe accidents in such vehicles extends the reach of plastics into a core structural role. Such a development could challenge conventional notions of automotive design, for example, the use of steel for frames and panels.

Chemical products can also play a role in the next round of cost reductions in renewable energy generation. For example, in the wind energy sector, light-weight plastic-based materials can help address the challenges of making longer turbine blades, thereby increasing generation efficiency. Innovative materials can also help increase the durability of wind turbines, thus reducing the cost of maintenance. This is especially beneficial in harsh environments, such as those offshore.

Indirect emissions associated with chemical products

Despite their benefits, chemical products also come with environmental burdens. For example, chemical products are now one of the main sources of VOC emissions. While such emissions from vehicles have increasingly come under scrutiny by regulators in recent years, less attention has been paid to emissions from chemical products. Recent research suggests that chemical products such as adhesives, paints and pesticides now rival vehicle emissions as the top source of urban air pollution (McDonald et al., 2018). This underlines the need for a careful assessment of the net emissions impacts of material selection.

Although chemical products can contribute to GHG emissions mitigation in other sectors, they also generate such emissions, both upstream and downstream. As discussed earlier in the chapter, the largest source of such (indirect) CO_2 emissions upstream is the provision of the energy demand of the sector. For instance, global CO_2 emissions from the electricity consumed in the chemical sector are estimated at around 110 $MtCO_2$, which is equivalent to 8% of the direct CO_2 emissions from chemicals production. Downstream, agriculture and waste management are the two sectors that generate most of the GHG emissions related to chemical products.

When nitrogen fertilisers are applied, they undergo chemical reactions with air and the water in soils during the process of delivering their nutrients to plants. These reactions emit nitrous oxide (N_2O) as a by-product to the atmosphere, a powerful GHG that is 265 times as strong as CO_2. Emissions of N_2O from synthetic fertilisers are estimated to be 2.3 Mt of N_2O per year. This is the equivalent of 610 $MtCO_2$, or about 40% of the direct chemical sector CO_2 emissions (FAOSTAT, 2018). Urea – the largest volume nitrogen fertiliser – contributes more than half of these N_2O emissions as well as releases the CO_2 that was embedded within it during manufacture. CO_2 emissions from urea decomposition are estimated at around 130 $MtCO_2$/yr, equivalent to about 9% of direct CO_2 emissions from the chemical sector. The oxidation of solvents, surfactants, explosives and fuel additives during use are other sources of downstream GHG emissions. These use-phase emissions quantities are uncertain, but, in any case, are likely to be dwarfed by the agriculture sector emissions (Neelis et al., 2005).

Environmental impacts of product disposal

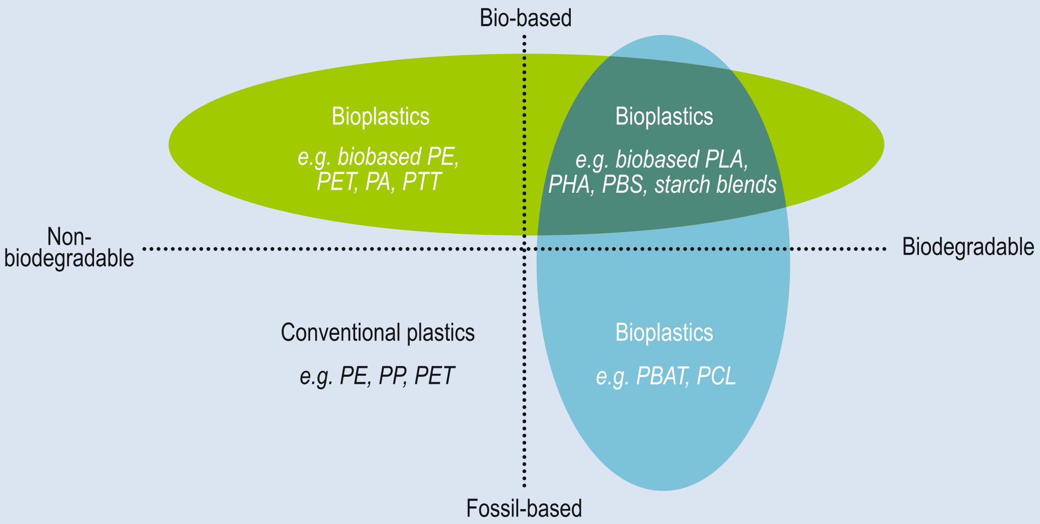
There are several environmental problems associated with the improper disposal and management of plastics, particularly after they enter waste streams. Aside from recycling (discussed previously), there are two other options for dealing with plastic waste: incineration and landfilling. Both tend to be much cheaper than recycling, mainly because the plastics need not be separated from the other components of solid municipal waste streams. Cost is not the only concern. Waste incinerators can cause local air pollution, if not properly designed and maintained. Landfills can lead to water pollution, air pollution, GHG emissions (e.g. methane). They are also an eyesore.

Box 3.2 • Distinguishing bio-based, biodegradable, and compostable plastics

"Biodegradable" plastics and "bio-based" plastics are often confused because they both include the prefix "bio". Bio-based plastics are by definition those made from biomass sources, such as corn and maize, whereas biodegradable plastics are not necessarily made from biomass feedstock. "Bioplastics" is a broad term used to refer to both of these plastic categories individually, or collectively.

Biodegradability is the property that enables a material to be broken down into water, CO_2, methane, and some other materials in a reasonable time frame. This work is carried out by microorganisms, which require certain conditions of light, temperature and humidity. In practice, a large portion of biodegradable plastic is made from traditional petrochemicals, in some cases with the biodegradable property enhanced by the use of additives.

Figure 3.8 • Origins and properties of bioplastics



Notes: PA = polyamide; PBAT = polybutylene adipate terephthalate; PBS = polybutylene succinate; PCL = polycaprolactone; PE = polyethylene; PET = polyethylene terephthalate; PHA = polyhydroxyalkanoate; PLA = polylactic acid; PP = polypropylene; PTT = polytrimethylene terephthalate.
Source: Image reproduced based on European Bioplastics (2018), *Bioplastic materials*, www.european-bioplastics.org/bioplastics/materials/.

Biodegradable plastics are also different from compostable plastics. Biodegradability is but one of the many properties required for a material to be compostable. For compostable plastics, the pace of degradation must be consistent with known compostable materials (e.g. cellulose), and the process should not generate any toxic residue. The European Union considers a material compostable only if over 90% of the original material can be broken down by biological processes within six months.

Biodegradability can be a useful feature in certain circumstances. However, the environmental benefits of biodegradable plastics are much-debated. When landfilled, or if they make their way into the ocean, they often do not degrade as advertised, as the necessary environmental conditions are not met. Even with favourable conditions, it can take years for these materials to degrade. As these plastics are not recyclable, they can compromise the quality of collected scrap materials when mixed in recycling bins, thus undermining the efficiency of recycling processes.

Furthermore, they can give a false sense that there is no problem in throwing away these plastics. When littered, there is a high chance of the degraded fragments being consumed by animals. It could be argued that the biodegradable quality expedites emission of the carbon contained in the material. Biodegradability does not offset the damage caused by irresponsible littering or the inadequate management of plastic waste.

Incineration of plastic waste can be carried out with or without energy recovery. The former requires more capital investment, but has the advantage of providing an energy source from waste. With or without energy recovery, in order to prevent pollution, sophisticated combustion and cleaning equipment, such as low-NO_x burners and flue-gas scrubbers, is needed to remove the toxic components of the exhaust gas to prevent local pollution.

Incineration of plastic waste without energy recovery should generally be avoided, but it persists today as an attractive option in jurisdictions that are land- and cost- constrained. This is because the plastic portions of waste are highly calorific, with many resins containing an amount of embedded energy that is similar to that of crude oil, per unit of mass. Burning waste reduces its volume by roughly 90%, which reduces the amount of land that is required for landfill sites. But, unconstrained, this approach to incineration results in CO_2 emissions while wasting a potential source of energy.

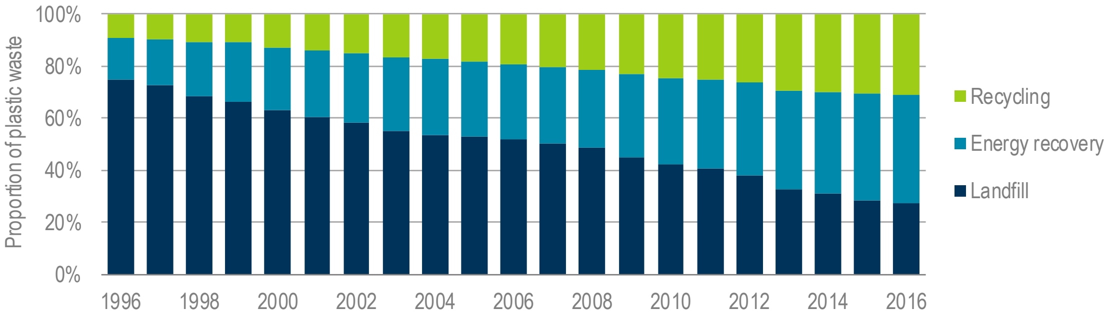
Leaving aside incineration without energy recovery, landfill is the least favourable option for managing plastic waste. Landfill leads to multiple sources of pollution, especially when poorly managed. It is estimated that 11% of global methane emissions stem from landfill sites (Global Methane Initiative, 2011). Landfill sites also contaminate water supplies and create significant health and safety hazards for nearby inhabitants.

Sorting both domestic and imported waste is a source of income in some developing economies, but working conditions tend to be insalubrious and unsafe in these mainly "informal sectors" of the waste management economy. Plastics are often "burned on the go" in the pursuit of more valuable materials, such as the gold and rare earth metals found in small quantities in waste electronic equipment. In areas with substantial stockpiles of such equipment and other valuable waste streams, "landfill mining" has emerged as a formal source of multiple scarce and valuable resources. Like its informal counterpart, landfill mining presents significant health and environmental risks if not conducted properly. Furthermore, plastics are of relatively little value, highly mixed and difficult to extract.

Compared with other materials, the low recycling rate for plastics (post-consumer collection rates for recycling), diminishes the environmental case for the increased use of chemical products in other sectors. Less than 20% of plastic waste is collected for recycling, whereas the rates for steel and paper amount to around 80% and 60%, respectively. This suggests that proper management of plastic waste and strengthened efforts to improve recycling are a crucial prerequisite to the claim that using them as substitutes has a positive impact on the environment overall.

Progress has been made in this direction in certain regions. In Europe, plastic recycling and energy recovery from plastic waste have both steadily increased by 6% annually during the past decade, and in 2016, recycling overtook landfilling as a destination for plastic waste for the first time. Korea and Japan achieved this feat several years earlier, with landfill rates in each country being in single digits.

Figure 3.9 • Plastic waste by management route in Europe



Notes: 1996-2004 = EU15, Norway and Switzerland; 2005-13 = EU27, Norway and Switzerland; 2013-16 = EU28, Norway and Switzerland.

Sources: Plastics Europe (2007), *The Compelling Facts About Plastics 2007*, www.plasticseurope.org/application/files/1515/1689/9283/2007CompellingFacts_PubOct2008.pdf; Plastics Europe (2013), *Plastics – the Facts 2013*, www.plasticseurope.org/application/files/7815/1689/9295/2013plastics_the_facts_PubOct2013.pdf; Plastics Europe (2017), *Plastics – the Facts 2017*, www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf.

Key message • Plastic recycling overtook landfilling for the first time in Europe in 2016.

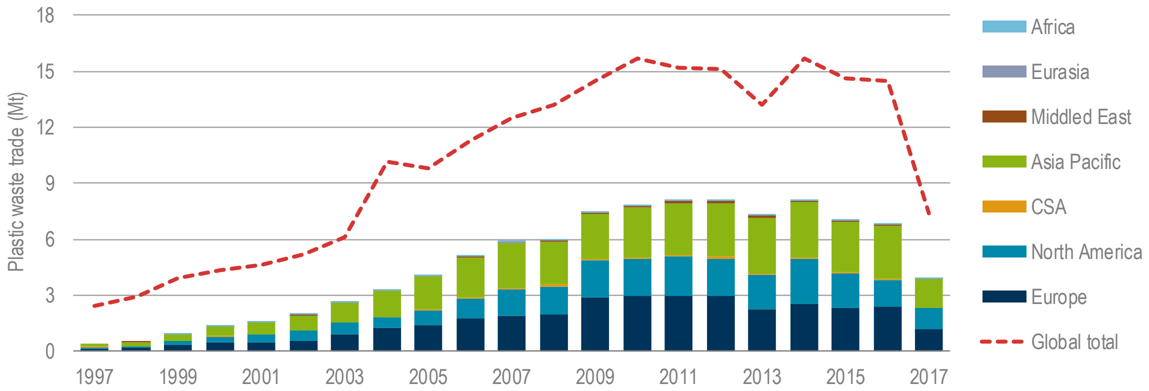
During disposal and recycling, enzymatic and other innovative chemical pathways can be deployed to decompose or degrade plastic waste. Mobilising these reactions requires capital-intensive process equipment and substantial quantities of energy, and it often incurs a significant yield loss. However, promising advances are taking place. In 2016, researchers identified a naturally occurring enzyme that evolved in Japanese landfills to “eat” polyethylene terephthalate (PET) plastic – now appropriately named “PETase” (Yoshida et al., 2016). In 2018 it was discovered accidentally that breaking down the PET plastic into manageable chunks increased the rate at which the enzyme can consume the PET (University of Portsmouth, 2018). This and similar innovations hold out a prospect of making chemical recycling competitive with virgin plastic production in the future, thus reducing costs and the consumption of energy and natural resources.

Plastic waste trade

Regional variations in waste management policy, including landfill, and the differing amounts of solid municipal waste produced by different economies have contributed to the phenomenon of waste being traded and shipped around the world. Trade in plastic waste peaked in 2014 at almost 16 Mt globally, the equivalent of nearly 5% of global plastic production in the same year. Global trade in plastic waste has since declined. A sharp decrease took place in 2017, when global traded volumes almost halved, compared to the previous year.

China receives around half of the plastic waste exported globally, with volumes amounting to 7 Mt in 2016 and 4 Mt in 2017. Asian countries supply around 40% of these quantities, with Europe and North America each supplying approximately a further 30% (United Nations, 2018a). In a radical recent shift in policy, as of 1 January 2018, China severely limited the import of post-consumer plastic waste from other countries. It intends to ban the practice completely in 2019. Recently compiled data on trade suggest plastic waste exports to China already decreased by roughly 40% in 2017, compared to the previous year. This policy development will put pressure on waste-exporting countries to implement measures that reduce waste generation and to develop adequate domestic infrastructure to manage the waste that is generated.

Figure 3.10 • Plastic waste exports to China by region



Notes: Exported plastic waste data are based on International Standard Industrial Classification Commodity Code No. 3915. CSA = Central and South America.

Source: United Nations (2018b), UN Comtrade Database, *https://comtrade.un.org/*

Key message • Plastic waste exports to China plummeted by roughly 40% during 2016/2017.

Water pollutants

There are many ways that chemical products enter waterways, including agricultural run-off, domestic and commercial wastewater containing cleaning and sanitary products, and leakage from landfills and disposal sites. Chemical products can be dissolved in these streams, float on top, or be dispersed on river or ocean floors. Two important examples, related to the largest synthetic chemical product families explored in this report (i.e. fertilisers and plastic), are plastic waste leakage and the contribution of fertilisers and detergents to eutrophication, whereby a surge in algae growth deprives all other life of oxygen, leading to suffocation.

Plastic pollution in the world's oceans has gained much attention in recent years. Plastics make their way into water courses in a variety of ways. One example is the plastic micro-beads, used in cosmetics and personal care products, which are flushed into the sewer system during and after use, thereby eventually ending up in waterways. Another is synthetic microfibres, which are shed from clothing during washing.

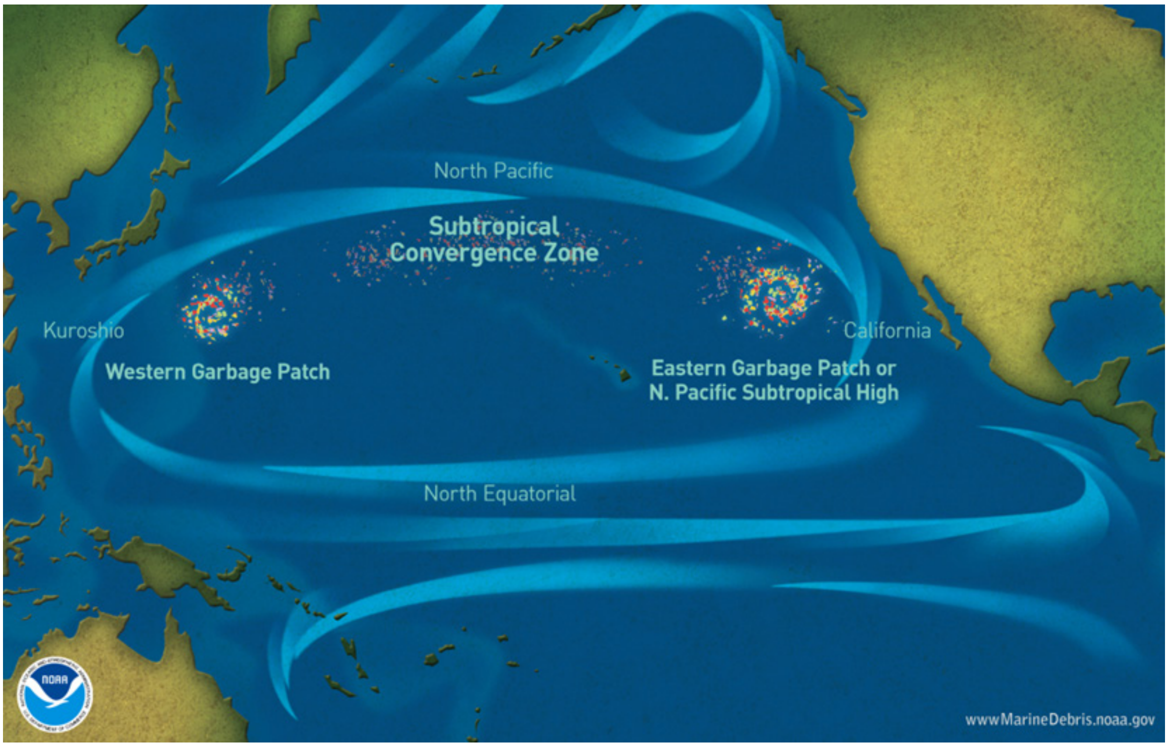
Unfortunately, the quantities and sources of plastic waste leaking into the oceans are particularly difficult to measure and identify. While the numbers are approximations, it has been estimated that the quantity of land-based plastic entering the ocean in 2010 was 5-13 Mt (Jambeck et al., 2015). In the absence of substantive remedial action, the leakage rate is likely to have increased in line with the strong growth in plastic demand/disposal.

It is estimated that 80% of the plastic in the ocean derives from land-based sources, as opposed to fisheries and ships, and that, of this portion, more than half can be attributed to five countries: China, Indonesia, Philippines, Thailand, and Viet Nam (Ocean Conservancy, 2015). Around three-quarters of the plastic leakage in the oceans that originates on land has never been collected as waste; but the other quarter leaks from within waste management systems.

When plastic waste finds its way into the ocean, ultraviolet radiation from the sun breaks it down into small pieces, reaching microplastic status at five millimeters or less in size (NOAA, 2014). Microplastics are commonly mistaken for plankton and are ingested by marine life, leading to choking and starvation. As the mass of larger debris – including containers, bottle caps, crates and old fishing gear – continues to degrade over time, the quantity of microplastics could increase 30-fold. The most common type of plastic waste found in marine debris is polyethylene (used in products such as plastic bags, bottles and plastic wrap) followed by polypropylene (used in bottle caps, food wrappers and food containers) (NOAA, 2014).

In the Pacific Ocean, currents have concentrated a substantial portion of this plastic into what has become known as the "Great Pacific garbage patch" or "Pacific trash vortex" (NOAA, 2017a). The name may suggest a large island of visible waste floating on the surface of the ocean. However, much of the debris comprises microplastics that are distributed throughout the water column and are not immediately visible to the naked eye.

Figure 3.11 • Pacific Ocean garbage patches



Source: NOAA (2014), *The Global Plastic Breakdown: How Microplastics are Shredding Ocean Health*, https://seagrant.noaa.gov/News/Article/ArtMID/1660/ArticleID/251/The-Global-Plastic-Breakdown-How-Microplastics-Are-Shredding-Ocean-Health.

Key message • The largest among the Pacific Ocean garbage patches is estimated to measure 1.6 million square kilometres (km^2), approximately equivalent to three times the size of France.

Various estimates of the size of the Pacific garbage patch have been made, the largest of which is 1.6 million km^2, or three times the size of France (Lebreton et al., 2018). The quantity of plastic has been estimated at 1.8 trillion plastic pieces, weighing some 79 kt. This is the equivalent to 250 pieces of plastic for each person in the world and the weight of 500 jumbo jets.

However, since there is not a single continuous patch of waste and, since ocean currents and winds are continuously mixing, moving and changing the concentration of the debris, it is difficult to assess the exact size, mass and location of the "patch" or "patches" (NOAA, 2017b).

Agricultural run-off containing excess fertilisers is changing aquatic ecosystems around the world through a process called eutrophication. Eutrophication occurs when an excess of nutrients enters a body of water, leading to large increases in the growth of plant organisms such as phytoplankton, more commonly known as algae. When the phytoplankton die, bacterial decomposition of the dead phytoplankton depletes oxygen levels in the water. This creates a low-oxygen environment that is inhospitable to animal life and results in "dead zones".

The Gulf of Mexico dead zone has become an annual event. The Mississippi River drains a 3.2 million km^2 catchment area – the third-largest in the world – into the Gulf. The river carries with it nitrogen and phosphorous nutrients from the fertilisers applied to farmland across the central United States and from as far north as Saskatchewan, Canada (National Park Service, 2017). Other nutrient sources, including animal manure, human waste, and industrial waste also contribute to nutrient enrichment.

In the autumn, winds from seasonal storms mix the oxygen-depleted deep water with oxygen-rich surface water, clearing the dead zone until the next run-off the following spring. In 2017, the dead zone reached its largest size ever recorded: at 22 700 km^2, it covered an area approximately the size of Wales (NOAA, 2017c).

Figure 3.12 • Gulf of Mexico dead zone

Source: NASA (National Aeronautics and Space Administration) (2017), *Mouth of the Mississippi*, NASA Earth Observatory, https://earthobservatory.nasa.gov/images/4733.

Key message • In 2017, the Gulf of Mexico dead zone reached its largest ever size, of 22 700 square kilometres, an area approximately equivalent to the size of Wales.

References

Bennett, S. and T. Stanley (2018), Commentary: US Budget Bill May Help Carbon Capture Get Back on Track, www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html (accessed 6 June 2018).

Bozsaky, D. (2011), "The historical development of thermal insulation materials", Periodica Polytechnica Architecture, Vol. 41/2, p. 49-56, https://doi.org/10.3311/pp.ar.2010-2.02.

Dai, Q., J. Kelly and A. Elgowainy (2016), Vehicle Materials: Material Composition of U.S. Light-duty Vehicles, https://greet.es.anl.gov/files/light-duty-vehicle-2016.

Dutch Government Parties Coalition (2017), Confidence in the Future, www.government.nl/documents/publications/2017/10/10/coalition-agreement-confidence-in-the-future (accessed 6 June 2018).

European Bioplastics (2018), Bioplastic materials, www.european-bioplastics.org/bioplastics/materials/ (accessed 6 June 2018).

FAO (Food and Agriculture Organization of the United Nations) (2018), Data; Synthetic Fertilizers, www.fao.org/faostat/en/#data/GY (accessed 6 June 2018).

Fischedick, M. et al. (2014), "Industry", in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter10.pdf.

German Government (2012), Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (Kohlendioxid-Speicherungsgesetz - KSpG), www.gesetze-im-internet.de/kspg/KSpG.pdf.

Global CCS (Carbon Capture and Storage) Institute (2018), Large-scale CCS Facilities, www.globalccsinstitute.com/projects/large-scale-ccs-projects (accessed 6 June 2018).

Global Methane Initiative (2011), Landfill Methane: Reducing Emissions, Advancing Recovery and Use Opportunities, www.globalmethane.org/documents/landfill_fs_eng.pdf.

IEA (International Energy Agency) (2016a), World Energy Outlook Special Report: Energy and Air Pollution, OECD/IEA, Paris.

IEA (2016b), World Energy Outlook Special Report: Water Energy Nexus, OECD/IEA, Paris.

Irlam, L. (2017), Global Costs of Carbon Capture and Storage, Global CCS Institute, https://hub.globalccsinstitute.com/sites/default/files/publications/201688/global-ccs-cost-updatev4.pdf.

Jambeck, J.R. et al. (2015), "Plastic waste inputs from land into the ocean", Science, Vol. 347/6223, p. 768-771, https://doi.org/10.1126/science.1260352.

Lebreton, L. et al. (2018), "Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic", Scientific Reports, Vol. 8/1, https://doi.org/10.1038/s41598-018-22939-w.

McDonald, B.C. et al. (2018), "Volatile chemical products emerging as largest petrochemical source of urban organic emissions", Science, Vol. 359/6377, p. 760-764, https://doi.org/10.1126/science.aaq0524.

NASA (National Aeronautics and Space Administration) (2017), Mouth of the Mississippi, NASA Earth Observatory, https://earthobservatory.nasa.gov/images/4733 (accessed 6 June 2018).

National Park Service (2017), Mississippi River Facts, www.nps.gov/miss/riverfacts.html, (accessed 6 June 2018).

Neelis, M. et al. (2005), "Modelling CO2 emissions from non-energy use with the non-energy use emission accounting tables (NEAT) model", Resources, Conservation and Recycling, Vol. 45/3, p. 226-250, https://doi.org/10.1016/j.resconrec.2005.05.003.

NOAA (National Oceanic and Atmospheric Administration) (2014), The Global Plastic Breakdown: How Microplastics are Shredding Ocean Health, https://seagrant.noaa.gov/News/Article/ArtMID/1660/ArticleID/251/The-Global-Plastic-Breakdown-How-Microplastics-Are-Shredding-Ocean-Health (accessed 6 June 2018).

NOAA (2017a), What is the Great Pacific Garbage Patch?, https://oceanservice.noaa.gov/facts/garbagepatch.html (accessed 6 June 2018).

NOAA (2017b), Debunking the Myths about Garbage Patches, https://response.restoration.noaa.gov/about/media/debunking-myths-about-garbage-patches.html (accessed 6 June 2018).

NOAA (2017c), Gulf of Mexico 'Dead Zone' is the Largest Ever Measured, www.noaa.gov/media-release/gulf-of-mexico-dead-zone-is-largest-ever-measured (accessed 6 June 2018).

Ocean Conservancy (2015), Stemming the Tide: Land-based Strategies for a Plastic-free Ocean, Ocean Conservancy supported by McKinsey Center for Business and Environment, https://oceanconservancy.org/wp-content/uploads/2017/04/full-report-stemming-the.pdf.

Oliveux, G., L.O. Dandy and G.A. Leeke (2015), "Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties", Progress in Materials Science, Vol. 72, p. 61-99, https://doi.org/10.1016/j.pmatsci.2015.01.004.

Plastics Europe (2007), The Compelling Facts About Plastics 2007, www.plasticseurope.org/application/files/1515/1689/9283/2007CompellingFacts_PubOct2008.pdf.

Plastics Europe (2013), Plastics – the Facts 2013, www.plasticseurope.org/application/files/7815/1689/9295/2013plastics_the_facts_PubOct2013.pdf.

Plastics Europe (2017), Plastics – the Facts 2017, www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf.

UN Environment and International Energy Agency (2017), Global Status Report 2017: Towards a Zero-emission, Efficient, and Resilient Buildings and Construction Sector, OECD/IEA/UNEP, Paris.

United Nations (2018a), Making Every Drop Count: An Agenda for Water Action, United Nations High-Level Panel on Water, https://sustainabledevelopment.un.org/content/documents/17825HLPW_Outcome.pdf.

United Nations (2018b), UN Comtrade Database, https://comtrade.un.org/ (accessed 6 June 2018).

University of Portsmouth (2018), Engineering a Plastic-eating Enzyme, http://uopnews.port.ac.uk/2018/04/16/engineering-a-plastic-eating-enzyme/ (accessed 6 June 2018).

US DOE (United States Department of Energy) (2013), Workshop Report: Light-duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials, www.energy.gov/eere/vehicles/downloads/workshop-reportlight-duty-vehicles-technical-requirements-and-gaps (accessed 6 June 2018).

WHO (World Health Organization) (2005), WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide, http://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf

WRI (World Resources Institute) (2018), Aqueduct Database, www.wri.org/our-work/project/aqueduct (accessed 6 June 2018).

Yoshida, S. et al. (2016), "A bacterium that degrades and assimilates poly(ethylene terephthalate)", Science, Vol. 351/6278, p. 1196-1199, https://doi.org/10.1126/science.aad6359.

Part B: Two contrasting futures for petrochemicals

Any number of possible futures exist for petrochemicals, and to forecast a specific future would be both unhelpful and fool-hardy. Yet future opportunities must be identified and constraints addressed. Scenario analysis offers a constructive way forward. Specifying the probable outcomes of the forward projection of carefully selected baseline assumptions can help to identify the policy interventions that may be required along the way, to shape an acceptable future.

The purpose of Part B of this publication is to explore two contrasting futures for the chemical sector. The first is shaped by the projection of the current trajectory, shaped by existing and announced policies (Chapter 4). The second is rather different. It stipulates up-front a more sustainable end-point and examines the course by which it might be realised (Chapter 5). The final chapter focuses on the policy areas and instruments which need most attention if a sustainable future for the chemical industry is to be attained (Chapter 6).

Chapter 4. What is the current trajectory for petrochemicals?

This chapter concentrates on drawing a plausible picture of the implications for energy and the environment of persistence into the future of current trends in the economy. This is done using the Reference Technology Scenario (RTS) (see Box 4.1). The chapter explores technological progress and innovation, feedstock availability, demand and several other important factors in the chemical industry.

On this basis, of the nearly 10 million barrels per day (mb/d) growth in total oil demand projected for 2030, the chemical sector is on course to account for more than a third. This share climbs to nearly 50% in 2050 (or almost 7 mb/d), compensating for slower growth or decline elsewhere. The sector also plays a significant role in global growth in gas demand, accounting for 7% of the roughly 850 billion cubic metres (bcm) increase between 2017 and 2030, and 4% of the increase projected for 2050. Consequently, direct carbon dioxide (CO_2) emissions from the sector increase by around 30% between 2017 and 2050.

Growing demand for chemicals in the RTS

On the current trajectory, demand for primary chemicals is set to increase by around 30% by 2030 and almost 60% by 2050. At this rate of growth, the sector's output of primary chemicals will exceed 1 billion tonnes (Bt) in 2050, reaching the same order of magnitude as that of cement and crude steel.

Production of **methanol** in the RTS is the highest area of global growth among primary chemicals, with output increasing by more than 50% by 2030 and almost doubling by 2050. Asia Pacific is responsible for nearly two-thirds of this growth, more than 60% of which occurs by 2030. The People's Republic of China[17] was already responsible for more than 50% of global methanol production in 2017, a figure that remains relatively consistent throughout the period to 2050. Although it accounts for a relatively small share throughout, North America is the region with the fastest rate of growth; by 2050, its methanol production nearly triples. Africa and Eurasia see similarly strong growth trajectories, again starting from a small share.

Box 4.1 • The RTS

The RTS is a modelled projection of what might take place in the chemical sector between now and 2050. The modelling is based on cost-optimal decisions on the equipment and operation of the industry. It occurs within an energy price and chemical demand context informed by the range of existing and announced policies and by established behavioural and other exogenous considerations.

The assumptions made about the future of the wider energy system are broadly in line with those of the International Energy Agency's (IEA) New Policies Scenario, featured in the *World Energy Outlook* (IEA, 2017). That scenario aims to provide a sense of where today's policy intentions seem likely to take the energy sector. It incorporates the policies and measures that governments around the world have already put in place, and the effects of announced policies, as expressed in official targets or plans.

The RTS is the baseline scenario used for this modelling, but it and the projections made therein are not forecasts. Whereas the IEA makes short-term forecasts for certain fuels and technologies, it does not make long-term forecasts. The modelling horizon (2050) and approach (constrained cost optimisation of technologies that are, at least, at the demonstration stage or beyond) in this publication are two important factors that make the results unsuitable to use as a forecast.

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[17] Hereafter, "China".

Technologies and policies can change rapidly, without much forewarning, and in 2050, there are likely to be new technologies available, the precursors of which have yet to be conceived in a laboratory. Prices for many fuels, such as oil and gas, tend to move in cycles, rather than follow consistent trends, and the markets in which they are traded remain out of equilibrium for extended periods. By contrast, the modelling underpinning this publication and that of the wider energy system informed by the *World Energy Outlook*, achieve equilibrium in these markets in the long-term. Despite these reservations, the approach adopted offers important insights into a range of possible futures for the chemical sector. The insights suggest where the best opportunities lie and what form of intervention might most profitably be addressed by policy makers.

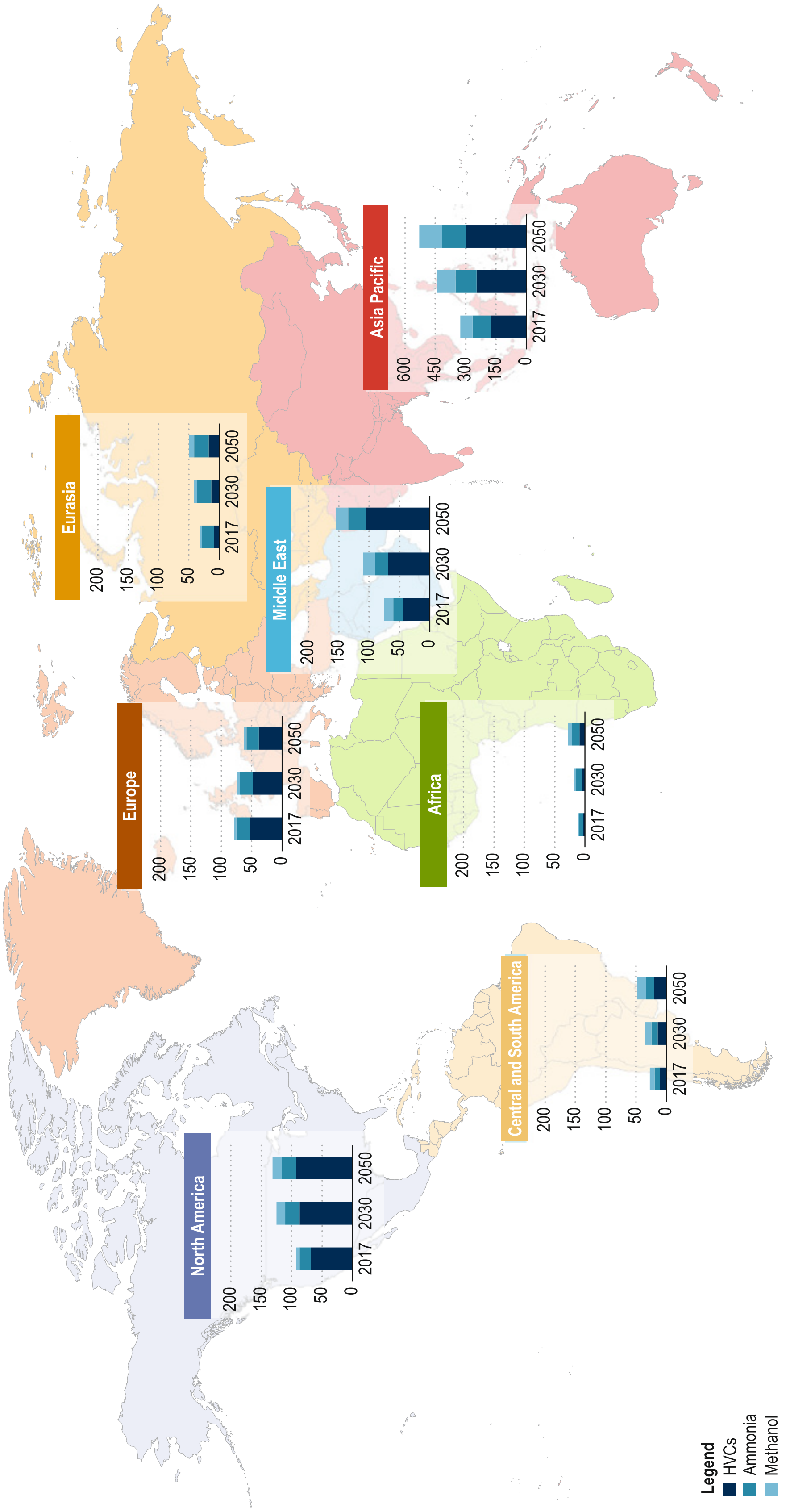
The underlying reasons for the high growth rates projected for methanol, especially in the short term, relate to two relatively new applications: its use as a fuel additive and its use as an intermediate for producing high-value chemicals (HVCs). Fuel-related applications of methanol, which currently account for about 35-40% of demand, are motivated by their capacity to reduce local air pollutants and improve the combustion performance of various fuels, both of which are likely to remain important in the future. Methanol's high octane number means it can be highly compressed before igniting, raising the power generated on ignition. Methanol can be blended directly with, and substitute for, varying quantities of hydrocarbon fuels, such as gasoline and bunker fuel, depending on the application. It can also remain in the chemical and refining sectors, undergoing further transformation into intermediates, such as methyl tert-butyl ether, which can be blended into gasoline, or dimethyl ether, which can be blended into liquefied petroleum gas (LPG).

Methanol's use as an intermediate for producing other primary chemicals, via the methanol-to-olefins (MTO) and methanol to aromatics (MTA) processes, is another important application. Whereas MTA is still at the demonstration phase, MTO is commercial and currently accounts for around 21% of global methanol production, all the capacity for which is in China. By 2020, the MTO-bound component of output almost doubles, contributing nearly half the global growth in methanol demand over this period.

Demand for **HVCs** grows by around 60% by 2050 (relative to 2017), the second-fastest rate among primary chemicals. About 55% of this growth materialises by 2030. Asia Pacific is the world's leading HVC-producing region by far in both 2017 and 2050. It increases its production levels by more than two-thirds during this period, its global share of HVC production rises from 48% to 51% by 2050. While Asia Pacific grows most in absolute terms, the Middle East and Africa are the fastest growing regions in the long run. Africa triples its production volume and the Middle East more than doubles it by 2050. North, Central and South America all grow at slower rates, but still reach nearly 115 million tonnes (Mt) of combined HVC production in 2050.

In the short term, plastics are expected to remain the key driver of demand for HVCs. The largest derivatives of ethylene and propylene are polyethylene and polypropylene respectively, each of which accounts for nearly two-thirds of the demand for their parent chemicals. Benzene, toluene and mixed xylenes (BTX) continue to have a broader set of downstream applications. Even so, approximately half is destined for plastic and other durable material uses.

Figure 4.1 • Regional production of primary chemicals in the RTS



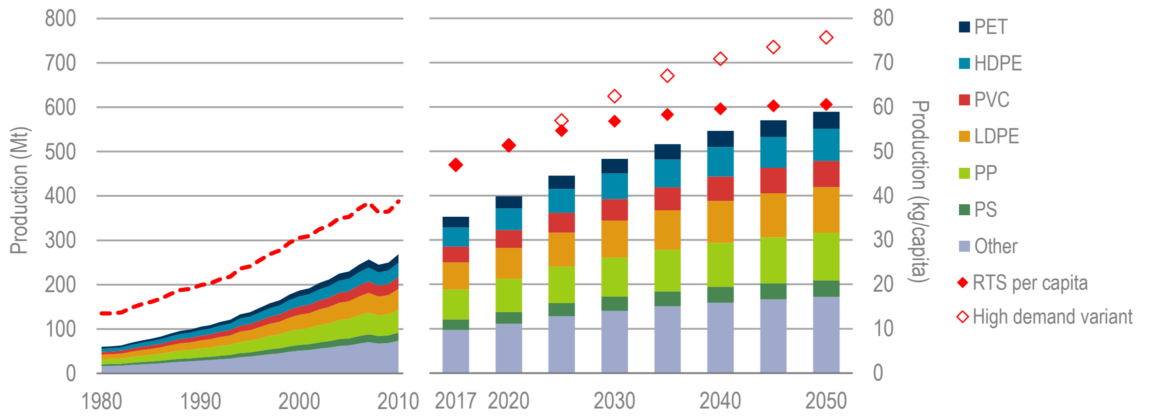
This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Key message • Asia Pacific maintains its dominant global position in absolute terms, but other regions see even stronger rates of growth in primary chemicals production.

As various regions grow both in population and in levels of wealth, plastic consumption is expected to show a robust rate of increase in the RTS, particularly for packaging and construction. Production volumes for a group of key thermoplastics (including polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP) and polystyrene (PS)) grow from approximately 350 Mt in 2017, to 5590 Mt in 2050, an increase of nearly 70%.[18] This represents a global per capita production increase of nearly 30%, with global average per capita production of these plastics increasing from around 47 kilogrammes per capita (kg/capita) in 2017 to more than 60 kg/capita in 2050.

The more than factor of 2 discrepancy between the per capita and absolute production increases is due to the plateauing of plastic consumption observed in several mature economies today, such as Europe and Japan. Although high quality, granular data on this sector are scarce, per capita consumption even appears to be declining slightly in some advanced economies. Widespread concerns about the environmental impacts associated with single-use plastics cast some doubt over the growth prospects for particular demand segments, but the majority of the current end uses for plastic – not to mention as-yet unforeseen applications – seem less likely to be subject to such concerns, especially in developing economies.

Figure 4.2 • Production of key thermoplastics in the RTS



Notes: *Other* refers to a selection of other thermoplastics: acrylonitrile butadiene styrene, styrene acrylonitrile, polycarbonate and polymethyl methacrylate. Volumes of plastic production shown are independent of the level of recycling. The impact of recycling is registered in the lowering of demand for primary chemicals required to produce the plastic volumes shown above. The RTS high demand sensitivity variant is a separate scenario performed to explore the sensitivity of our results to higher than expected demand. Only the per capita demand figures are show for the high demand sensitivity variant in Figure 4.2. Details of the high demand sensitivity variant analysis can be found in the online annex accompanying this publication.

Sources: Data consulted in making projections from Geyer, R., J.R. Jambeck and K.L. Law (2017), “Production, use, and fate of all plastics ever made”, https://doi.org/10.1126/sciadv.1700782; Levi, P.G. and J.M. Cullen (2018), “Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products”, https://doi.org/10.1021/acs.est.7b04573; OECD (2018), *Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses*.

Key message • Production of key thermoplastics grows by nearly 70% in the RTS between 2017 and 2050, with global average per capita demand increasing by just under 30%.

Virgin plastic production requires inputs of HVCs, but recycling using plastic scrap does not. Plastic recycling rates have been increasing rapidly in Europe over the past two decades, and this trend continues in the RTS. Collection rates for recyclable plastic waste double in Europe,

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[18] Resin quantities exclude fibre and additives.

reaching near their maximum practical limit for most resins by 2050. However, without firm commitments to move to secondary production routes in developing economies, this considerable, but localised, recycling effort results in less than 20% of recyclable plastic waste being collected globally by 2050, in the RTS.

Ammonia grows at the slowest rate among primary chemicals, but its growth is evenly distributed over the period to 2050. An increase of more than 15% by 2030 and by more than 30% by 2050 is registered globally. In general, developed economies cede ground to developing economies in terms of shares of global ammonia production. The strongest regional growth rates for ammonia production occur in Africa and the Middle East. Africa nearly doubles its production, although it still provides less than 5% of global production in 2050. The Middle East almost doubles its ammonia production volume by 2050.

Ammonia is, and remains, a product less regionally concentrated than HVCs and methanol, perhaps because its importance was well established before globalisation. While the Asia Pacific region remains the dominant regional production centre throughout the RTS, its share of global production declines slightly, dropping below 50% in 2050.

Historically, ammonia production has been driven primarily by demand for nitrogen fertilisers. This continues to be the case in the RTS, but with significant saturation taking hold in developed economies. A decline in the absolute level of production even begins to appear in certain established production centres, such as Europe. Demand in developing economies, and indigenous production in those regions, continues to be governed by agriculture, but even this growth is tempered by increased efficiencies in fertiliser application over time.

In industrial uses, both ammonia and its largest volume derivative, urea, continue to be sources of growth in the short to medium term. Despite its predominant use as a fertiliser, urea has a small but expanding portfolio of non-agricultural uses, including AdBlue, which is used to reduce air pollutants from diesel engines. Important industrial applications include explosives used in the demolition and mining industries, and various synthetic materials, such as nylon, acrylic fibres and nitrile rubber. These non-fertiliser uses of ammonia currently account for about 10-20% of global demand. Their increased growth does not fully compensate for the slow-down in agricultural uses, which contributes to the plateauing of global demand towards 2050.

On the supply side, current capacity and utilisation levels, along with the volume of capacity under construction or likely to be deployed, inform our short-term projections, and a range of macro-economic trends shape the medium-long term (post-2025) projections. Datasets on population and GDP – along with observations of the levels of wealth at which demand for various products tends to become saturated – are used to derive the growth in consumption. The patterns of trade between regions and the shares of propylene and BTX aromatics sourced from the refining sector are assumed to evolve in line with current trends.[19]

Plastic recycling in the RTS

Increased efficiency in the use of materials is another factor expected to affect the supply and demand of primary chemicals. Growth in plastic recycling reduces primary chemical demand – particularly for HVCs – by reducing the tonnages of virgin plastics, relative to plastics produced from scrap. There are three main factors in recycling when targeting primary chemical savings: the collection rate, the yield rate and the displacement rate.

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[19] Refer to the online annex for further details on the production projections.

The most familiar of these is the collection rate, which describes the proportion of plastic waste that is collected for recycling, relative to the quantity of recyclable plastic waste available.[20] The recycling yield rate accounts for the material losses incurred during the pre-processing and recycling processes. The displacement rate refers to the amounts of plastic resins and products that, when recycled, are remanufactured into forms that either fulfil their original purpose or do not prevent the material from being recycled again, or both. When these requirements are not met, the result is down-cycling. A real-life example of down-cycling is provided in Chapter 1 (Box 1.3), which describes how PET bottles are recycled to produce PET fibre, for which there is currently no commercial recycling route available.

These three factors – the collection, recycling yield and displacement rates – are multiplicative, meaning that improvements are needed across the board to effect significant reductions in virgin primary chemical demand.

Not all plastics are equal, either, in terms of their recycling potential or in terms of the impact their recycling has on primary chemical demand. Consider two contrasting examples, PET and PVC:

- PET resin (excluding polyester fibre) is almost exclusively used for packaging, much of which is single-use and therefore short-lived. PET is made from purified terephthalic acid and ethylene glycol. The terephthalic acid is derived from para-xylene (part of the BTX aromatics) and ethylene glycol is derived from ethylene. One unit of PET requires approximately 0.6 units of BTX aromatics and 0.2 units of ethylene, in mass terms.[21]
- One unit of PVC[22] requires twice as much ethylene, but less than 0.1 units of BTX aromatics and a further 0.1 units of propylene. The largest use of PVC is in construction. PVC windows, pipes and doors tend to stay locked in the built environment for 20 years or more. Even when they become available, they are hard to extract from the other building materials that accompany them.

Recycling 1 unit of PET results in 38% more primary chemical savings than for PVC. There are also more abundant stocks available to recycle as newer (and therefore larger) volumes of packaging material are readily available. The PVC incurs a substantial delay before it is available for recycling.

Establishing an expectation of future rates of recycling is complex. It depends on a variety of factors, including: which recycling technologies will reach maturity, what levels of government support will be maintained or realised in various regions, how the relative costs of virgin plastic production evolve, and consumer behaviour, among other considerations. The RTS assumes that collection rates increase only marginally across most regions, with much stronger increases taking place in those regions already more committed to action towards sustainable plastic waste management. Europe, Japan and Korea are leading the way in this.

In the RTS, average rates of collection for the main thermoplastics increase by around 25% above today's relatively low levels by 2050, with the average rate in Europe – already high in global terms – nearly doubling. Current levels of recycling yield are estimated to be 70-82%, and the displacement rate to be 32-37%. Yield and displacement rates are resin-specific rather than geography-specific, and the improvements to these rates in the RTS globally are incremental.

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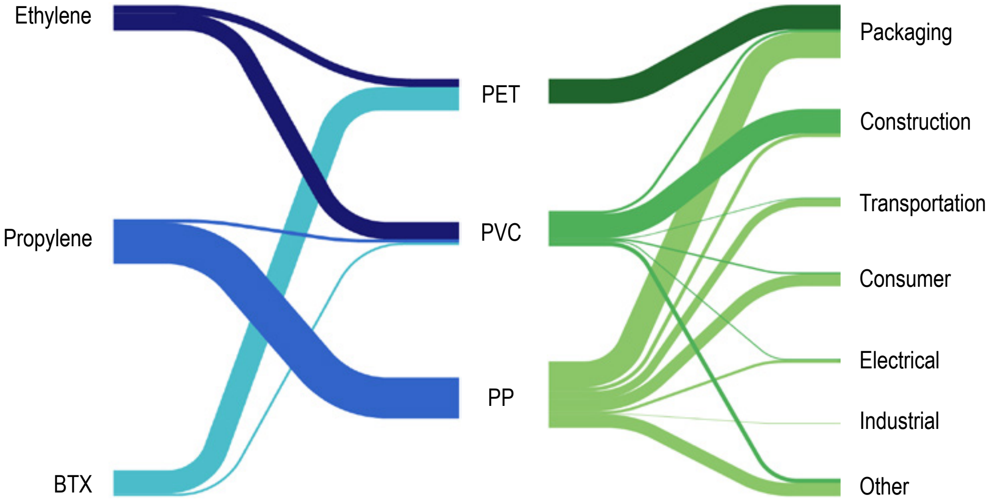
[20] As plastics typically remain in use for between a day and half a century, existing plastic waste and plastic production differ at a given point in time.

[21] Secondary reactants are also needed.

[22] Including the plasticiser dioctyl phthalate that normally accompanies pure PVC resin.

Figure 4.3 • Composition and end uses for key plastic resins



Notes: All flows are shown in mass terms. Flows between primary chemical inputs and polymers on the left are shown on a per-unit-of-plastic basis, whereas polymer to end-use category flows on the right are shown on an absolute basis using 2016 production volumes.

Sources: Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use, and fate of all plastics ever made", https://doi.org/10.1126/sciadv.1700782; Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", https://doi.org/10.1021/acs.est.7b04573.

Key message • Plastics differ in both their composition and use profile.

The relatively modest increases in collection rates in most regions means the global average collection rate remains at less than 60% of that seen in Europe today. This is explained by the changing regional shares of global plastic consumption and waste. Developing economies sharply increase their share of global plastic consumption, whereas the share of developed countries – in which the highest rates of recycling take place – shows no increase or, in many cases, declines. For example, Europe's share of global plastic consumption declines by approximately 40% between 2017 and 2050, whereas India's more than doubles. This dynamic, combined with the minimal increases in yield and displacement rates, means plastic recycling has a limited impact in the RTS, despite the significant efforts deployed in certain regions.

Feedstocks in the RTS: No radical change

Feedstock choices in the RTS are based mainly on cost, and the trend is to continuity of choice in each region. Towards the end of the period assessed, the CO_2 emissions reduction commitments of certain countries – those that already have a strong policy or legal backing – start to take hold, but have a limited impact on feedstock choice. Existing carbon capture, utilisation and storage (CCUS) projects persist, and the few that have been announced (but not built) come to fruition. In some cases, a modest switch to some alternative feedstocks takes place. These are oddities rather than the norm. They are overshadowed by enormous growth in the consumption of traditional feedstocks.

Oil feedstock demand for primary chemicals increases by 30% by 2030 and then undergoes a further increase of 25% by 2050, driven by robust demand for HVCs. Gas feedstock for primary chemicals experiences the strongest increase among conventional feedstocks, growing by 36% by 2030 and by a further 22% by 2050. Gas feedstock's growth, which has a broad geographical base, is derived primarily from the rise in demand for ammonia and methanol. Use of coal as primary chemical feedstock grows initially, by 26% by 2030, but slows thereafter. This trend is first shaped by increasing demand for coal-based methanol production in facilities already in the pipeline in China, but soon after 2030, methanol and ammonia demand are relatively flat.

Ethane and naphtha remain the main feedstocks for **HVC** production, with other oil products – LPG and gas oil, along with some refinery gases – forming the rest of the supply. Ethane is the preferable feedstock, where it is available, because its price tends to be low relative to its high yield (0.8 tonnes of HVCs per tonne of ethane). However, few regions outside the United States and the Middle East have access to a plentiful and cost-efficient supply. Consequently, naphtha is the dominant feedstock globally, accounting for more than half of cumulative HVC production during 2017-50.

Ethane consumption for HVC production in the favoured regions grows by approximately 70% by 2030 in the RTS, in part due to demand for exports to other regions, such as Europe. However, regions with continuing strong growth in HVC production after 2030 increasingly rely on other feedstocks, mostly naphtha. This is mainly due to tightening ethane supply as a result of the flattening natural gas liquids (NGLs) output from United States (US) shale gas, and stagnating tight oil production in the second half of the 2020s. In the Middle East, where ethane feedstock grows by around 70% in the period 2017-30, growth slows to 17% between 2030 and 2050, whereas naphtha consumption more than quadruples over the same overall period. Naphtha overtakes ethane as the region's largest feedstock by 2050. Were there an unlimited supply of ethane available, the chemical sector would readily absorb additional volumes (see Box 4.2).

Box 4.2 • Enthusiasm for ethane

The effect of the US shale revolution on global hydrocarbon supply is hard to overstate. Between 2010 and 2017, US shale gas output tripled to 477 bcm, while NGL output doubled to 3.7 mb/d (net of condensate). The incremental output of shale ethane, LPG and natural gasoline together equated to 20% of global oil demand growth over the same period. This led to lower prices for these products: US ethane prices dropped by about two-thirds, while propane prices fell by more than half. Even with increasing output and switching from other feedstocks, the US petrochemical sector could not absorb all the ethane supply growth.

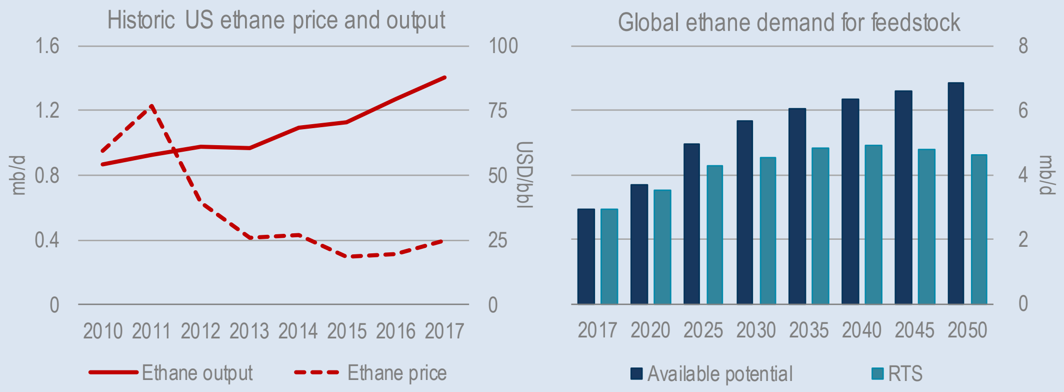
Pipeline infrastructure also initially constrained ethane delivery, putting huge pressure on wellhead ethane prices, which even fell below parity with natural gas prices in 2013, and only started recovering in 2016. This meant that producers cut ethane yields, leaving some ethane molecules in the natural gas stream, rather than separating the whole ethane fraction, a practice known as "ethane rejection". At its peak, some 400-600 thousand barrels per day (kb/d) of ethane was estimated to have been subjected to such rejection.

Demand, however, proved to be flexible. Low ethane prices ushered in a wave of petrochemical projects on the US Gulf Coast, which started coming online in 2014, and cumulative ethane cracking capacity additions between 2014 and 2017 reached nearly 4 Mt. This helped ethane prices and yields rebound. The start of regular ethane exports to Europe, in late 2016, and to India, in 2017, offered additional support. As soon as seaborne exports were possible, there was sufficient interest from global petrochemical operators.

Given the attractive pricing of ethane relative to crude-derived naphtha and its higher ethylene yields, ethane demand could, theoretically, be significantly higher than in the RTS, without increased demand for downstream chemical products. Ethane feedstocks provide lower propylene yields than naphtha, which might have been an obstacle, but propylene production from propane dehydrogenation (PDH) plants has gained a lot of traction in the United States and China in recent years.

In the RTS, these two factors – attractive pricing and new-found ethylene/propylene flexibility – help ethane demand to grow to such an extent that, post-2025, it becomes impossible for supply to keep up. As US shale gas production increasingly moves towards drier plays (gas with lower quantities of NGLs) and US tight oil production levels out in the 2020s, ethane supply reaches a peak in the late 2020s and then starts to decline. Without this constraint on supply, HVC demand could consume nearly 50% more than the ethane demand observed in the RTS, or 6.7 mb/d by 2050. This suggests that, if US shale output were to exceed expectations, the global petrochemical sector would readily absorb the additional output.

Figure 4.4 • Ethane supply, demand and prices for feedstock



Note: USD/bbl = United States dollars per barrel.

Sources: Ethane prices from Argus Media (2018), *Key Prices*, www2.argusmedia.com/en/methodology/key-prices; ethane production quantities from EIA (2018), *Petroleum and Other Liquids*, www.eia.gov/petroleum/.

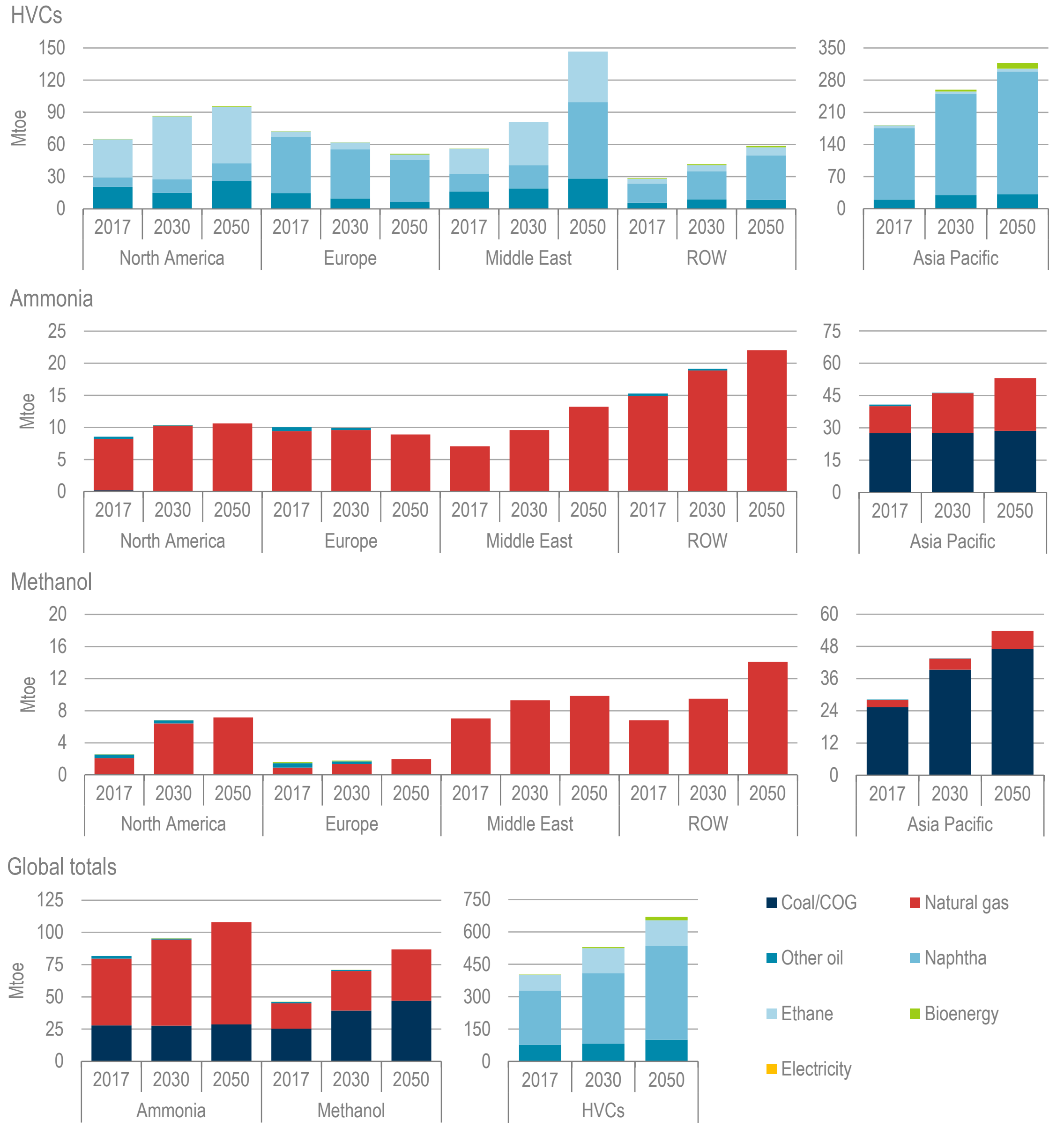
Key message • The chemical sector could readily absorb additional quantities of ethane.

Alternative feedstocks for HVC production grow five-fold by 2030 and then almost triple during the period 2030-50. Despite this, they still account for just 2% of global feedstock consumption in 2050. Bioethanol (used to make bioethylene) makes up most of the alternative feedstock supply in 2050 in the RTS, contributing more than 95%. Most of this is consumed in Asia Pacific and Central and South America (mainly in Brazil), with small additional amounts (less than 1 million tonnes of oil-equivalent [Mtoe]) in Europe and North America. Electrolysis-based routes to ammonia and methanol remain at the pilot project scale in the RTS, barely registering any production in global terms.

The consumption of feedstock for **ammonia and methanol** production tells a similar story. Globally, in the RTS, natural gas provides the majority of the growth in feedstock consumption for both chemicals, but their uses of coal diverge: growth for methanol and stagnation for ammonia. The distinction between ammonia and methanol stems from their differing growth trajectories in China, which remains the major centre for the use of coal as feedstock for both chemicals in the RTS. Whereas methanol continues growing strongly, leading to further coal-based capacity additions, ammonia production stagnates.

MTO projects (and those in the pipeline) lock in significant amounts of coal-based methanol capacity, whereas no such outlet exists for ammonia. The MTO process does not make sense in the RTS unless the methanol is cheap. In China, this still means production based on coal, at least in the short term. Both the natural gas and coal routes to methanol, and then on to HVCs, are motivated by rising oil product prices in the RTS. The factors underlying these price dynamics can only be explored by looking at the broader context of oil demand (IEA, 2018).

Figure 4.5 • Feedstock demand in the RTS



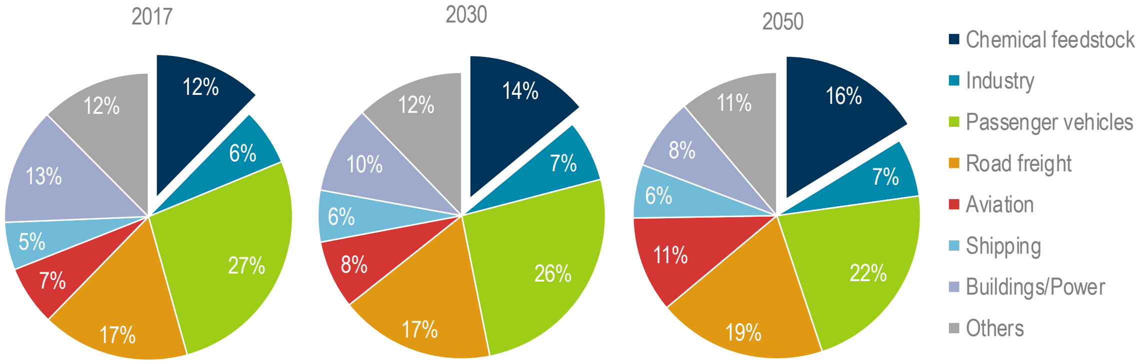
Notes: Tabulated results are provided in the online annex. COG = coke oven gas; ROW = rest of the world. *Electricity* denotes the use of electrolytic hydrogen, and is displayed in terms of electricity input.

Key message • With few exceptions, regions stick to traditional feedstocks in the RTS.

Oil demand for feedstock in the context of the RTS

Today the production of chemicals requires oil as feedstock, so the growth of demand for primary chemicals – HVCs in particular – naturally translates into higher demand for oil products, predominantly naphtha, ethane and LPG. In 1990, global oil demand for chemical feedstock represented just 8% of total oil demand. While oil demand in other sectors has been significantly impacted by energy efficiency improvements and fuel switching, demand for chemical feedstock has continued its upward journey, increasing the prominence of the industry as a source of oil demand. With around 12 mb/d, global oil demand for chemical feedstock accounted for about 12% of total oil demand in 2017. The share is even higher (14%) when oil consumption for process energy in the chemical sector is included, though this figure is relatively small.

Figure 4.6 • Share of total oil demand by sector in the RTS



Key message • Chemical feedstock plays an increasing role in total oil demand, with its share rising from 12% in 2017 to 16% by 2050.

In the context of the RTS (and more broadly in the IEA New Policies Scenario), oil demand growth is increasingly offset, in many sectors, by a combination of energy efficiency, fuel switching and electrification. For example, despite the size of the global car fleet more than doubling between 2017 and 2050, oil demand for passenger vehicles flattens, mainly as a result of improvements in fuel economy and, to a lesser extent, the uptake of electric and other alternative vehicles.

Demand for other transport modes is also affected by a degree of efficiency improvement and fuel switching although the impact is less prominent. In buildings, oil faces increasing competition from natural gas and electricity, particularly for space heating. And in power generation, renewables and natural gas are increasingly substituted for oil use in many regions.

The dampening influence on oil demand in these sectors does not fully apply in relation to chemical feedstock. The impact of energy efficiency and the electrification of heat pertain to process energy requirements rather than to feedstock consumption. Although certain trends in the RTS – such as recycling and greater uptake of catalytic processes – yield some feedstock savings, these are more than offset by the robust growth in demand for chemical products.

Alternative feedstocks such as biomass or carbon dioxide (CO_2) and water do not gain a substantial share of chemical feedstock in the RTS. As a result, global oil demand for chemical feedstock continues to grow by around 6 mb/d, to almost 18 mb/d in 2050, representing almost half of the total oil demand growth during that period. The share of chemical feedstock in total oil demand also increases from 12% in 2017 to 16% in 2050. The figure is 18% (in volumetric terms) if process energy is included.

Oil demand for chemical feedstock grows most in the Middle East, where countries are increasingly moving into the oil refining and petrochemical businesses as a means of increasing the value of their indigenous oil production and diversifying their economies. Given the cost advantage over steam crackers in other regions, new crackers in the Middle East are likely to maintain higher utilisation rates, adding 3 mb/d of feedstock demand between now and 2050. China follows closely behind, as national companies add new capacity to increase self-sufficiency in chemical production, and independent refineries transform themselves into petrochemical companies. Feedstock consumption in the United States grows until around 2030 before entering a period of gradual decline in the wake of tightening ethane supply from shale formations. There is some growth in oil demand for feedstock in India and other developing economies in Asia. Demand in advanced economies in Europe and Asia tends to decline.

Box 4.3 • Oil supply security and petrochemicals

Oil supply security has remained the cornerstone activity of the IEA since its creation in 1974. Each IEA member country has an obligation to hold oil stock levels that equate to no less than 90 days of net imports and to have ready emergency response mechanisms that can be activated in the case of a crisis, such as a demand restraint.

The primary purpose of collective emergency action by IEA member countries is to mitigate the economic damage associated with a disruption of oil supply. By temporarily replacing disrupted supplies or reducing demand the action is intended to help oil markets re-establish the supply/demand balance at a lower price level than would otherwise have been the case.

At the time of the creation of the IEA, the petrochemical sector was substantially smaller than it is today. As the primary concern of the countries establishing the IEA was to protect the economic activities heavily dependent on oil as an energy source (notably transport, power generation and heating), non-energy use was not included in the calculations of stockholding requirements. This was done simply by excluding from the net-import calculation all flows of naphtha and deducting a naphtha yield from amounts of crude oil, both to establish the basis for the stockholding obligation and to determine what type of stocks contribute to the obligation.

The situation is fundamentally different today. Growing demand for primary chemicals translates into considerable oil demand. In the coming decades, petrochemical feedstock is projected to be the strongest growth segment of global oil demand. With oil products making up the overwhelming bulk of petrochemical feedstock supply, the petrochemical industry has a very strong interest in assuring oil supply security.

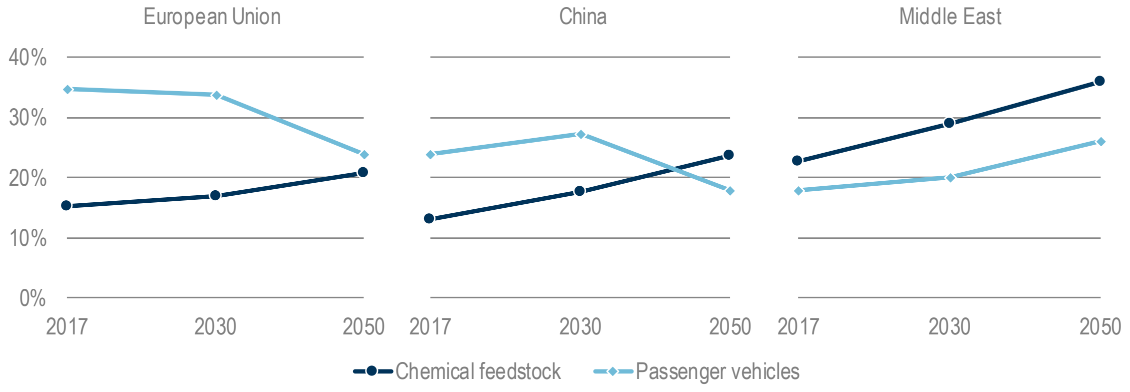
Whether or not the portion of the oil barrel that is used for petrochemicals should remain excluded from the stockholding calculation is part of an overall assessment currently underway at the IEA. This assessment, initiated by IEA ministers at their November 2017 meeting, is designed to underpin any necessary improvements in the emergency oil stockholding requirements.

Declining oil demand for chemical feedstock in advanced economies does not mean that the share of chemical feedstock in total oil demand shrinks in these regions. In fact, oil demand for chemical feedstock in these regions is also more resilient than demand for other segments (e.g. road transport). Indeed, the share of chemical feedstock in total demand increases in virtually every region.

For example, in the European Union, the share grows from 15% today to 21% by 2050, approaching that of passenger vehicles by the end of the projection period, even though demand for both sectors declines in absolute terms. In China, oil demand for both chemical feedstock and passenger vehicles grows strongly until 2030, but passenger transport demand then falls as policy efforts to improve fuel efficiency and promote electric vehicles lead to the share of the chemical industry in total Chinese demand exceeding that of passenger transport by 2050. In the Middle East, oil demand for both chemical feedstock and passenger vehicles continues to grow to 2050, raising the shares of both segments at the expense of the share for power generation.

The contribution of chemicals to oil demand growth is even more prominent within the industry sector. While total industrial energy consumption has grown by 60% over the past 25 years, oil has been continuously displaced by other fuels, such as natural gas and renewables (or by electricity produced from these fuels), and it has registered virtually no growth in absolute terms. This effect was mainly driven by the phasing out of oil price subsidies, environmental regulations, and the technical ease of substituting natural gas for oil in some industrial equipment, such as boilers and furnaces. However, in the more complex processes of the chemical sector, these substitutions have proven more difficult.

Figure 4.7 • Shares of oil demand for chemical feedstock and passenger vehicles in the RTS

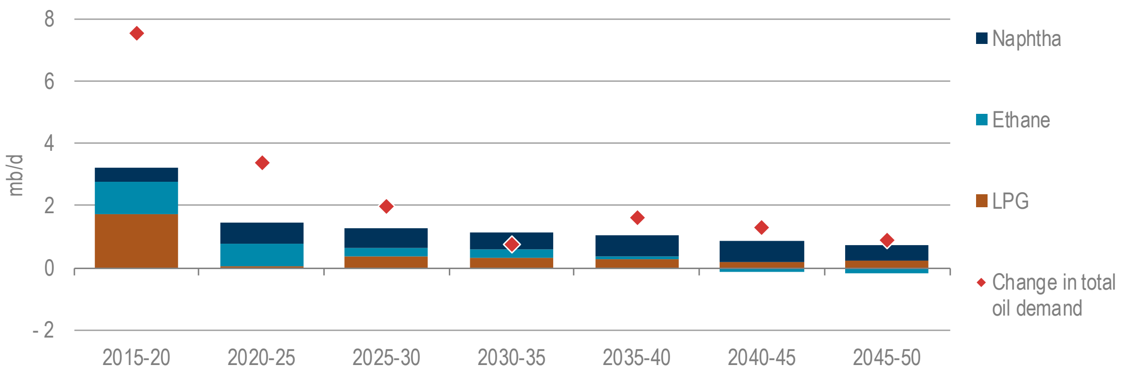


Key message • The growing share of chemical feedstock in total oil demand surpasses that of passenger vehicles in certain regions.

Various site- and process-specific constraints often make fuel switching investment-intensive or incur an energy penalty. Oil consumption for process energy in the chemical sector has grown by 40% during the past 25 years, raising the share of chemicals in total industrial oil consumption (when including both process energy and feedstock) from 54% in 1990 to over 70% in 2017. In the RTS, this trend continues through to 2050, albeit at a slower pace, elevating the share of chemicals in industry oil consumption to around 80% by 2050.

The rising share of the chemical sector in global oil demand has consequences for demand in a range of oil products. Robust demand for chemical feedstock in the RTS translates into strong growth for lighter oil products such as naphtha, ethane and LPG, their combined demand growth amounting to 8 mb/d between today and 2050. Total demand for middle distillates remains robust on the back of strong road freight and aviation activities, but demand for gasoline and high-sulphur fuel oil declines. As a result, the share in total demand of the lighter – often dubbed “top of the barrel” – products, used as chemical feedstock continues to grow, rising from 18% in 2017 to 23% by 2050, at the expense of the share of transport fuels, gasoline in particular. Refiners will need to adapt to these changing product demands (more on this in Chapter 5).

Figure 4.8 • Change in oil product demand for chemical feedstock in the RTS



Key message • Chemical feedstock registers the strongest growth among various oil products, taking an increasing share in total oil demand growth in the RTS.

Process selection is driven by feedstock availability in the RTS

Production process trends in the RTS are dictated by the availability and economic attractiveness of feedstocks. The penetration rates of different production processes therefore directly reflect feedstock decisions, especially in the case of processes supplying a single product, such as ammonia or methanol.

For **HVCs**, the technology story is slightly more nuanced. Processes delivering multiple chemicals (e.g. steam cracking) or a single one (e.g. PDH) complement each other across various regions, with each region adopting a process combination that makes best use of the most attractive feedstocks available. Thanks to the use of catalysts, naphtha catalytic cracking (NCC) produces HVCs with greater selectivity than standard steam cracking, but, as yet, only one such commercial plant is operating (in Korea).

The energy efficiency of NCC is roughly 15% higher than that of the world's best performing naphtha steam cracker, and the process requires nearly 25% less naphtha feedstock per unit of HVC produced. However, the process, which is relatively new and complex (involving a catalyst), thus entails a higher level of investment risk. Starting from this modest level of installed capacity in 2017, NCC achieves only marginal deployment levels by 2050 in the RTS. In the Middle East and Asia Pacific respectively, 2% and 3% of total HVC production is produced through NCC by 2050.

Single-product processes for HVC production include bioethanol dehydration (BDH) and PDH. BDH is an attractive process route when only ethylene is required. It ranks second, after ethane steam cracking, in terms of ethylene yield. Most of the current installed capacity of BDH is located in Brazil. This technology is deployed in the RTS in most regions to some degree by 2050, especially where ethane is not abundant and bioethanol stocks are available, ultimately contributing 3% of global HVC supply.

If LPG (which contains propane as a constituent) is available at a reasonable cost, PDH is an important strategy to bridge the "propylene gap" that can emerge when there large amounts of ethane-based capacity or when high ratios of propylene to ethylene are required. The deployment of PDH peaks before 2030 in the RTS, with more than half of its utilisation taking place in China by 2050.

MTO/MTA processes are a special case among HVC production technologies. These processes encompass a range of variations that facilitate both multi- and single-product arrangements. Whereas MTA is at a demonstration phase today, MTO is already commercial. All the existing global MTO capacity, which turns coal into HVCs via methanol, is in China. Although MTO achieves significant growth in the first half of the RTS, almost doubling by 2030, it levels off thereafter, due to rising fuel costs and its high capital intensity relative to other process options. No deployment of MTO takes place outside China in the RTS.

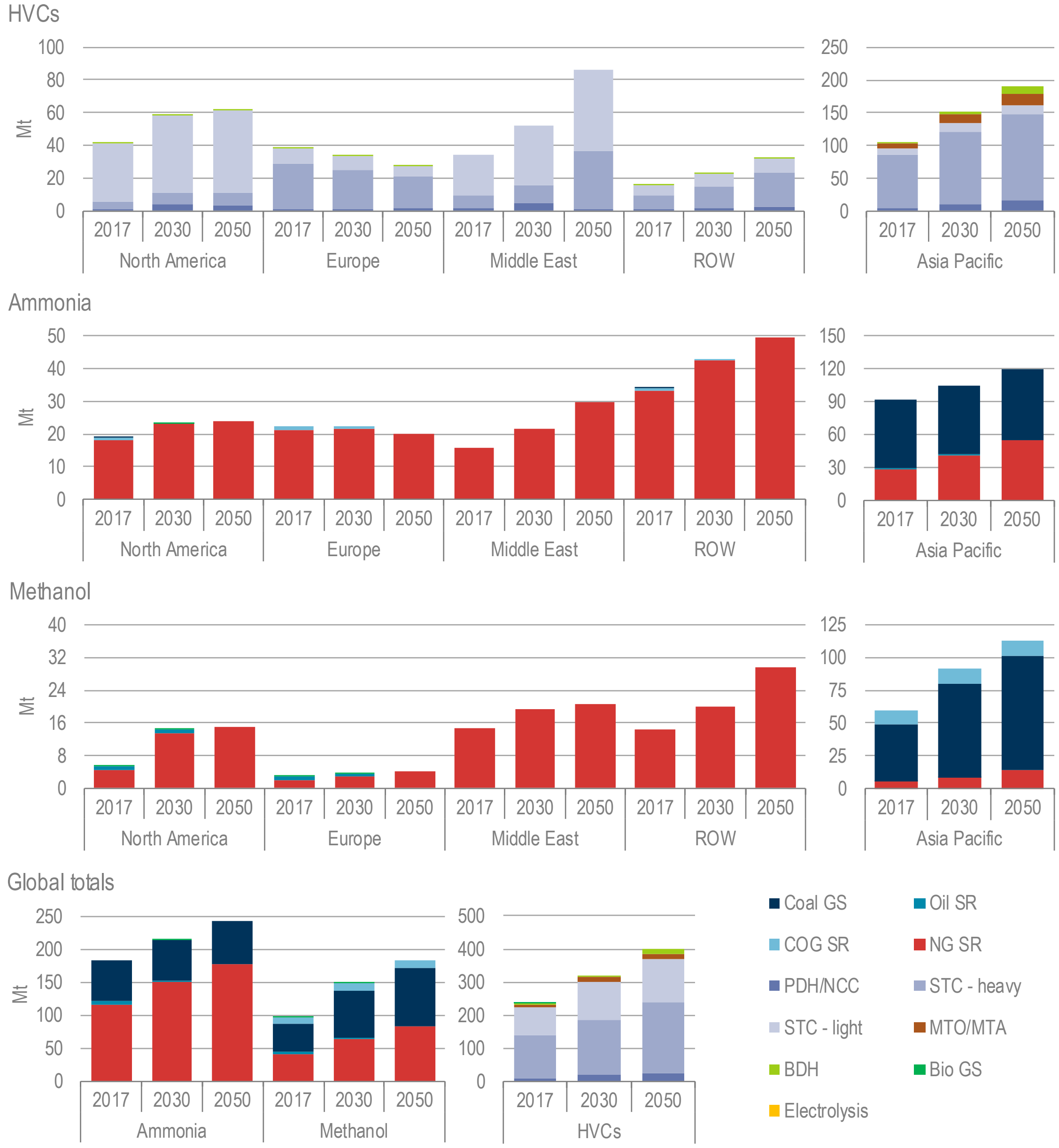
For **methanol** production, there is a distinction between the use of coal and COG, with the use of COG growing in line with availability. COG is a by-product from producing coke, most of which is generated for use as a reducing agent in the iron and steel industry. Because the COG comes in gaseous form and already contains the main components of syngas (carbon monoxide and hydrogen), used for making methanol, this process is significantly less capital- and energy-intensive than making methanol using coal.

All the existing global COG-based methanol production is concentrated in China. Excess steelmaking capacity in China has led to the redirection of COG away from its traditional use as fuel in steel mill utilities to feedstock for methanol. In the RTS, where global crude steel demand increases by around 30% between 2017 and 2050, there is a limit on the amount of COG available sufficiently close to chemical facilities to make its use for that purpose economic.

Process changes in the production of **ammonia** in the RTS are mainly tied to an increasing share of gas relative to coal globally. China maintains its coal-based ammonia capacity, but because its production levels stagnate and production in other regions continues to grow, the overall process mix shifts towards gas. The consequences for technology are straightforward.

Approximately 60 Mt of ammonia production capacity based on coal (partial oxidation units using gasifiers) is maintained and replaced as necessary in China between 2017 and 2050. Elsewhere, steam reformers – which require less than half the investment needed to build the equivalent capacity based on coal – are used to construct the additional capacity required. The share of gas in global ammonia production rises from 63% in 2017 to 74% in 2050.

Figure 4.9 • Production routes for primary chemicals in the RTS



Notes: Tabulated results are provided in the online annex. Bio = bioenergy; GS = gasification; SR = steam reforming; STC - heavy = naphtha and gas oil steam cracking; STC - light = ethane and liquid petroleum gas steam cracking.

Key message • Feedstock availability – and price – drives technology selection in the RTS.

Box 4.4 • Least-cost modelling

The modelling results that underpin this publication are generated using a cost-optimisation (TIMES-based) model of the chemical sector. The aim of the modelling architecture is to facilitate technology decision-making on a least-cost basis, specifically, discounted capital investment and fuel costs.

The chemical sector TIMES model covers 39 model regions (seven aggregated reporting regions) and a detailed portfolio of technology options for the production of primary chemicals (HVCs, methanol and ammonia). Primary chemicals account for around two-thirds of the sector's overall energy consumption. The remaining energy consumption in the sector, which is distributed across thousands of different products and facilities, is modelled using a simulation module.

Each technology characterised in the model for primary chemicals production is characterised with as much technological detail as is feasible, including yields, quantities of various by-products, capital expenditure, fixed operational expenditure, energy performance by fuel, emissions levels, construction and decommissioning times and vintages of plants.

The model is driven by the need to satisfy regional demands for primary chemicals, which are projected and translated to their producing regions exogenously. Demand projections are based on country- or regional-level data for GDP, disposable income, installed and announced industrial capacity, current material consumption, regional-demand saturation levels derived from historical data, and resource endowments. The model must satisfy these demands, while conforming to various scenario-specific constraints, such as limits on the availability of certain fuels and on CO_2 emissions (allowing for the need to supply urea plants with CO_2 feedstock).

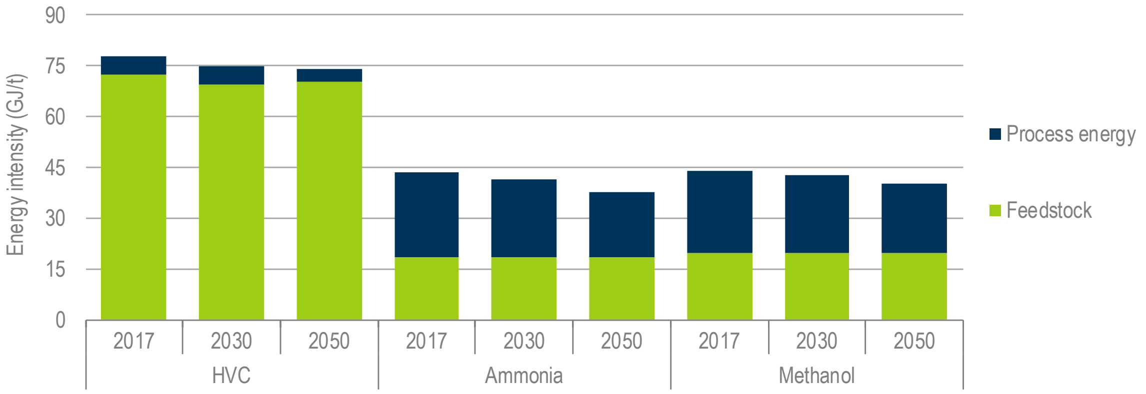
The model interacts with other models in the IEA via price signals (e.g. for fuels), available alternative feedstocks (e.g. COG), and user constraints (e.g. allocation of CO_2 emission quotas). The integrated and iterative approach is aimed at providing a coherent scenario that takes account of the complex interdependencies within the energy system. For this publication, the wider energy system context is provided by results from the World Energy Model, the latest results of which are described in the *World Energy Outlook* (IEA, 2017).

Feedstock and energy intensity of primary chemical production in the RTS

The overall energy intensity of primary chemical production in the RTS in 2017 falls by 3.4% by 2030 and by a further 2.6% by 2050. However, the feedstock intensity of primary chemicals stays relatively flat, declining gently, from 43.3 gigajoules per tonne (GJ/t) in 2017 to 42.7 GJ/t in 2030, and then climbing again to 43.9 GJ/t (or around 1 tonne of oil-equivalent per tonne) in 2050. This reflects that, although the situation is more complicated for HVCs, in general, it takes a fixed amount of feedstock – akin to a material input – to obtain a unit of chemical output. No significant ground-breaking improvements are envisaged for the yields from these large-volume chemical processes because it is assumed modern catalysis has already delivered most of the practical gains that can be achieved.

Because multiple process routes are available for high-value chemical production, each of which has a different yield structure, the feedstock intensity for these chemicals does vary slightly, both geographically and over time. In the RTS, the feedstock intensity of HVC production declines initially, from 72.3 GJ/t of HVC in 2017 to 69.5 GJ/t of HVC in 2030, and then rises again, to 70.3 GJ/t of HVC in 2050. The initial fall in feedstock intensity stems from the increased share of lighter feedstocks by 2030, followed by a gentle decline since light feedstocks (such as ethane) tend to have higher yields. This undulating share of lighter feedstocks explains all of the variation in the global feedstock intensity. The feedstock intensity for methanol and ammonia remains flat at nearly 20 GJ/t by 2050 because, for these chemicals, feedstock change does not imply a fundamental technological shift in the synthesis process.

Figure 4.10 • Average energy intensity by primary chemical in the RTS



Notes: Net process energy intensities are depicted for feedstock. In steam crackers, the conversion of feedstock to chemicals results by-product off-gases, which can be used to provide process energy. When utilised, this reduces the quantities of process energy required. The same is true for both ammonia and methanol, but to a much lesser extent because lower quantities of calorific gases are generated from the conversion of the feedstock.

Key message • Feedstock intensity remains steady, while process energy intensity declines.

The net process energy intensity of primary chemical production falls from 16.2 GJ/t in 2017 to 14.7 GJ/t in 2030, and further in 2050 to 12.0 GJ/t. It is important to note these figures refer to the additional process energy required, after fuel gas generated by feedstock processing (mainly in HVC production) has been used. Energy efficiency measures and process integration drive these process energy-intensity reductions towards best-performing levels, reflecting energy market dynamics and a suite of regional policy instruments. Some examples are energy efficiency improvement targets (such as the Perform Achieve Trade project in India), minimum equipment performance standards, adoption of energy management systems, gradual phase-out of the fossil fuel subsidies related to industrial use, and CO_2 emissions reduction targets (as in the nationally determined contributions stemming from the Paris Agreement).

For ammonia, the declines in process energy intensity are the steepest, from 25.1 GJ/t in 2017 to 22.8 GJ/t in 2030 and to 19.0 GJ/t in 2050. This drop of nearly a third by 2050 is more than twice the rate of decline seen for methanol and HVC production. Most of the process energy intensity decline of ammonia production is driven by the increase in the global share of natural gas, relative to that of coal. When using a heavier, solid feedstock to produce a chemical, it is generally the case that the process energy intensity is higher. This is because extra energy is required to operate equipment for handling and processing the feedstock.

Environmental impact of growing chemicals demand in the RTS

Chemical sector **CO_2 emissions** increase by more than 30% by 2050 in the RTS. Nearly two-thirds of this increase takes place before 2030, with emissions continuing to climb more slowly during 2030-2050, reaching just under 2 gigatonnes of carbon dioxide per year ($GtCO_2$/y). Emissions levels in 2050 are virtually the same as those in 2030. This growth in emissions is driven by the robust increase in primary chemical demand – 32% by 2030 and 56% by 2050 in the RTS, relative to 2017.

Sustaining this increase in primary chemical production while limiting increases in CO_2 emissions to 32% means that a significant decrease in the CO_2 emissions intensity of chemical activities is achieved. In fact, the emissions intensity of primary chemical production overall decreases from 1.7 tonnes of carbon dioxide per tonne (tCO_2/t) in 2017 to 1.4 tCO_2/t in 2050 in the RTS – nearly a

20% reduction. For all primary chemicals, this reduction is driven primarily by shifts to lighter feedstocks and the achievement over time of best energy performance levels.

Today, producing a tonne of ammonia results in approximately 2.4 tonnes of direct CO_2 emissions on average, with the figures for methanol being 2.3 tonnes and 1.0 tonnes for HVCs. All regions exhibit steady declines in emissions intensity for all primary chemical production throughout the RTS.

Whereas methanol tends to be at the lower end of the emissions intensity spectrum for the production of primary chemicals in most regions, today it is the most emissions-intensive among those produced in Asia Pacific. The emissions impact of gradual improvements in energy efficiency for all production processes offsets the decreasing share of COG in the feedstock mix for methanol production, resulting in modest improvements in emissions intensity. Capacity based on COG – a less emissions-intensive process route – remains fairly level, but coal-based capacity additions in China continue to rise, meaning that methanol remains the most emissions-intensive primary chemical in the region, in both 2030 and 2050.

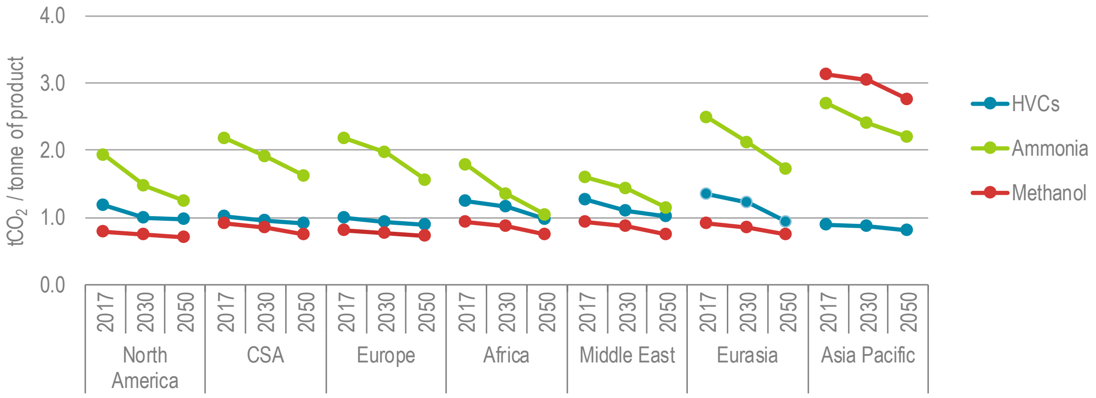
Ammonia production is also more emissions-intensive in Asia Pacific than elsewhere. This is again a result of Chinese coal-based production, which persists in China throughout the RTS. This coal-based capacity is new and efficient, leaving limited scope for emissions-intensity reductions related to energy efficiency improvements. However, the capacity additions in other countries in the Asia Pacific region are considerable and based on gas, which has the effect of gradually lowering the emissions intensity for the region as a whole.

For HVC production, the capacity installed in Asia Pacific is new, efficient and, therefore, consistently the least emissions-intensive production centre for these chemicals. Because this capacity is already quite close to best-performance levels, relatively small gains take place in the RTS.

Outside Asia Pacific, the sharpest declines in emissions intensity are achieved in Eurasia and Africa (ammonia and HVCs) and Europe (ammonia). Beyond feedstock choice, the age of existing plants in a given region is an important factor in the level of CO_2 emissions intensity for all products. Regions with younger plants (e.g. Asia Pacific) typically rely on state-of-the-art technologies and, thus, have higher levels of energy performance; this means smaller gains are available in absolute terms. In the shorter term, this is mainly driven by the shift towards ethane and LPG in steam cracking. As supplies of these lighter oil products grow tighter after 2030, the additional use of naphtha and gas oil does not offer scope for any further reductions in CO_2 intensity. The CO_2 intensities of production processes for HVCs undergo the steepest improvements in North America, Africa, the Middle East and Eurasia.

The final factor that reduces the CO_2 emissions intensity in the RTS is the application of CCUS. The volume of CO_2 utilised for urea production grows by nearly 50% during 2017-50. Ammonia offers the greatest scope for emissions reductions. The fact that around a quarter of the emissions not captured and used at present are process emissions, which are highly concentrated, means that decarbonisation can take place at relatively low cost. Process CO_2 emissions from ammonia production are the primary source of CO_2 for this application, accounting for 97% of the CO_2 cumulatively utilised between 2017 and 2050. No dilute CO_2 emission streams have capture processes applied in the RTS.

Figure 4.11 • CO_2 emission intensities in the RTS



Note: CSA = Central and South America.

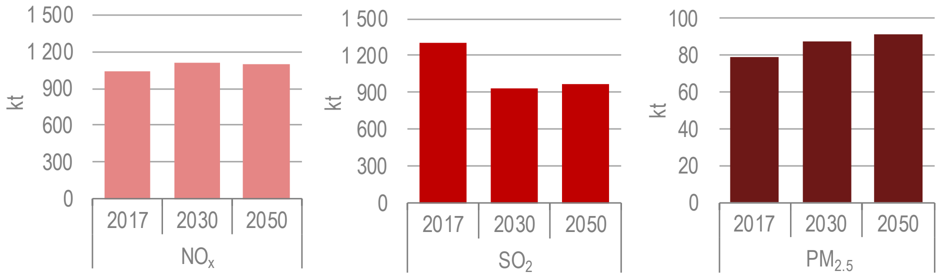
Key message • Gentle declines in CO_2 emissions intensity take place for all chemicals across all regions.

Deployment of carbon capture and storage (CCS) in the RTS is limited to regions in which the existing infrastructure, political environment and public attitudes are favourable: North America, and Asia Pacific. The expansion of the 45Q tax credit in the United States lays the groundwork for further development of CCS projects. Chemical industry CCS projects offering nearly 10 million tonnes of carbon dioxide ($MtCO_2$) of annual capture capacity are at various stages of development in the United States and are anticipated to come online around the 2020s. China is developing chemical industry CCS projects with an overall capacity of 1.3 $MtCO_2$ annual capture, with operation due to start in the early 2020s. These firm announcements are realised in the RTS, resulting in the cumulative capture of approximately 375 $MtCO_2$ for storage in the RTS between 2017 and 2050. The Netherlands has announced a target to store 18 $MtCO_2$ annually by 2030, all from industrial point sources (Dutch Government Parties Coalition, 2017). However, without firm and specific commitments, this capacity is not realised in the RTS.

Globally, the amounts of key **air pollutants** – NO_x, SO_2 and $PM_{2.5}$ – generated in combustion processes per unit of primary chemical output decrease globally: on average, by more than 30% by 2050 in the RTS. In the case of SO_2, the figure more than halves. In the RTS, the average air pollutant intensity of primary chemical production decreases from 4.7 tonnes per kt of primary chemical in 2017 to a little over 2.6 tonnes per kt of primary chemical in 2050.

Once again, a gradual decline in the share of coal-based production in Asia Pacific yields significant benefits, leading to a flattening of air pollutant emissions, especially SO_2, which decline by more than 20% by 2050, despite an increase of more than 60% in the production for primary chemicals. This effect is diluted slightly at the regional level in Asia Pacific owing to a small increase in coal used for process energy elsewhere in the region. NO_x levels in the RTS undergo a worrying increase by 2050 in Africa and in the Middle East (both increasing by just under 25%), mainly because of the use of some heavy oil as process energy in HVC production.

Figure 4.12 • Air pollutants from primary chemical production by region in the RTS



Notes: NO$_x$ = nitrogen oxides; SO$_2$ = sulphur dioxide; PM$_{2.5}$ = fine particulate matter. Estimates of air pollutant emission levels refer to combustion-related sources in primary chemical production. International Institute for Applied Systems Analysis/IEA joint analysis. kt = kilotonne; ROW = rest of the world.

Key message • Air pollutants decline in all regions in the RTS, apart from the Middle East and Asia Pacific, where the strongest growth in primary chemical production takes place.

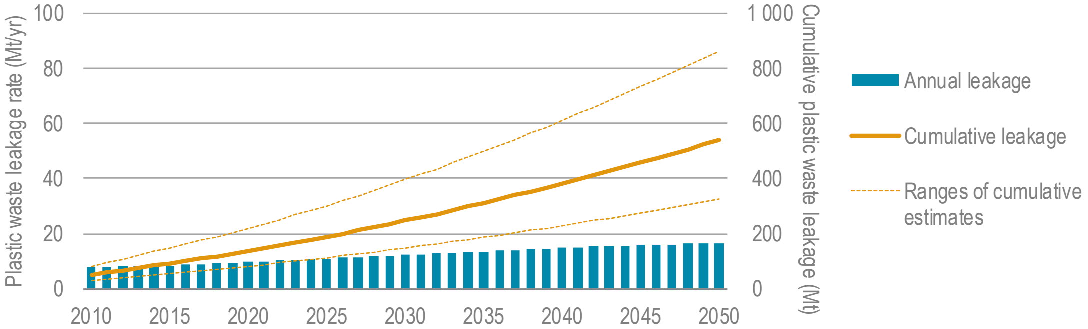
Plastic waste can escape from waste management systems if adequate care is not taken during use or at the end of life of goods containing plastic. This waste can "leak" into the environment, frequently making its way into water courses and eventually into the ocean, where it damages marine life and ecosystems. It is estimated that around 100 Mt of plastic waste is already in the oceans and that this amount is increasing by 5-15 Mt per year (Jambeck et al., 2015; Ocean Conservancy, 2015). However, the data on this phenomenon are plagued by uncertainty, as much of the leakage takes place in areas with little or no waste management.

If no action is taken, the current rate of **plastic waste leakage** is likely to result in more than a doubling of cumulative plastic waste in the oceans by 2030, and a continuing rise thereafter. This is a starkly unacceptable feature of the RTS. This environmental problem has received more attention from the public in recent years, yielding policy developments in the form of commitments to action by governments to drastically decrease plastic leakage to the environment.

Increases in recycling rates observed in recent years, particularly in Europe, are positive developments that are expected to continue in the RTS. However, these increases do not in themselves result in the mitigation of plastic leakage, given that there are still large quantities of non-recycled plastic waste that can be mismanaged. The *European Strategy for Plastics in a Circular Economy* (European Union, 2018) is cause for encouragement, though specific legal instruments are yet to materialise. Without ambitious action being taken globally, particularly in regions in which plastic demand is growing rapidly, current trends of plastic leakage are unlikely even to slow, let alone reverse.

Scattered waste volumes, including plastic waste, can often prevent waste management businesses from conducting profitable operations, in order to reduce the costs of this essential public service. Simultaneously, lack of means or information can prevent consumers and private entities from disposing adequately of the waste they generate.

Figure 4.13 • Plastic waste leakage in the RTS



Notes: Quantities of plastic leakage are estimated based on projections of plastic waste and estimates of current rates of leakage, the latter of which are assumed to remain constant. The range presented for cumulative estimates reflects the range of estimates for current rates of leakage. The ranges for annual quantities are omitted for clarity.

Source: Estimates of current rates of leakage from Jambeck, J.R. et al. (2015), "Plastic waste inputs from land into the ocean", https://doi.org/10.1126/science.1260352.

Key message • By 2050, the quantity of plastic in the ocean exceeds 500 Mt in the RTS (with an estimated range of 320-860 Mt), rising far beyond already unacceptable levels.

Digital technologies can transform waste management systems by connecting waste generators with a local recovery service. They can facilitate on-demand waste recovery, tailored to each specific waste material. Smart sensors installed in collection containers can facilitate the sorting of waste and so reduce waste recycling costs. The smart waste collection market is estimated to have the potential to grow almost fourfold by 2025, reaching about USD 224 million globally (Navigant, 2016).

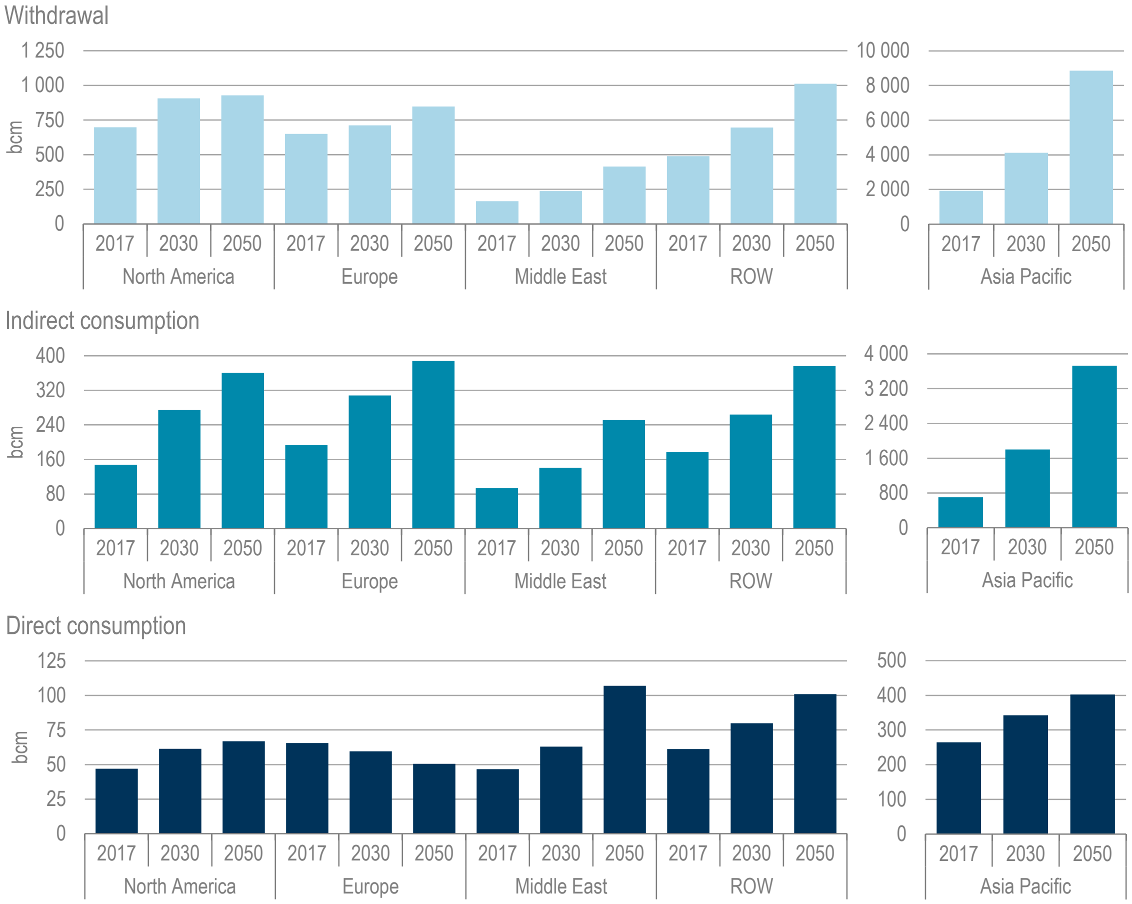
Global **freshwater withdrawals** for primary chemical production more than triple during 2017-50, rising to 12 bcm. Indirect water withdrawals account for most of the increase and, as a result, the share of total indirect water withdrawals for primary chemical output rises to almost 95%. Water withdrawals for the first few years remain relatively stable, due to counteracting changes in the power sector that affect withdrawals. The retirement of less-efficient subcritical coal plants (replaced in part by supercritical and ultra-supercritical coal plants) depresses water withdrawals, while more nuclear and concentrated solar power increases withdrawals.

Water consumption increases from nearly 2 bcm in 2017 to nearly 5 bcm by 2050, consumption as a share of primary chemical-related water withdrawals rising slightly from 46% to 48% over the same timeframe. The high share of consumption, relative to withdrawals, is due to heavy reliance on coal, oil and natural gas for chemical processes. Primary energy production is the largest source of water consumption in the energy sector. As with withdrawals, indirect consumption is responsible for the majority of the increase.

Asia Pacific accounts for approximately half of cumulative primary chemical production in the RTS. As a result, the trend in water use for primary chemicals in Asia Pacific underpins many of the changes at the global level. The region accounts for roughly 80% of the global increase in both withdrawal and consumption of water for these products. A more than ten-fold global increase in bioenergy production (albeit from minimal levels today), mostly in Asia Pacific, underpins much of the rise in water demand because biofuels are the largest source of water withdrawals and consumption in primary energy production.

Similarly, greater use of electricity for chemical processes pushes up water use. An improvement in the average level of efficiency of China's coal fleet derives from the decline in the share of coal-fired generation from subcritical power plants. China also shifts away from coal-fired generation that relies on once-through cooling systems, towards wet-tower systems, which lower withdrawals but temper the rate of decline in consumption. Despite its declining share, coal still plays a critical role in power generation in the RTS, as does nuclear, thus elevating water demand.

Figure 4.14 • Water demand for primary chemical production in the RTS



Notes: Direct water demand estimates for primary chemical production include water uses for feedstock (e.g. steam cracking). Water demand for process heating is excluded due to the wide range of possible configurations for steam systems across chemical sites.

Key message • Asia Pacific accounts for about 80% of the global increase in water withdrawal and consumption for primary chemicals.

As discussed in Chapter 3, many countries already face some degree of water stress, and it is estimated that, by 2050, 5 billion people could suffer water shortages (WWPA and UN Water, 2018). Though water use in primary chemical production is low, compared to other sectors, certain regions that are already, or are projected to become, large chemical producers, are likely to face water stress. Water availability could, therefore, become an inhibiting factor for primary chemical production. This makes understanding and managing water inputs all the more important in order to ensure that the chemical sector does not unduly affect water resources or become constrained by water resource considerations. Key chemical-producing regions such as China, the Middle East and parts of the southern United States are all expected to experience high or extremely high levels of water stress (WRI, 2018).

References

Argus Media (2018), *Key Prices*, www2.argusmedia.com/en/methodology/key-prices (accessed 6 June 2018).

Dutch Government Parties Coalition (2017), *Confidence in the Future*, www.government.nl/documents/publications/2017/10/10/coalition-agreement-confidence-in-the-future (accessed 6 June 2018).

European Union (2018), *A European Strategy for Plastics in a Circular Economy*, http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy.pdf.

EIA (United States Energy Information Administration) (2018), *Petroleum and Other Liquids*, www.eia.gov/petroleum/ (accessed 6 June 2018).

Geyer, R., J.R. Jambeck and K.L. Law (2017), “Production, use, and fate of all plastics ever made”, *Science Advances*, Vol. 3/7, e1700782, https://doi.org/10.1126/sciadv.1700782.

IEA (International Energy Agency) (2017), *World Energy Outlook 2017*, OECD/IEA, Paris.

IEA (International Energy Agency) (2018), *Market Report Series: Oil 2018*, OECD/IEA, Paris.

Jambeck, J.R. et al. (2015), “Plastic waste inputs from land into the ocean”, *Science*, Vol. 347/6223, p. 768-771, https://doi.org/10.1126/science.1260352.

Levi, P.G. and J.M. Cullen (2018), “Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products”, *Environmental Science and Technology*, Vol. 52/4, p. 1725-1734, https://doi.org/10.1021/acs.est.7b04573.

Navigant (2016), *Smart Waste Collection*, www.navigantresearch.com/research/smart-waste-collection (accessed 6 June 2018).

Ocean Conservancy (2015), *Stemming the Tide: Land-based Strategies for a Plastic-free Ocean*, Ocean Conservancy supported by McKinsey Center for Business and Environment, https://oceanconservancy.org/wp-content/uploads/2017/04/full-report-stemming-the.pdf.

OECD (Organisation for Economic Co-operation and Development) (2018), *Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses*, OECD Publishing, Paris.

WRI (World Resources Institute) (2018), *Aqueduct Database*, www.wri.org/our-work/project/aqueduct (accessed 6 June 2018).

WWPA (United Nations World Water Assessment Programme) and UN-Water (2018), *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*, http://unesdoc.unesco.org/images/0026/002614/261424e.pdf.

Chapter 5. Towards a clean chemical sector

In this chapter, an alternative future for the chemical sector is explored, using the Clean Technology Scenario (CTS; see Box 5.1). In contrast to the analysis in Chapter 4, which projects the development of the sector based on existing policies and intentions, the CTS works backwards from a pre-defined end-point, derived from the United Nations Sustainable Development Goals. These express an ambition to "end poverty, protect the planet and ensure prosperity for all" (United Nations, 2018c).

The wider boundary of this analysis is intended to address aspects of Sustainable Development Goals 3, 6, 7, 13, 14 and 15, and aims to demonstrate the feasibility of concurrently addressing multiple facets of sustainability. A clean chemical sector has much to contribute to such a sustainable future, which goes well beyond limiting climate change. The CTS explores opportunities to mitigate air and water pollution, and the water demand associated with primary chemical production, alongside the over-arching goal of reducing carbon dioxide (CO_2) emissions.

Taking CO_2 emissions from the chemical sector as an indicator of the level of ambition set in the analysis, the level of emissions in 2050 relative to the Reference Technology Scenario (RTS) explored in Chapter 4, must be 60% lower in the CTS. This must be achieved in a sector in which demand for primary chemicals increases by around 40%, despite sharp increases in plastic recycling rates. Alongside these substantial CO_2 emission reductions, emissions of air and water pollutants must be steeply reduced, and solutions for these to be even ceased must be explored, if the chemical sector is to follow a more-sustainable trajectory.

Box 5.1 • The CTS

The CTS was generated using the same tools and methodologies as those of the RTS (see Box 4.4). For example, process choices are still based on minimising capital investment and fuel costs, but with the addition of various constraints. The key additional constraint is that the model requires direct CO_2 emissions to be reduced by 45% by 2050, compared to current levels, despite a 40% increase in primary chemical output.

This is not the only additional constraint. The assumptions made about the extent of the required mitigation of other environmental impacts, such as those related to air pollution and water and about other aspects of the future energy system, are in line with those adopted in the IEA Sustainable Development Scenario. Featured for the first time in the *World Energy Outlook* (IEA, 2017), the Sustainable Development Scenario takes a fundamentally different approach from the New Policies Scenario of the *World Energy Outlook,* to which the RTS is aligned.

The Sustainable Development Scenario takes as its starting point a vision of where the energy sector needs to go and works back from that to the present, rather than projecting forward from today's trends. The Sustainable Development Scenario contributes to the achievement of three core goals (derived from the energy-related aspects of the United Nations Sustainable Development Goals):

- universal access to modern energy services by 2030, including not only access to electricity but also clean cooking
- objectives of the Paris Agreement on climate change, including a peak in greenhouse gas emissions being reached as soon as possible, followed by a substantial decline in such emissions
- a large reduction in other energy-related pollutants, to deliver a dramatic improvement in global air quality and a consequent reduction in premature deaths from household air pollution.

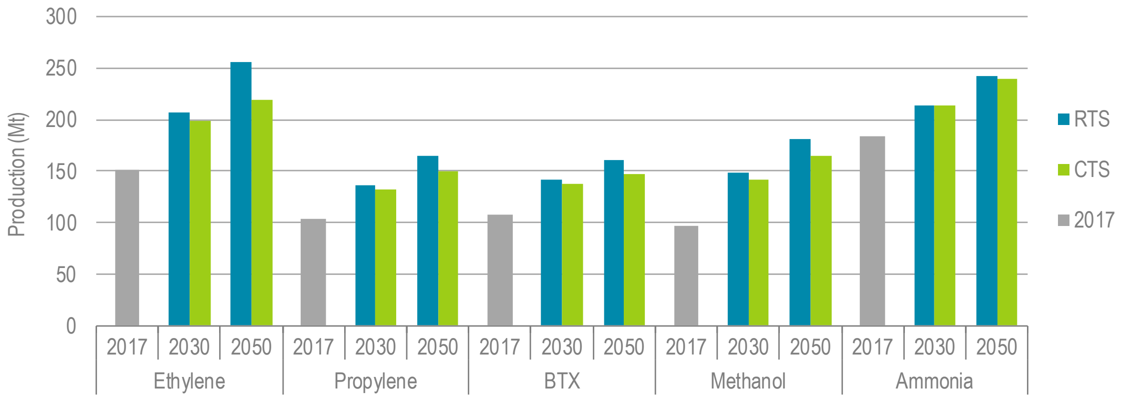
These goals have direct implications for sectors beyond the energy sector, including the chemical sector, mainly by raising prices or lowering the availability of certain fuels. For example, the increased demand for liquefied petroleum gas (LPG), relative to other oil products, for clean cooking in developing economies limits the supply available to other sectors, and increases its price. LPG currently accounts for around 16% of oil feedstock for primary chemical production.

Slower, but continuing growth in primary chemical demand

As discussed in Chapter 1, chemical products play an instrumental role in facilitating a sustainable transition of the energy system and the economy more broadly. As a result, the growth in primary chemical demand remains robust in our CTS projections. Demand for primary chemicals increases by almost 30% by 2030 and around 40% by 2050 in the CTS, around 4 and 13 percentage points less than in the RTS, respectively. The shares of benzene, toluene and mixed xylenes (BTX) and high-value chemicals (HVCs) being sourced from the refining sector remain the same as in the CTS.

These slower rates of growth are attributable to increased plastic recycling, which reduces the demand for virgin plastic. The demand for plastic overall is assumed to be the same in the CTS as in the RTS. New end uses of plastic (e.g. plastic components in electric vehicles) are likely to provide new avenues for growth, while others, such as single-use plastics are likely to be phased out in the context of the CTS. Projecting these developments is plagued by uncertainty, so the overall demand is kept constant in the core results,[23] in order to isolate the effect of increased recycling.

Figure 5.1 • Global primary chemical production by scenario



Note: Mt = million tonnes.

Key message • Substantial increases in plastic recycling lower demand for primary chemicals by 7% by 2050 in the CTS relative to the RTS. The differences are most noticeable for HVCs.

Plastics recycling

Waste plastic collection rates, recycling yield rates and the extent to which recycled plastics displace demand for their virgin counterparts all increase substantially in the CTS. Secondary plastic production volumes from recycled resins increase by 65% in the CTS, compared to the RTS, by 2030, and more than double by 2050. This results in 16 million tonnes (Mt) of primary chemical savings by 2030 and about 70 Mt by 2050. Plastic recycling is a key underlying source of emissions reductions in the CTS.

As discussed in Chapter 4, the changing regional shares of plastic consumption over time have a significant impact on global average rates of plastic waste collection. In the RTS, global average collection rates increase by 25%, from relatively low levels today. Large increases in

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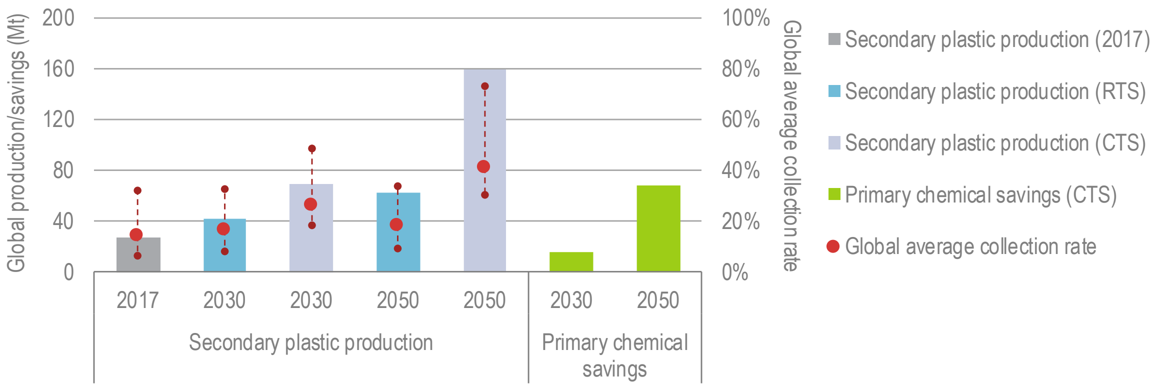
[23] Details of a high demand sensitivity variant analysis can be found in the online annex accompanying this publication.

several mature economies, notably Europe, are dampened by increasing shares of plastic consumption in regions where collection rates are low.

In the CTS, the trend is much more positive. Already by 2030, the global average collection rate has nearly doubled, and almost tripled by 2050. This is mainly because developing regions with strong growth in plastic consumption (e.g. the People's Republic of China, India and developing economies in Southeast Asia) increase their collection rates from today's negligible levels, attaining those currently observed in Europe by 2050. To achieve a full transition to the CTS, developed countries must achieve collection rates for certain resins in excess of 75% by 2050 – a significant technical challenge. Europe, Japan and Korea manage this in the RTS, but are joined by the majority of mature economies in the CTS, cementing the impact.

Increases in recycling yields also gather pace in the CTS, rising from an average of around 75% in 2017 to nearly 85% in 2050. Displacement rates double, from around a third in 2017 to two-thirds in 2050. Again, significant technical advances in recycling processes will be required. Efficient, closed loop recycling of large portions of total plastic waste must be achieved by 2050, whereas many sectors today have only a few inefficient options available.

Figure 5.2 • Impact of recycling by scenario



Notes: Error bars show the range of resin-specific global average collection rates. Projected volumes of total plastic production are independent of the level of recycling. The impact of recycling is registered in the lowering of demand for primary chemicals.

Sources: Data consulted in making projections from Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use, and fate of all plastics ever made", https://doi.org/10.1126/sciadv.1700782; Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", https://doi.org/10.1021/acs.est.7b04573; OECD (2018), *Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses*.

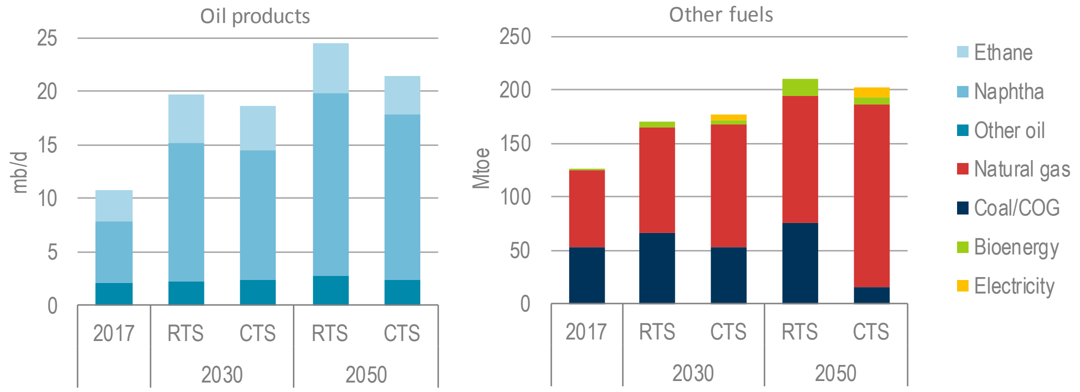
Key message • By 2050, the plastic waste collection rate for recycling more than doubles in the CTS, relative to the RTS, delivering around 70 Mt of primary chemical savings.

Regional differences affect both the shares of demand for different plastic resins, and those within waste streams. The resin composition of waste streams does not match that leaving the factory gate and entering the built environment, because of the different lifetimes of each end use (e.g. packaging or buildings). Strong demand today for short-lived plastics results in large volumes in waste streams tomorrow. This is why growth in collection rates, must be broad-based in the CTS, not just across regions, but also across resins. By 2050 in the CTS, the lower end of the range of average resin collection rates (e.g. those for polystyrene) approaches the upper end of the range today (e.g. average rates for polyethylene terephthalate).

Feedstock changes in a sustainable transition

As discussed earlier, plastics are primarily derived from HVCs. Only very small amounts of methanol and ammonia make their way into the major recyclable plastic resins. As a result, of the about 70 Mt of primary chemical savings achieved in 2050 in the CTS, relative to the RTS, 95% are HVCs. Three-quarters of the HVC savings are olefins (ethylene and propylene), and the remainder are BTX aromatics. Because feedstock for HVCs currently comes almost entirely from oil – and continues to do so in the RTS – the impacts of increased recycling on feedstock demand in the CTS are primarily reflected in reduced oil demand, although the impact is not as large as one might expect.

Figure 5.3 • Feedstock demand in the RTS and CTS



Notes: COG = coke oven gas. Electricity used as feedstock for electrolysis-based hydrogen production. *Electricity* denotes the use of electrolytic hydrogen, and is displayed in terms of electricity input.

Key message • More than 90% of the impact of plastic recycling in 2050 is felt by oil feedstock.

Oil feedstock demand for primary chemical production in the CTS is 5% lower in 2030 and 13% lower in 2050, relative to the RTS. The other fuels used as feedstock see even smaller declines, with natural gas consumption actually increases in the CTS, as it displaces coal. The relatively modest declines between scenarios, despite large collection rate increases, are due to three main factors:

- First, there is the time-lag of plastic products entering the waste stream after use, a period which varies between months and decades, depending on the product application. Underlying this analysis is a stock model for the key plastics considered, used to estimate the impact of this delay, and thus the quantity and composition of the plastics available to recycle. While plastic demand is growing, as it does throughout the CTS, the volumes available to recycle are always smaller than those being produced.
- Second, a recycling yield loss is incurred. Although recycling yields increase over time in the CTS, even in 2050, the quantities of secondary plastic produced are around 10-15% less than the quantity of scrap plastic used to produce them.
- And finally, there is a limited extent to which secondary plastic materials can displace primary plastic demand, and therefore reduce primary chemical production. The displacement rate increases dramatically in the CTS, reflecting both technological advances and a strong policy push, for example in the area of closed loop recycling. However, in 2050, still around a third of the secondary plastics considered are not able to provide direct substitutes for their virgin counterparts.

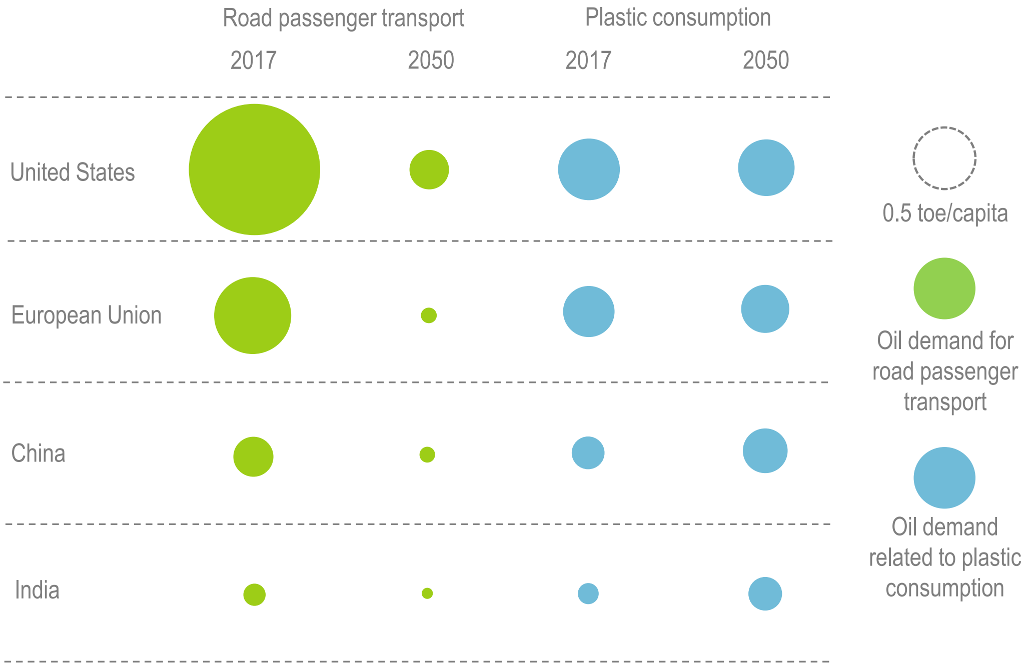
As described in Chapter 4, the overall impact of the increased recycling efforts is further diminished by the fact that the collection, yield and displacement rates are multiplicative.

A last aspect to note is the incomplete scope of the primary chemical value chains considered. The chemical sector downstream of primary chemicals is vast and complex, making a complete account of all derivatives and their recycling potential nearly impossible. The key thermoplastics incorporated in the analysis of recycling account for about half of total primary chemical demand, and more than almost 85% of total HVC demand in 2050 in the CTS. The remainder is for a huge roster of other chemical products, such as synthetic fibre and rubber, which are considered to have more limited potential for recycling, relative to the key thermoplastics considered.

Implications for oil supply and refining

In the RTS, growing oil demand for chemical feedstock and declining demand for oil products for passenger vehicles shift the overall pattern of oil product demand, with "top of the barrel" products taking an increasing proportion. This effect is amplified in the CTS (and also in the IEA Sustainable Development Scenario), in which chemicals take the lead between the two main end uses in many regions.

Figure 5.4 • Per capita oil demand for selected end uses in the CTS

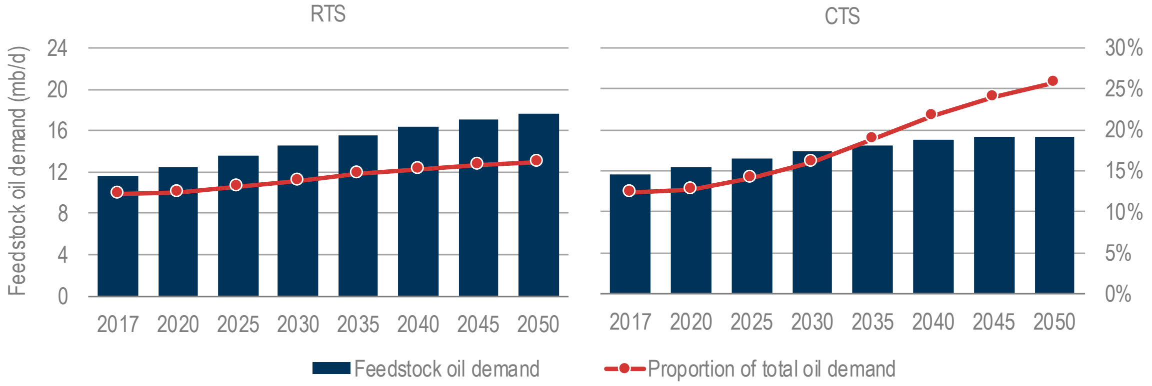


Notes: toe/capita = tonne of oil-equivalent per capita. Oil demand for plastic consumption is calculated based on global average HVC energy intensities, including both feedstock and process energy, to reflect that plastics are widely traded.

Key message • By 2050, per capita oil demand for plastic consumption over-takes that of road passenger transport in several regions in the CTS.

Enhanced efforts are made in these sustainable scenarios to decarbonise other modes of transport, for example, through systematic improvements in road freight operations or much larger uptake of alternative fuels in shipping and aviation. In petrochemicals in the CTS, a growing share of bio-based feedstock and wider uptake of plastic recycling results in a nearly 3 million barrels per day (mb/d) reduction in oil demand for chemical feedstock in 2050, relative to the RTS. However, the demand for oil for this purpose still grows. The share of chemical feedstock in total oil demand more than doubles, from 12% in 2017 to 26% by 2050, much higher than the 16% in the RTS. This shift in the balance of sectoral demand poses an unprecedented challenge to the refining industry.

Figure 5.5 • Oil demand for chemical feedstock and share in total oil demand by scenario



Key message • The share of chemical feedstock in total oil demand in the CTS is much higher than in the RTS, despite lower absolute volumes, because oil demand for other sectors declines much more sharply.

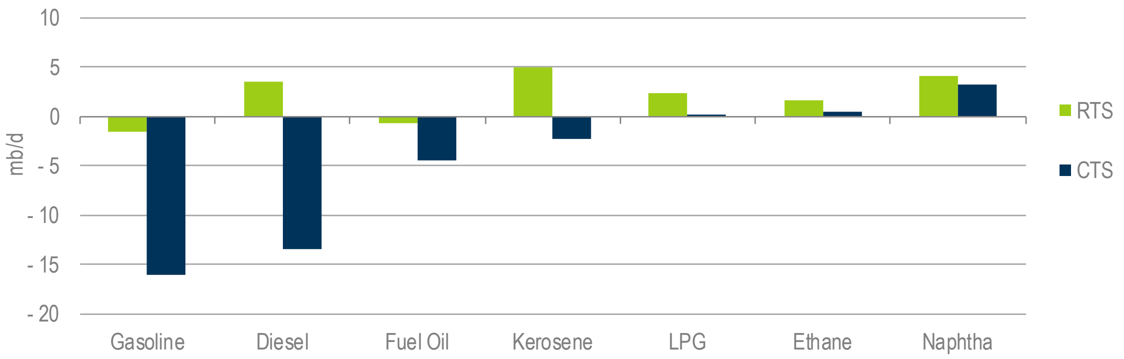
In the CTS, the shift in demand is acute in transport fuels, with demand for gasoline and diesel falling by 16 mb/d and 13 mb/d respectively between 2017 and 2050. Fuel oil demand more than halves and kerosene demand declines by 30% over the same period. However, demand for the products used as a chemical feedstock remains relatively resilient, with naphtha, ethane and LPG demand registering positive growth over the analysed period. In 2050, the share of these three major feedstocks in total oil demand amounts to 35%, significantly higher than 18% in 2017.

The shifting demand towards lighter products in this scenario will force refiners to rethink their operational strategy. Light tight oil (LTO) may offer a helping hand. Prior to the growth of LTO production in the United States, global crude oil production had been getting heavier, with the share of heavier crude growing from 13% in 2000 to 16% in 2011; but the recent surge in United States (US) LTO production, which is expected to continue over the next ten years, will reverse this trend, easing the supply position for petrochemical feedstock.

Light crude oil has certain drawbacks as a refinery feedstock (e.g. limited scope to remove hydrocarbon gases), but it facilitates the supply of a higher proportion of lighter oil products. It can be particularly attractive for refinery facilities integrated with petrochemical operations, or for those located in Asia, a region that relies on imports to meet its growing appetite for chemical feedstocks, such as naphtha and LPG. The combination of US LTO and condensate production will help refiners to meet the changing patterns of product demand in the medium term observed in the CTS.

Long-term might be a different story. There is some uncertainty over the durability of the surge in US LTO production. In our analysis, it continues to grow until the mid-2020s, dominating global production growth, but the tide turns after the mid-2020s, when production peaks and begins to fall, reducing the availability of lighter crude. Moreover, the projected peak in US LTO production coincides with the period when the mismatch between the configurations of refineries (as it stands at present) and product demand becomes acute – for example, gasoline demand starts to plummet from the mid-2020s. Historically, the refining industry has shown a remarkable capacity to adapt to changing market environments, but a combination of lower overall demand, shifting product demand patterns and reduced long-term availability of lighter crude in the CTS, will set a new order of challenges.

Figure 5.6 • Change in oil products demand in the CTS, 2017-50



Key message • Chemical feedstock is the most enduring use of oil in the CTS, underpinning a large-scale shift towards "top of the barrel" products.

The change in the pattern of product demand will have ripple effects. Falling gasoline demand means that the large component of naphtha that is currently converted into gasoline components may no longer be needed for this purpose, suggesting that more naphtha may be available to the petrochemical market. However, the supply of ethane continues to tighten in this scenario, as shale gas development increasingly moves away from wet plays to drier plays (those with fewer natural gas liquids (NGLs)), albeit later than in the RTS.

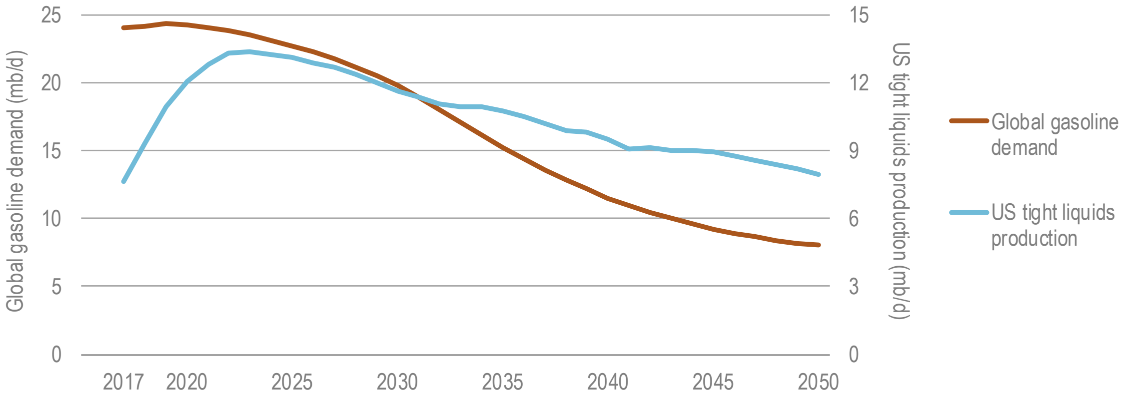
The share of LPG in petrochemical feedstock is likely to be reduced, due to the combined effect of limited supply and growing demand from other sectors. LPG is usually supplied from refineries or by fractionating NGLs. Lower oil demand in the CTS translates into lower refinery utilisation, implying a lower supply of LPG from this source. Furthermore, NGLs are a by-product of natural gas production, so their supply tends to be determined principally by demand for natural gas – in other words, LPG price signals from the demand side do not necessarily trigger a supply response. The supply of LPG in this scenario, therefore, remains substantially lower than in the RTS.

Meanwhile, there are stable or growing needs for LPG across various sectors, in particular, in response to the Sustainable Development Goal of providing universal energy access by 2030, one aspect of which is access to clean cooking facilities. LPG is a common solution to this challenge, especially in urban areas. For example, in 2016, India rose to the third place among the largest LPG importers in the world, reflecting its success, since 2010, in halting the rise in the number of people without access to clean cooking, despite a rapidly growing population. A growing appetite for LPG in this scenario is also visible in other demand sectors. For example, LPG makes further inroads in transport, due to its relatively low emissions of various air pollutants.

The significant reduction of gasoline and diesel demand in the CTS does not bode well for the traditional pricing dynamic, whereby profits from gasoline and diesel determine refinery earnings. Refiners will therefore be forced to consider other sources of income. Raising prices for naphtha and LPG could be one solution, but it is hard to imagine a rise in prices taking place that fully compensates for the losses from gasoline and diesel sales.

One possible response to the challenges of this increasingly competitive refining landscape is refining-petrochemical integration, as already discussed in Chapter 2. Closely tying refining and petrochemical operations (beyond just co-location) offers a chance for companies to increase chemical product yields, enhance feedstock flexibility and increase income. Integration can be aided further by technologies, such as high-olefins fluid catalytic cracking, which can produce much higher volumes of ethylene and propylene (over 30% compared to less than 10% in conventional technologies). These technologies allow fluid catalytic cracking units to produce more chemical products, relative to gasoline products, and therefore help companies to cater for changing product demand. There are other operational benefits too.

Figure 5.7 • Global gasoline demand and US tight liquids production in the CTS



Key message • The projected peak in US LTO production in the mid-2020s coincides with the timing of the expected sharp fall in gasoline demand.

Deeper integration allows a considerable cost reduction via economies of scale, process optimisation across a diverse facility and infrastructure sharing. There is also the chance to use "non-monetised" products from one operation in another operation, for example, using surplus hydrogen from chemical facilities in refining operations or using refinery gases for petrochemicals. The scene seems to be set for the further blurring of the boundary between refining and petrochemicals businesses. Crude-oil-to-chemicals is an example of a technology that may be adopted in such a context.

The need for lighter crude oil, which is best-suited for integrated facilities, favours the regions producing this grade, such as the United States, West Africa and the Russian Federation. For the petrochemical industry, standalone steam crackers that procure naphtha from outside are likely to face greater challenges. Plummeting gasoline demand – and therefore increased availability of naphtha – may push down naphtha prices. For standalone crackers, this effect could be offset by the rise of integrated facilities, reducing the amount of naphtha freely available in the market.

Mapping the clean transition

Collective action throughout the value chain will be required to accomplish the multiple goals set in the CTS and a suite of technologies and operational choices are available in the chemical sector to facilitate the transition from the RTS to the CTS. From the perspective of the necessary CO_2 emission reductions (the main driving force behind the scenario), the deployment of carbon capture, utilisation and storage (CCUS) plays a critical role in the necessary transformation of primary chemical production, accounting for around 35% of the emission reductions by 2050. Shifting to natural gas from process routes dependent on coal delivers a further 25% of the reductions, with coal almost phased-out globally by 2050. Although powerful, this mitigation option cannot be repeated. Energy efficiency, state-of-the-art technology, process integration and effective operational practices are also instrumental, accounting for a further 25% of reductions. The deployment of innovative alternative feedstocks, together with the impacts of recycling contribute a further 15%.

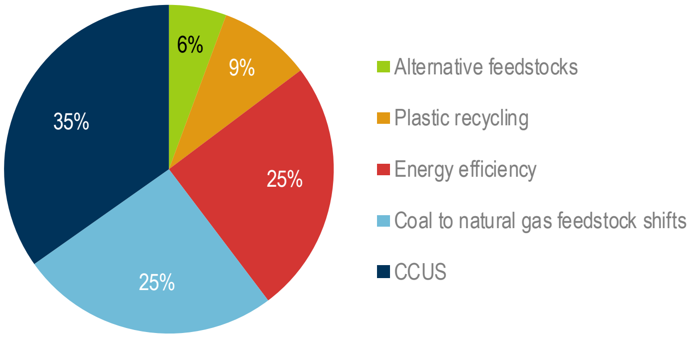
There are interactions between mitigation options that depend on the measures taken. For example, the installation of carbon capture equipment typically increases the specific energy intensity of a given process, as additional energy is needed to operate the CO_2 separation and handling equipment. This then affects the share, magnitude and role of energy efficiency in the facilitation of CO_2 emission reductions. Plastic recycling is, however, independently sustainable. By reducing the demand for primary chemicals, this measure not only avoids CO_2 emissions, but also diminishes air pollutants and water demand and reduces the generation of waste, thus helping to prevent its leakage into the environment.

As always, the key determining choices en route to a sustainable future are energy costs (including feedstock) and the capital expenditure required for process equipment. In the CTS, both bioenergy and electricity prices tend to increase over time, whereas fossil fuel prices tend to flatten out or even decrease. This divergence arises from the fact that, in a CTS context, the demand for low-carbon energy carriers increases throughout the energy system, whereas fossil fuels are in decline.

For example, the buildings sector sheds demand for natural gas for space heating and replaces it, in part, by electricity, which is supplied by a power sector that has decreased its CO_2 emissions intensity by around 80% by 2040, relative to current levels. The transport sector reduces its consumption of fossil-based liquid fuels, switching in part to biofuels.

These dynamics depress prices for fossil fuels and drive up the prices for their alternatives. Although the CTS indicates that specific capital expenditure for less mature alternative technologies actually is reduced over time, as they get scaled up, capital expenditure generally plays a small role in primary chemical production on a levelised cost basis, relative to energy costs.

Figure 5.8 • Cumulative direct CO_2 emission reductions in the CTS



Notes: Cumulative direct CO_2 emission reductions refer to primary chemical production and not to the total chemical sector, and cover the period 2017-50. Coal to natural gas savings include the reduction of process emissions in the production of methanol and ammonia. CO_2 emission savings resulting from feedstock shifts within the same energy commodity (e.g. naphtha to ethane) are included in energy efficiency.

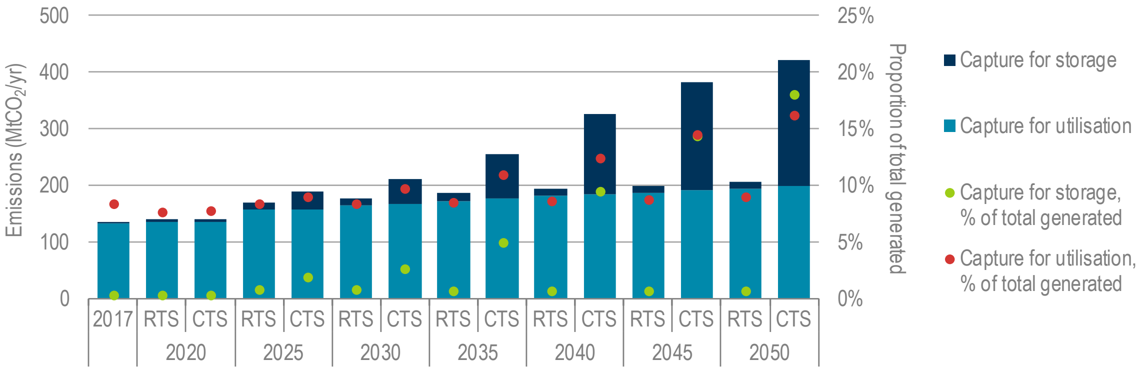
Key message • A broad range of options is required to deliver the CTS transition in primary chemical production.

CCUS

The diverging energy price context between fossil fuels and low carbon energy carriers – particularly between natural gas and electricity – largely underpins the leading role of CCUS among innovative low-CO_2 processes in the CTS. Carbon capture and utilisation (CCU) plays a similar role in the CTS as in the RTS, as the demand for urea – the largest existing utilisation application within the chemical sector – varies only slightly, and CO_2 utilisation for producing methanol via electrolysis achieves limited penetration.

In the CTS, carbon capture and storage (CCS) deployment increases from almost 3 million tonnes per year ($MtCO_2$/yr) in 2017, related to two existing enhanced oil recovery projects associated with ammonia production in the United States, to around 220 $MtCO_2$/yr in 2050. Around 3 gigatonnes of carbon dioxide ($GtCO_2$) is captured cumulatively by 2050, 10% of which is captured before 2030. The large-scale shift from primary chemical production based on coal to natural gas greatly reduces the potential burden placed on carbon capture in the CTS. Capacity based on natural gas requires far less carbon capture per unit of primary chemical production.

Figure 5.9 • CCUS deployment in the CTS and the RTS



Key message • Additional CO_2 capture capacity deployed in the CTS relative to the RTS is primarily for storage applications.

Around 40% of the cumulative CCS capacity in the CTS is deployed to capture concentrated CO_2 emission streams, with 60% being applied to dilute streams, most of which arise from energy-related CO_2 emissions. Concentrated CO_2 streams are captured first, accounting for around 80% of cumulative emissions captured before 2030. The fact that CO_2 separation is an inherent part of the production process for methanol and ammonia makes these capture options cheaper and therefore more attractive, albeit limited in scope. The only additional capital investment required within the production facility is for CO_2 compression, which involves less than a fifth of the capital cost associated with capture applications for dilute streams in the chemical sector. However, the availability of these more attractive streams is limited.

After 2030, the feedstock shifts that have taken place, from coal to natural gas, result in fewer such concentrated streams of emissions being available for capture for permanent storage, so that approximately almost 20% of CCS is applied to dilute streams after 2030. Ammonia accounts for the majority of the cumulative CCS, both before and after 2030. Methanol accounts for 11% of the cumulative captured CO_2 emissions for storage whereas HVCs make up cumulatively 9% of total cumulatively CCS by 2050 – only 4% before 2030. Ammonia is the only primary chemical for which its share of cumulative CO_2 emissions captured for storage is larger before 2030 than after. This is in part because coal-based capacity which presents a low-cost capture opportunity before 2030, is phased out by 2050.

Coal to natural gas shifts

Switching to less carbon intensive fossil feedstocks (still concentrating for the moment on fossil fuel based feedstocks, as opposed to alternative feedstocks) is an important lever for delivering

CO_2 emission reductions in the CTS. As described in Chapter 2, reductions in emissions can be facilitated by utilising a different feedstock, even while remaining within the same family of process routes.

Lighter feedstocks tend to have higher yields than their heavier counterparts, on a mass basis. This means fewer tonnes of material need to be processed for a given level of production. If the lighter feedstock is replacing a solid (e.g. switching from coal to natural gas), additional gains are achieved through negating the need to gasify the feedstock.

For methanol and ammonia, an almost entire shift away from coal, to natural gas and coke oven gas, takes place in the CTS. Whereas ammonia capacity based on coal shrinks to zero, some methanol capacity based on coal remains. Newly built MTO plants utilising low-cost methanol based on coal are the main incentive for retaining this capacity in 2050. The MTO route becomes less attractive as methanol production based on coal disappears, leading the deployment of this process route to decline below the levels seen in the RTS by 2050.

This dramatically reduces process emissions from the production of these chemicals, but it should be noted that this is a one-time emission dividend, and cannot be repeated. As the major region for both ammonia and methanol production and the only region with a large coal-based chemical industry, Asia Pacific is instrumental in this shift. As with the RTS, in all regions, the use of oil products as feedstock for methanol and ammonia is phased out early in the period to 2050. In most cases in the CTS, the shares of various feedstocks for HVC production do not alter dramatically, relative to the RTS.

Energy efficiency

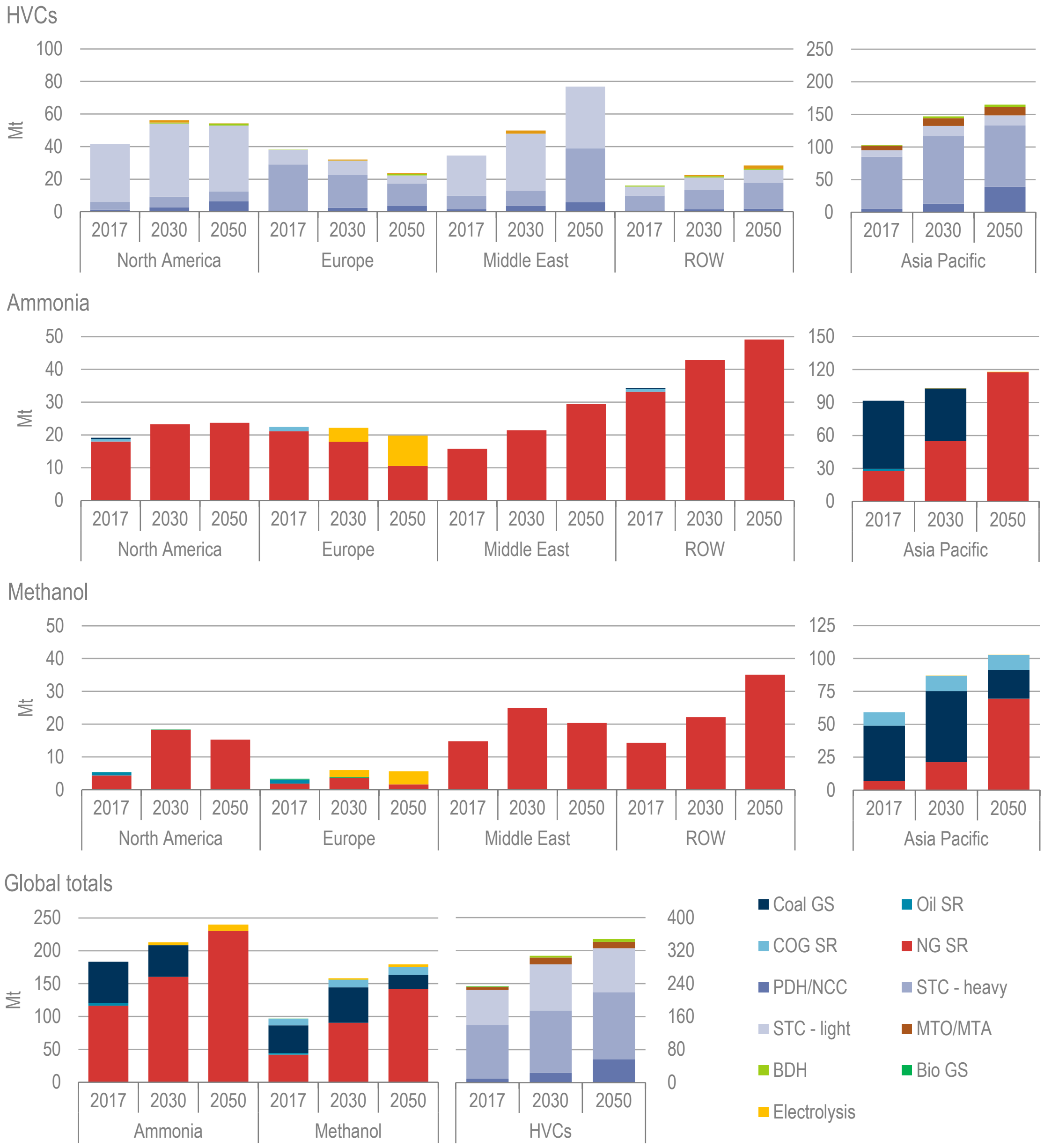
As in the RTS, process **energy efficiency** improvements are attained both by implementing technical and operational measures to progress towards the best performing technologies, and by switching process technology to provide a fundamentally more energy efficient production route. For individual technologies, only incremental improvements take place in the CTS, over those achieved in the RTS, as process energy efficiency improvements are already well incentivised by fuel costs, and further stimulated by the further progressive phase-out of fossil fuel subsidies. For most technologies, best energy performance levels are attained approximately five-years earlier in the CTS than in the RTS, at the expense of acceptance of longer payback periods for investments in process improvements.

Two key technology shifts in the CTS are the move from coal gasification to natural gas steam reforming and the emergence of naphtha catalytic cracking (NCC). The coal to natural gas technology shift goes hand in hand with the accompanying feedstock shift discussed above, complementing the process emissions savings achieved with reductions in energy-related emissions. NCC consumes less naphtha, relative to its non-catalytic counterpart, naphtha steam cracking. Globally 50 Mt of HVCs is projected to be produced using this technology in 2050, compared with only 8 Mt in the RTS. Deployment of NCC takes place mainly in the Middle East and Asia Pacific regions.

Innovative low-CO_2 processes

Apart from CCUS (discussed above), there are two key groups of innovative processes that play a role in delivering the CO_2 emissions reductions required in the CTS: **bioenergy routes** and **electrolysis**. These technologies compete with each other on cost, generally after the maximum gains from energy efficiency have been exploited, as these tend to be the most economic.

Figure 5.10 • Production routes for primary chemicals in the CTS



Notes: Tabulated results are provided in the online annex. BDH = bioethanol dehydration; Bio = bioenergy; COG = coke oven gas; GS = gasification; SR = steam reforming; MTA = methanol to aromatics; MTO = methanol to olefins; PDH = propane dehydrogenation; STC - heavy = naphtha and gas oil steam cracking; STC - light = ethane and liquid petroleum gas steam cracking.

Key message • Gas dominates the feedstock mix for ammonia and methanol in the CTS, with ethane and naphtha still the dominant sources of HVCs. Alternative process routes, utilising bio-based and electrolytic routes, play regionally important – but globally marginal – roles.

Bioenergy plays a small role in CO_2 emission reductions in the CTS, both relative to the other innovative process options and overall. Bioethylene, produced via ethanol dehydration, is deployed at similar levels relative to overall production, in the CTS and RTS, accounting for less than 5% of cumulative HVC production by 2050. As in the case of the RTS, its deployment is regionally concentrated, with around 90% taking place in Asia Pacific and the Americas. Ammonia and methanol produced via gasification of biomass are not projected to be deployed at appreciable levels, reflecting the significant investment cost and efficiency losses relative to traditional routes, even when equipped with carbon capture.

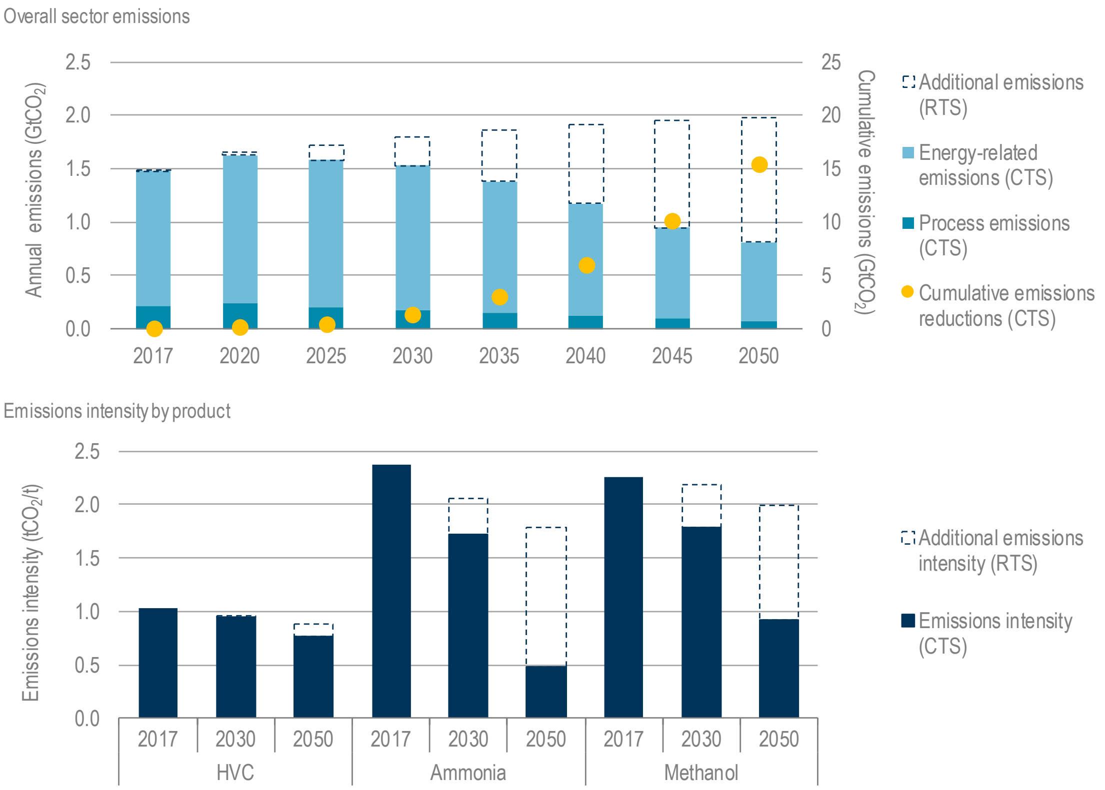
Electrolysis sees relatively limited deployment globally, but plays a substantial role in Europe, (and to a more limited extent in Korea and Japan), where either the legal context for CCUS appears unfavourable, or the appetite for alternatives appears strong, even in the face of increased costs. In these regions, electrolysis plays a much larger role than CCUS in reducing CO_2 emissions. By 2050, nearly half of total ammonia and two-thirds of methanol is produced via electrolysis, whereas less than 10 $MtCO_2$/yr are captured from all primary chemical production.

Despite these regional pockets of significant deployment of electrolytic and bioenergy-based routes, among innovative low-CO_2 processes, CCUS accounts for the majority of emissions savings globally. The limited penetration of electrolytic and bioenergy-based routes in part reflects the fact that a key benefit of these technologies does not accrue to the chemical sector itself – the potential to reduce emissions that take place downstream as a result of the fossil-based feedstock locked into chemical products. The technical global potential of both bioenergy and electrolysis are explored further later in this chapter.

Environmental benefits in the CTS

In the CTS, a 45% reduction in chemical sector direct **CO_2 emissions** is attained in 2050, relative to current levels. Emissions are 60% lower in the CTS than in the RTS by 2050. In cumulative terms, the reduction is 5% (or around 1.2 $GtCO_2$) by 2030 and 25% (or 15 $GtCO_2$) by 2050, compared with the RTS.

Figure 5.11 • Direct CO_2 emissions and primary chemical emission intensities by scenario



Overall sector emissions

Emissions intensity by product

Key message • Chemical sector emissions of CO_2 decline by 45% by 2050 in the CTS, with energy-related emissions declining much less steeply than process emissions.

The steepest declines in emissions intensity are achieved in ammonia production, where emissions reduce from 2.4 tonnes of carbon dioxide per tonne (tCO_2/t) in 2017 to 1.7 tCO_2/t in 2030 (almost 30%) and 0.5 tCO_2/t in 2050 (80%), meaning that ammonia goes from being the most CO_2 emission intensive primary chemical to the least intensive, among those considered. A large contribution to this decarbonisation is made by the almost complete elimination of process CO_2 emissions from ammonia production, which maintain similar levels in the RTS.

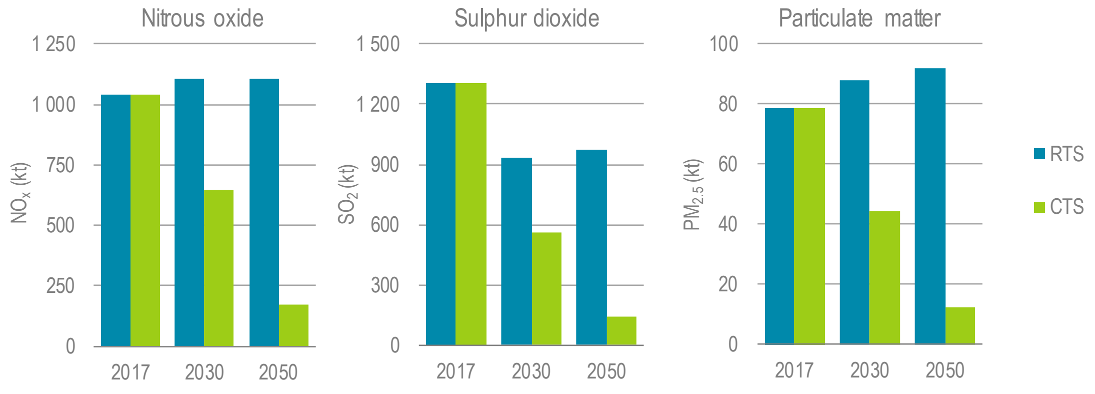
The CO_2 intensity of methanol production declines steeply too: by 20% by 2030 and by almost 60% by 2050. Methanol production halves process emissions by 2050 in the CTS, compared with a doubling in the RTS. Relative to 2017, CO_2 emissions from HVC production are around 20% higher in 2030 and 10% higher in 2050, in the context of 45% and 64% increases in production, respectively in the CTS. These figures represent a drop in CO_2 emissions intensity of 83% by 2030, and of 68% by 2050.

Emissions of air pollutants plummet across the board in the CTS, with their declines taking similar trajectories. Relative to current levels, nitrogen oxides (NO_x) emissions decrease by 38% by 2030, and 83% by 2050; sulphur dioxide (SO_2) by 57% by 2030, and 89% by 2050; and fine particulate matter ($PM_{2.5}$) by 43% by 2030 and 84% by 2050.

The first choices for mitigating **air pollutants** are to use less polluting fuels, increase energy efficiency and, where practicable, to avoid combustion. When these options are exhausted, two categories of mitigation technologies for reducing air pollutants from stationary point sources, such as those dedicated to primary chemical production, remain: advanced combustion technologies and practices, and "end-of-pipe" measures. Both approaches are deployed in the CTS to reach the level of air pollutant abatement observed.

Low-NO_x burners in process heaters and boilers operate by phasing air and fuel injection to achieve lower temperature flames, making use of the fact that there is an exponential (positive) relationship between combustion temperatures and thermal generation of NO_x. Another enhanced combustion opportunity is fluidised-bed technology for solid fuels, which reduces emissions of both SO_2 and NO_x.

Figure 5.12 • Global air pollutant emissions from primary chemical production by scenario



Notes: Estimates of air pollutant emission levels refer to combustion-related sources in primary chemical production. International Institute for Applied Systems Analysis/IEA joint analysis. kt = kilotonne.

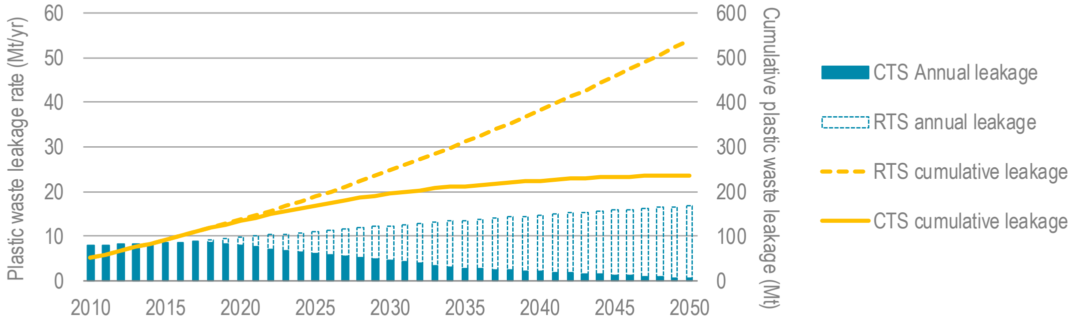
Key message • Air pollutant levels from primary chemicals plummet by between 80% and almost 90% in 2050 in the CTS, relative to the RTS.

End-of-pipe technologies focus on the removal of SO_2, NO_x and $PM_{2.5}$ from flue gases before their release to the atmosphere, by means of either physical separation or chemical reactions. This group of technologies includes electrostatic precipitators (to separate PM from gaseous streams) and flue-gas desulphurisation plants that use a sorbent (typically alkaline compounds such as limestone) to absorb or oxidise SO_2 into solid matter, which is then physically separated from the flue gases.

A final set of mitigation technologies uses chemical products during the production operation: selective catalytic reduction systems (using ammonia) or selective non-catalytic reduction systems (using urea) that reduce the NO_x in the flue gas to nitrogen and water.

In the CTS, **water pollution** from leakage of waste plastic begins to decline immediately, as a result of a strong push by governments to improve waste management systems. Although increased recycling does not necessarily result in lower quantities of plastic waste leakage, the waste management infrastructure needed to achieve higher recycling rates – waste collection, sorting etc. – provides many of the pre-requisites for mitigating plastic leakage. In the CTS, global average collection rates for recycling exceed the levels seen in Europe today.

Figure 5.13 • Annual and cumulative ocean-bound plastic leakage by scenario



Notes: For details of the RTS projection, see Figure 4.13. Only the central RTS estimate is shown here for clarity. Mt/yr = million tonnes per year.

Source: Current rates of leakage from Jambeck, J.R. et al. (2015), "Plastic waste inputs from land into the ocean", https://doi.org/10.1126/science.1260352.

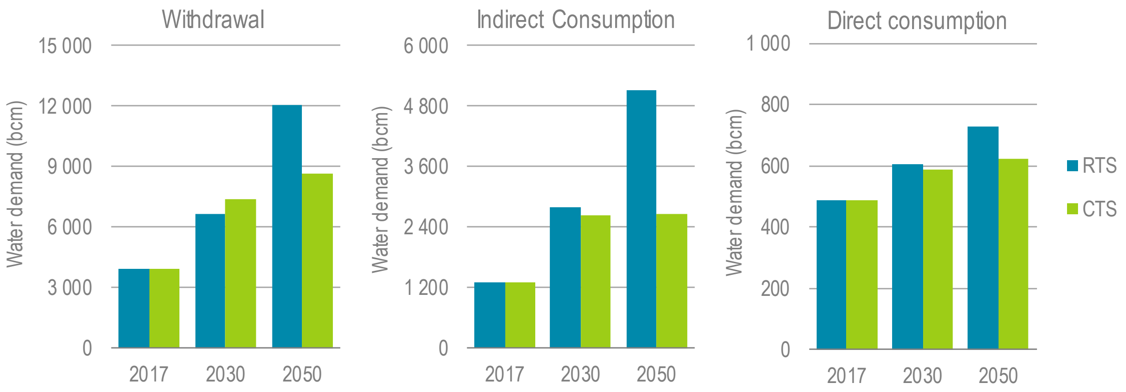
Key message • Cumulative plastic waste leakage more than halves in the CTS, relative to the RTS.

Achieving this goal entails a transformation in waste management practices across the globe, including widespread waste collection in regions that have poor systems in place at the moment, if at all. It also entails the elimination of materials that defy collection, such as microbeads and ultra-thin plastic films. In the CTS, net annual rates of plastic waste leakage are halved by 2030, with steady reductions continuing thereafter. This more than halves the cumulative amount of plastic waste leakage by 2050, relative to the RTS. This near-stabilisation of cumulative leakage does not take into account any subsequent efforts to remove plastic waste after leakage occurs, for which many proposals and small scale examples exist today.

In the CTS, annual **water withdrawals** for primary chemical production rise to almost 9 billion cubic metres (bcm) in 2050, while consumption rises to roughly 3 bcm. Relative to the RTS, total cumulative water withdrawals for primary chemical production are 8% lower, while water consumption is around 20% lower. Given that indirect withdrawals and consumption account for most of water use in both scenarios, the divergence reflects the different primary chemical demand trajectories and different fuels and technologies produced and used in the power sector in the CTS.

Overall, energy demand is almost 10% lower in the CTS, with coal use in particular around 40% lower than in the RTS cumulatively, with much of this decline occurring in the Asia Pacific region, as China shifts away from coal-based chemical processes. While the share of electricity in total energy demand is similar in both scenarios, the shift in its composition changes the power sector's water use. The continued shift away from coal and the retirement of existing subcritical and supercritical coal power capacity lowers water withdrawals and consumption, while a rise in nuclear, bioenergy and concentrated solar power generation increases both.

Figure 5.14 • Water demand for primary chemical production by scenario



Notes: Direct water demand estimates for primary chemical production include water uses as feedstock (e.g. steam cracking). Water demand for process heating is excluded due to the wide range of possible configurations for steam systems across chemical sites.

Key message • In the CTS, water withdrawal for primary chemical production is reduced by almost 30% in 2050 and water consumption by nearly 45%, relative to the RTS.

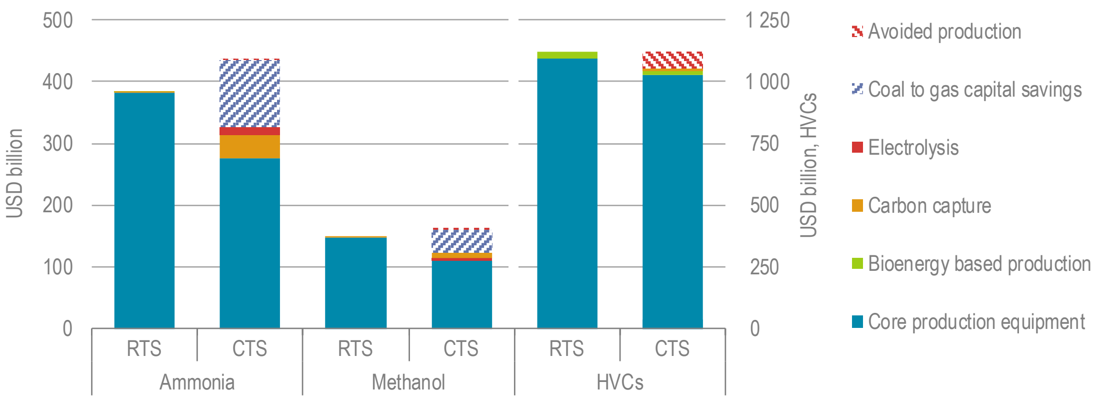
The global trends in water withdrawal and consumption are heavily dependent on developments in the Asia Pacific region. Water withdrawals for primary chemical production in Asia Pacific are two-thirds lower in 2050 than in the RTS, while water consumption is almost 60% lower, as the amount of electricity and coal used for chemical processes declines.

Investments required in the CTS

Cumulative **investments** required by 2050 for the production of primary chemicals in the CTS (USD 1.5 trillion) are marginally lower than in the RTS (USD 1.7 trillion). Ammonia offers the most cost-attractive carbon mitigation options among primary chemicals and thus experiences the steepest rate of decarbonisation in the CTS. Cumulative capital investment in ammonia production is about 15% lower in the CTS than in the RTS, and accounts for nearly USD 330 billion of the total CTS investment. The extra expense of deploying two key carbon emission mitigation levers, carbon capture and electrolysis, is more than off-set by the savings on coal-based core production equipment, which is entirely avoided in the CTS.

Cumulative capital investment in methanol production is nearly 20% less in the CTS than in the RTS. It accounts for almost 10% (around USD 120 billion) of the cumulative investments in the CTS. As with ammonia, the shift from coal to natural gas feedstock leads to core production equipment savings that offset the additional expenses incurred for electrolysis and carbon capture equipment. Coal-based methanol production, including that required for MTO, accounts for almost 50% of cumulative production in the RTS compared with less than 30% in the CTS. This difference reduces cumulative investment in the CTS by roughly USD 40 billion.

Figure 5.15 • Cumulative capital investment in the RTS and CTS by primary chemical



Key message • The shift from coal to natural gas and avoided primary chemical production as a result of recycling, offsets the additional investments required for alternative carbon mitigation.

HVC production accounts for approximately 70% of cumulative investments in the CTS, around 6% less than in the RTS, due to lower production volumes. In the CTS, plastic recycling results in the elimination of around 70 Mt of primary chemical demand annually by 2050, 95% of which are HVCs (the small remainder is made up of both ammonia and methanol).

Box 5.2 • Assessing investments

Technology selection in the modelling underlying this analysis is based on constrained least-cost optimisation covering energy and investment costs. The investment estimates provided include the capital expenditure on core process technology and CO_2 emission mitigation technologies, including carbon capture, installed between 2017 and 2050. The assessment is expenditure based within the sites of primary chemical production. Therefore, costs associated with plastic waste collection, sorting, processing and secondary production are not included, nor are costs relating to CO_2 transportation and storage. Investments required for air pollution mitigation technologies are not included. Investment costs are not attributed to energy savings from improved operation and maintenance practices, unless they require new process equipment. Installation, construction and labour costs are not included since it is the investments that relate to the chemical sector specifically that are relevant to this analysis. If included, variation in local construction and labour practices would cloud the underlying trends, not to mention the greater uncertainty associated with such costs. All cumulative investment cost estimates are quoted in undiscounted terms.

Consequently, appreciable quantities of production capacity do not need to be constructed and maintained. The impact of reducing production has a profound effect in some regions, as the most expensive marginal investments are avoided. The savings attributable to the avoidance of this capacity amount to almost USD 65 billion. Carbon capture equipment in HVC applications adds slightly to investment in the CTS, around USD 15 billion.

Cumulatively around 3 $GtCO_2$ is captured for storage in the CTS, requiring around 220 $MtCO_2$/yr of capture capacity globally by 2050. Since minimal amounts of carbon capture take place in the RTS, more than one-third of the cumulative CO_2 emissions savings in primary chemicals between the scenarios are delivered via this lever. Additional cumulative investments for this technology in the CTS, excluding transportation and storage infrastructure, amount to approximately USD 60 billion.

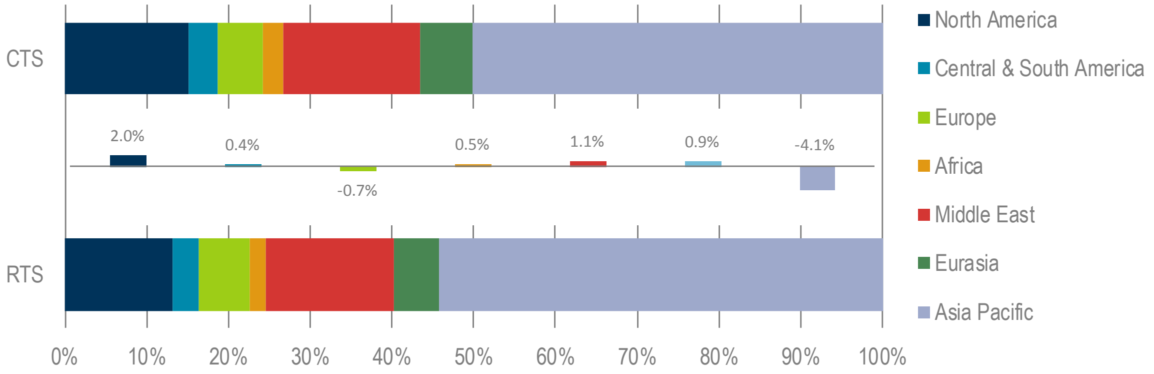
Electrolysis-based routes contribute nearly 4% cumulative ammonia and methanol production in the CTS, and account for a slightly smaller share of cumulative capital investment.

Electrolysers – the key piece of equipment in electrolytic routes – undergo a 65% reduction in capital cost between 2017 and 2050, and the majority of the deployment of these routes takes place in the latter half of the CTS. This results in comparatively low investment costs per unit of production, relative to traditional routes equipped with CCS. The economic barrier to greater uptake of these routes is more to do with the electricity price (a topic explored further later in this chapter).

Because bioenergy plays a similar role per unit of primary chemical output in each scenario, the related investment differences between the two scenarios are small.

Regional shares of cumulative investment remain very similar in the RTS and CTS. Because Asia Pacific is the largest producing region, the impact of plastic recycling on primary chemical demand is felt most keenly there; and China (in Asia Pacific) is the country with the most of the coal-based chemical capacity that shifts towards natural gas in the CTS. Both of these changes reduce disproportionately the amount of investment required in the CTS in Asia Pacific, thereby reducing its share of global cumulative investments very slightly, by 4 percentage points.

Figure 5.16 • Cumulative capital investment in primary chemical production by scenario



Note: Vertical bars describe the percentage point change in regional share of cumulative investment between the RTS and CTS.

Key message • Regional investment shares remain broadly unchanged. The impact of recycling and switching from coal to natural gas is felt most in Asia Pacific, reducing its share marginally in the CTS, relative to the RTS.

Beyond the CTS: Alternative feedstocks – bioenergy, water and CO_2

Primary chemicals sourced from alternative feedstocks (e.g. bioenergy, water and CO_2) play a minor role in the CTS. This section, nonetheless, explores some of the key technologies that would be instrumental and the challenges faced in displacing all fossil fuel feedstock via these routes.

Why look for alternative feedstocks?

Chemical feedstock cannot be decarbonised – carbon is required to provide the structure and properties of most primary chemicals, and the chemical products they go on to constitute. However, the source of the carbon in chemical feedstock need not be derived from fossil fuels. Feasible alternative sources include bioenergy, the hydrogen component of water molecules, CO_2 that would otherwise be released to the atmosphere, and waste.

There are two main motivations for limiting the amount of fossil fuels in chemical feedstock. Firstly, process emissions are not insignificant. If process CO_2 emissions did not need to be mitigated, it would eliminate the need for approximately 40% of the CCS deployed in the CTS. Direct process CO_2 emissions account for around 14% of cumulative emissions in the RTS and 12% in the CTS. When the feedstock is a fossil fuel, this results in a net release of emissions, but if the feedstock were renewably sourced, the emissions would be neutral on a net basis, if they occurred at all.

Secondly, the carbon atoms embedded in chemical feedstock lead directly to CO_2 emissions during the use and disposal of chemical products downstream. The way that this happens is described in more detail in Chapter 3, but two important sources are the decomposition of urea, which releases most – if not all – of the CO_2 that was embedded during its manufacture and the incineration of plastic waste with or without energy recovery, which turns the large carbon component of plastics (typically 50-80% by weight) into CO_2.

Polyethylene (the largest-volume plastic resin, accounting for more than a third of plastic production) can be used to give a rough sense of scale of the carbon stored in plastics. The total volume of polyethylene produced in 2017 (just over 100 Mt, including high-density polyethylene, low-density polyethylene, linear low-density polyethylene; excluding any additives) contains approximately 95 Mt of embedded carbon. If all this plastic were to be combusted, it would release approximately 340 million tonnes of carbon dioxide, or around a quarter of the chemical sector's direct CO_2 emissions in 2017. If this CO_2 were captured, it could theoretically be recycled to make new polyethylene or other carbon-containing chemical products.

How can technology help?

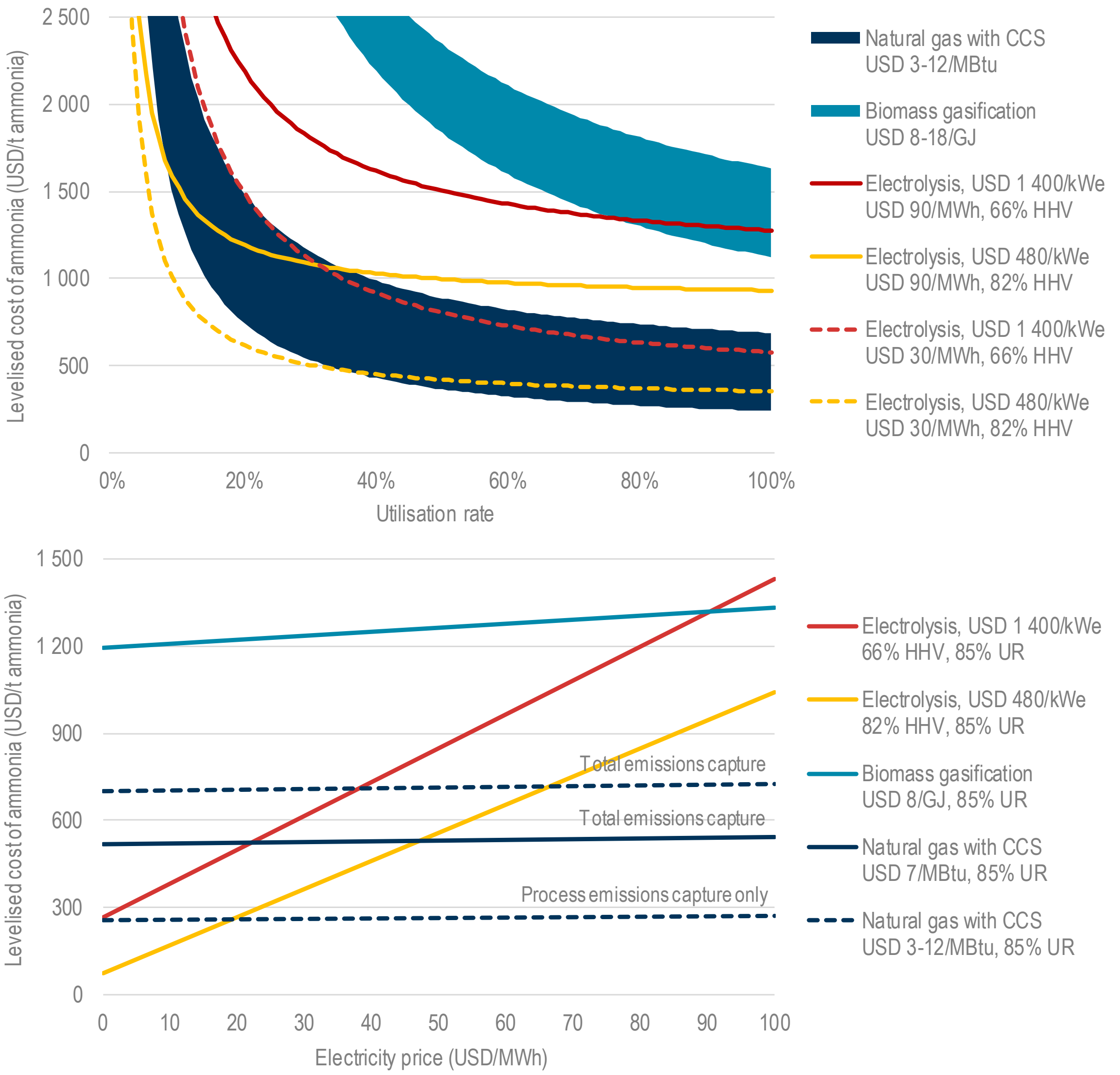
There are two families of technologies available for producing primary chemicals without reliance on fossil fuel feedstock. They use either electricity or bioenergy. For pathways within these families to be classified as renewables, the origin of the electricity and the bioenergy must be sustainable. For electricity, possible sources include a raft of conventional and established renewable generation technologies such as hydropower, wind and solar. For bioenergy only short-cycle carbon sources that are renewably replenished can be categorised.

There are three direct routes from bioenergy to primary chemicals: biomass gasification for producing both ammonia and methanol, and bioethanol dehydration to produce ethylene. With currently demonstrated technology, the propylene and aromatics components of HVCs then need to be produced, using methanol.

There are a number of existing routes, such as MTO and MTA processes, which yield both propylene and aromatics via methanol, while olefin metathesis yields propylene from ethylene and butylene. Indirect routes incur higher losses, due to the multiple chemical transformations involved; so research continues to develop both more selective indirect routes, and new direct routes where none are currently available.

Hydrogen-based pathways use hydrogen generated via electrolysis (i.e. water-splitting), powered by renewable electricity. Additional elements, such as carbon and nitrogen, are also required and must either be produced using more renewable electricity (air capture and separation) or be captured from a process that would otherwise emit them to the atmosphere. Both ammonia and methanol can be produced directly, whereas all HVCs must be produced indirectly, using the array of processes described above for the indirect bioenergy pathways.

Figure 5.17 • Simplified levelised cost of ammonia via various pathways



Notes: Energy cost assumptions: USD 3-12 per million British thermal units (MBtu) for natural gas; USD 8-18 per gigajoule (GJ) for biomass; USD 30-90 per megawatt hour (MWh) for electricity. CAPEX assumptions: USD 860 per tonne (t) of ammonia for natural gas steam reforming; USD 50-270/t captured CO_2 for carbon capture, with the range encompassing both concentrated (process CO_2) and dilute (energy-related CO_2) sources and a 90% capture rate applied to each source; USD 6 000/t ammonia for biomass gasification; USD 9/t nitrogen for air separation unit; USD 95/t ammonia for air separation unit; USD 480-1 400 per kilowatt electrical capacity (kWe) for electrolysis. CAPEX assumptions stated per unit of output, apart from electrolysis which is stated per unit of electricity input. Fixed operational expenditure: 2.5-5.0% of CAPEX. Electrolyser efficiency = 66-82% on a higher heating value (HHV) basis. Energy performance of an average ammonia plant. Storage and transportation costs as USD 20/t captured CO_2. Discount rate: 8%. A 25 year design life is assumed for all equipment. UR = utilisation rate.

Sources: Bazzanella, A.M. and F. Ausfelder (2017), *Low Carbon Energy and Feedstock for the European Chemical Industry*, https://dechema.de/dechema_media/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf; Schmidt, O. et al. (2017), "Future cost and performance of water electrolysis: An expert elicitation study", https://doi.org/10.1016/j.ijhydene.2017.10.045.

Key message • Given a natural gas price of USD 7/MBtu, electrolysis competes with gas-based production equipped with CCS at electricity prices between USD 20-45/MWh, depending on electrolyser efficiency and cost.

All technologies described in this section were considered in the modelling of the RTS and CTS, but some do not compete effectively on cost with the other mitigation options in which fossil fuel feedstocks are maintained (e.g. conventional production units equipped with CCUS). Electrolysers are projected to undergo a 65% decline in capital expenditure (CAPEX) cost between 2017 and 2050 in both the RTS and CTS. Also during this period, the efficiency obtained rises from 66% today to 82% by 2050 (on a higher heating value (HHV) basis). All other technologies are assumed to be mature and therefore do not experience any capital cost declines over time.

As in the discussion of regional cost advantages in Chapter 2, it is instructive to compare the alternative technology pathways with conventional routes. Taking ammonia as an example, for which there are direct alternative pathways based on bioenergy and renewable electricity, the levelised cost of production via these routes can be compared with the cost of natural gas-based production equipped with CCS. Energy prices, CAPEX and utilisation rates are sensitive variables, and so a range is explored.

The bioenergy pathway to ammonia is competitive with the electricity pathway only in a very limited set of circumstances, namely when electricity prices are high (more than USD 90/MWh) and biomass prices are low (less than USD 8/GJ). Utilisation rates must also be high, as must be the CAPEX requirements for electrolysers. This is due to the comparatively high level of CAPEX required for biomass gasification (3-12 times more per unit of ammonia relative to the electrolytic route) and high energy intensity (15-40% more energy-intensive per unit of ammonia). It should be noted that bioenergy utilised to produce ethylene via bioethanol dehydration is much more cost competitive relative to the other options and sees some deployment in both the RTS and CTS in certain regions (see Chapters 4-5). This pathway is much more efficient than producing ethylene via the MTO process.

The electricity pathway at low utilisation rates, is highly sensitive to CAPEX, and at higher utilisation rates, to electricity prices. Given a middling natural gas price of USD 7/MBtu (typical of prices in Europe today, but significantly higher than in the United States and the Middle East), electrolysis starts to compete with gas-based production equipped with CCS at low electricity prices of USD 20-45/MWh, depending on electrolyser efficiency and CAPEX levels. This assumes both dilute and process emissions streams are captured. If only the concentrated process emissions streams are captured (and the ammonia is therefore only partly decarbonised), electricity prices must be below USD 20/MWh for the electricity pathway to compete.

To put this into context, average power generation costs are USD 50-80/MWh in most regions today and most increase over time in the context of the CTS. Electricity generation costs tend to be higher in low-CO_2 scenarios. As a result, for both concentrated and dilute CO_2 emission streams from ammonia plants, natural gas plants equipped with CCS tend to be a more competitive mitigation option over the vast majority of energy price combinations encountered in the CTS. This explains its considerable deployment in that scenario.

Challenges and opportunities

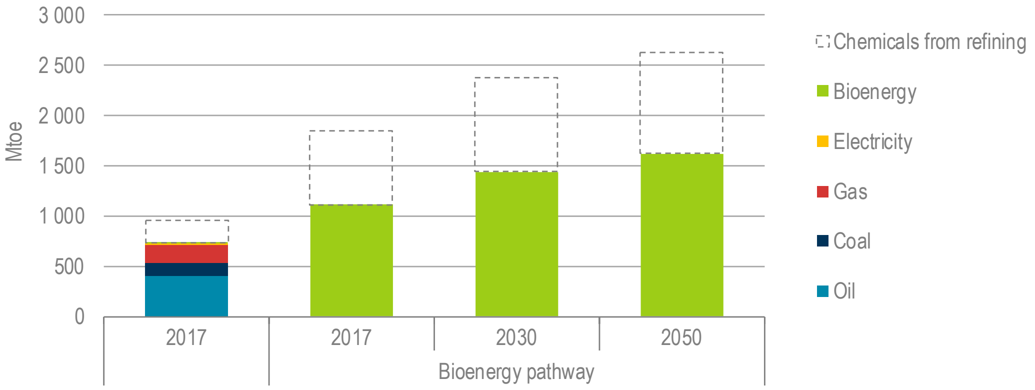
The main challenge associated with the idea of providing primary chemical feedstock entirely via renewable pathways is the large quantities of bioenergy or electricity required. However, there are other specific challenges, such as where one would procure the volumes of carbon or CO_2 required in what would be a largely decarbonised energy system.

In this section, a "what if?" analysis of each alternative pathway is provided, in order to offer some sense of the main challenges and opportunities associated with any wide deployment of these production routes. None of the figures presented in this section are part of a scenario analysis: they were derived in isolation. Only the process energy and feedstock used directly for primary chemical production are included. Where necessary, a broad context (e.g. order of magnitude comparisons) and basic inputs (e.g. primary chemical demand) come from the CTS. Primary chemicals produced in the refining sector are also included in the analysis, as it seems unlikely the chemical sector would undergo the fundamental transformations described below, while the refining sector remains unchanged.

In the bioenergy pathway, approximately 1 450 million tonnes of oil equivalent (Mtoe) (60 exajoules (EJ)) of bioethanol and other assorted biomass is required by 2030 to meet global primary chemical demand in full, rising to 1 620 Mtoe (68 EJ) by 2050. Of this energy input, approximately 60% is provided as feedstock (either via gasification or dehydration) and the remainder as process energy (bioenergy used to raise steam and provide process heat) in 2050. The process energy required to convert methanol into olefins and aromatics is included.

If primary chemicals sourced from the refining sector are also included, a further 934 Mtoe (39 EJ) by 2030 and 1 003 Mtoe (42 EJ) by 2050 are required. To put these figures into perspective, current global primary demand for bioenergy is 1 350 Mtoe (57 EJ). In the CTS, this is expected to rise to 1 502 Mtoe (63 EJ) by 2040; it should not exceed 3 344 Mtoe (140 EJ) in 2050 if the supply is to remain sustainable (IPCC, 2011). This pathway would require the use of more than half the world's sustainable biomass supply for primary chemical production.

Figure 5.18 • Bioenergy requirements to satisfy all primary chemical demand



Notes: Primary chemical production is based on the CTS projection. The energy required to produce primary chemicals from refining is estimated based on the average energy intensity of HVC production in 2017.

Key message • The equivalent to half the global sustainable biomass supply would be required by 2050 to shift fully to bio-based routes for primary chemical production.

Of the cumulative energy demand for primary chemical production in the bioenergy pathway, approximately one-third is for ammonia and methanol, while two-thirds goes into HVC production. This is not in proportion with production volumes, which are divided fairly evenly between these two groups. The imbalance occurs because of the need for intermediate production of methanol for propylene and aromatics production (this is also an issue for the electricity pathway, discussed below) and the relatively high energy intensity of the direct bio-route to ethylene, compared with ammonia and methanol.

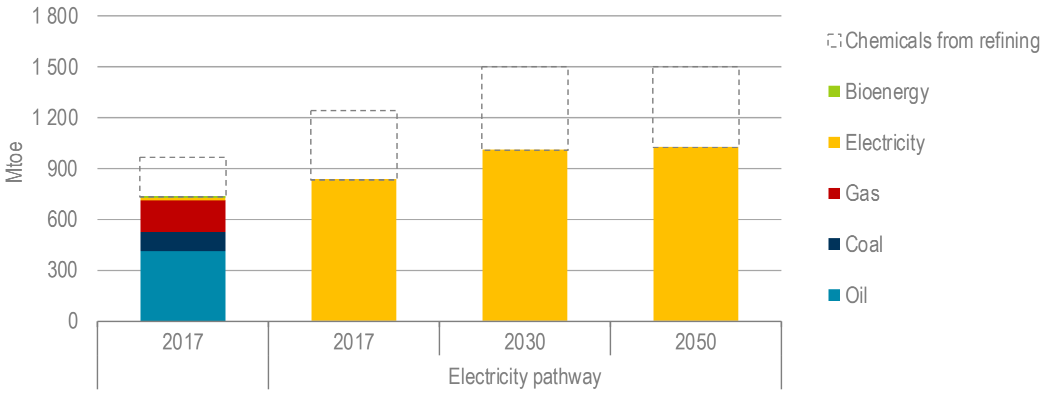
In the electricity pathway, approximately 1 007 Mtoe (11 714 terawatt hours TWh) of electricity is required in 2030 to fulfil global primary chemical demand, and 1 025 Mtoe (11 922 TWh) in 2050. Of this energy input, approximately 75% is consumed by electrolysers (producing hydrogen). The remainder is used to convert methanol to HVCs and to separate air and run the synthesis units.

If primary chemicals sourced from the refining sector are also included, 1 499 Mtoe (17 430 TWh) are required by 2030, increasing to 1 504 Mtoe (17 495 TWh) in 2050. To put these figures in perspective, current global electricity generation is 2 208 Mtoe (25 679 TWh). In a CTS context, this is expected to rise to more than 3 189 Mtoe (37 083 TWh) by 2040.

The burden of electricity demand is not spread evenly across primary chemicals. Of those produced within the chemical sector in the CTS, switching to the renewable electricity pathway is most costly in electricity terms for HVCs – as for bioenergy. Ethylene consumes almost twice the cumulative energy consumption of ammonia in 2050, despite being produced in similar volumes. BTX aromatics and propylene account for around a quarter of the cumulative electricity demand, but only 17% of cumulative production.

This imbalance – between ammonia and methanol, on the one hand and HVCs on the other – is due to the MTO and MTA conversion process. Two molecules of methanol are required for one of ethylene, three for one of propylene, and six to eight for a molecule of the aromatics. Some 2.8 tonnes of methanol is required per unit of olefins, and 4.3 per tonne of aromatics. These figures may improve as the processes mature, but as it stands these are transformations involving expensive stoichiometry.

Figure 5.19 • Electricity requirements to satisfy all primary chemical demand



Notes: Primary chemical production is based on the CTS projection. The energy required to produce primary chemicals from refining is estimated based on the average energy intensity of HVC production in 2017.

Key message • Around 12 000-17 500 TWh of renewable electricity would be required to produce all primary chemicals via the electricity pathway in 2050. Total electricity generation is around 37 000 TWh in 2040, two-thirds of which is generated from renewable sources.

These quantities of electricity generation would require very substantial capacity investment, as all of the electricity would need to be sourced renewably for the pathway to be coherent. With the exception of hydro generation, non-bioenergy renewables tend to have a low capacity factor, mostly under 50%, and many under 20%. Generating 10 000+ TWh could therefore require many times the global capacity of renewable electricity generation that is currently installed, which stood at 2 336 gigawatts.

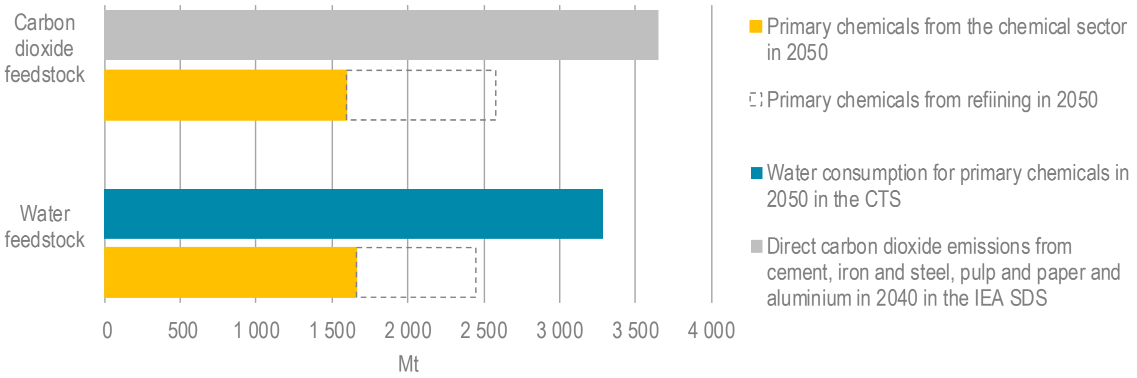
Responding to the demand for this quantity of electricity from a manufacturing industry would present an opportunity to enhance flexibility in the electricity grid: electrolysers can be readily ramped up and down. Perhaps with the aid of some short term storage, this feature could contribute to the response to load shedding (ramping down) or provide additional supply (ramping up) when needed by the grid. A more detailed discussion of this complex topic can be found in other dedicated IEA publications (IEA, 2014).

For the electricity pathway, an external source of carbon is required to produce methanol and HVCs. It can be assumed that this carbon would come in the form of CO_2, as this is one of the key ways in which this can contribute to complementary sustainability objectives, forming a "carbon sink" for other sectors emitting CO_2. To satisfy the demand for methanol and HVCs via this pathway, 1.5 $GtCO_2$ would be required in 2030, rising to 1.6 $GtCO_2$ in 2050.

If refineries were no longer available to provide their proportional contribution of primary chemical production, these figures would rise to approximately 2.3 $GtCO_2$ in 2030 and 2.6 $GtCO_2$ in 2050. To put these quantities in perspective, direct industrial CO_2 emissions from energy-intensive sectors, excluding the chemical industry, make up around 3.6 $GtCO_2$ by 2040 in the IEA Sustainable Development Scenario (IEA, 2017). Total direct CO_2 emissions from the chemical sector in 2017 were 1.5 $GtCO_2$.

The specific source of this CO_2 cannot be specified, as this pathway does not identify the plethora of other changes that may take place in the energy system. It may well be the case that if the formidable commitment was made to move away from fossil feedstock, the rest of the energy system would already be largely decarbonised. In that case, the carbon locked in chemical products could theoretically be continuously recycled, within the chemical sector. This could satisfy the demand for carbon only if a) there were no growth in demand for chemical products, and b) the carbon could be perfectly extracted and captured from all products, including those that disperse during use (e.g. fertilisers). These conditions seem unlikely to be met, so an external carbon source would probably be needed.

Figure 5.20 • Non-energy inputs for primary chemicals in the electricity pathway in context



Notes: SDS = Sustainable Development Scenario; *WEO* = *World Energy Outlook*.

Source: Emissions from other industrial sectors from IEA (2017), *World Energy Outlook 2017*.

Key message • Some 1.6 $GtCO_2$ and 1.7 Gt of feed water would be needed in the renewable electricity feedstock pathway by 2050.

Approximately 30% of the energy inputs into the bioenergy pathway and 60% into the electricity pathway in 2050 go to produce methanol as an intermediate chemical for olefins and aromatics. By 2050, about 380 Mt of methanol is required in the bioenergy pathway, and 1 000 Mt (more than total primary chemical demand in the CTS) in the electricity pathway. These figures differ because ethylene can be produced directly from bioenergy, but only indirectly, via methanol, when utilising electricity.

The scale of the industrial activity required to produce an energy-intensive primary chemical merely for intermediate use is a significant disadvantage of both pathways, but particularly so for the electricity pathway. Virtually all of this difficulty arises in relation to the production of HVCs (apart from ethylene in the bioenergy pathway), as the production of methanol and ammonia for direct consumption does not require a thermodynamically costly intermediate step.

A world in which electricity displaces all other feedstocks for primary chemicals not only drastically increases global electricity demand but also direct water consumption in the chemical sector. In the electricity pathway, direct water consumption for the production of primary chemicals is approximately two and a half times greater than in the CTS in 2050. While these figures are large relative to the chemical sector's current consumption, they are not unmanageable in global terms.

However, the choice of location of electricity-based capacity on this scale would need to take careful account of the availability and competition for resources, and the prospects of these resources in the future. Water stress issues could be avoided if electrolysis technologies using sea water as a feedstock could be optimised for hydrogen production. Brine electrolysis, used for the production of chlorine on an industrial scale, uses concentrated sea water (and the salt it contains) as an input. Water desalination and purification are other possibilities that could facilitate the use of sea water for electrolysis, thereby avoiding contributing to water stress.

Despite not consuming any substantial amount of water directly, a world in which all feedstocks are derived from bioenergy could be even more challenging, in terms of water use, than the electricity pathway. Indirect water needs for irrigation means that bioenergy has a high water intensity. In addition to the potential impact on water resources, both in terms of quantity and quality, questions also arise regarding the availability of land, potential competition with agriculture, the risks of increased deforestation and soil degradation.

All of these factors could constrain a dramatic expansion of bioenergy-based primary chemical production. The severity of these factors is all crop dependent, with some bioenergy crops consuming far less water than others. But whatever the crop, many of the key chemical producers, such as the Middle East and China, already suffer from water constraints and would hesitate before becoming over-reliant on biofuels. Water imports may be one option for reducing the local impacts of water stress, but an exporting trade partner without such constraints may not be readily available.

Both of these renewable pathways would improve air pollution, relative to using fossil fuels. However, the electricity pathway is far superior in this regard, as no combustion need take place. Water pollution from disposal of end-use products is, of course, a different matter. Neither pathway makes a distinct contribution in this respect. Chemical products derived from bioenergy are often confused with those that are biodegradable (see Box 3.2). But, once manufactured, the primary chemicals, whether created with electricity or bioenergy as feedstock, are identical in composition to their fossil fuel counterparts, despite the differing origins of their carbon and hydrogen atoms.

References

Bazzanella, A.M. and F. Ausfelder (2017), *Low Carbon Energy and Feedstock for the European Chemical Industry*, DECHEMA (Gesellschaft für Chemische Technik und Biotechnologie e.V.), https://dechema.de/dechema_media/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf.

Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use, and fate of all plastics ever made", *Science Advances*, Vol. 3/7, e1700782, https://doi.org/10.1126/sciadv.1700782.

IEA (International Energy Agency) (2014), *The Power of Transformation*, OECD/IEA, Paris.

IEA (2017), *World Energy Outlook 2017*, OECD/IEA, Paris.

IPCC (Intergovernmental Panel on Climate Change) (2011), *Renewable Energy Sources and Climate Change Mitigation*, Cambridge University Press, Cambridge.

Jambeck, J.R. et al. (2015), "Plastic waste inputs from land into the ocean", *Science*, Vol. 347/6223, p. 768-771, https://doi.org/10.1126/science.1260352.

Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", *Environmental Science and Technology*, Vol. 52/4, p. 1725-1734, https://doi.org/10.1021/acs.est.7b04573.

OECD (Organisation for Economic Co-operation and Development) (2018), *Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses*, OECD Publishing, Paris.

Schmidt, O. et al. (2017), "Future cost and performance of water electrolysis: An expert elicitation study", *International Journal of Hydrogen Energy*, Vol. 42/52, p. 30470-30492, https://doi.org/10.1016/j.ijhydene.2017.10.045.

United Nations (2018), *Sustainable Development Goals: 17 Goals to Transform Our World*, www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed 6 June 2018).

Chapter 6. Effecting the transition

There can be no single prescription for delivering a sustainable chemical sector. The changes envisaged in Chapter 5 and the investments underlying them offer a practical and economic path for the transition. However, they are unlikely to be made without carefully considered policy measures.

An interdisciplinary approach will be required for appropriate interventions throughout the value chain, from primary chemical production to waste management. This final chapter defines and describes the main areas of policy concerned and the measures that might be considered. Since most policy instruments and interventions must be specific to the circumstances of a particular locality, crafting individual solutions is largely a matter for national and regional authorities.

The current landscape for policy makers to survey

Over the past few decades, the development of the chemical industry has been shaped, primarily, by access to advantaged feedstocks and access to growing demand in emerging markets. Today's circumstances pose an important question as to whether the current recipe for success will apply in the future. The scope for advantageous access to feedstock is diminishing. Ethane prices are rising in the United States as a wave of new conversion capacity comes online and a shift to heavier feedstock is already visible in the Middle East. Competition in emerging markets is increasing. Specialty chemicals, once a route to new sources of high income, are becoming commoditised.

The need to maintain a competitive edge in the chemical sector has motivated a swathe of merger and acquisition activities in recent years, with record-highs in terms of value reached, in 2015 and 2016, through a series of mega-deals. The aggregate deal value almost reached USD 150 billion (United States dollars) in 2015 and increased to USD 230 billion in 2016, four times higher than the level registered in 2010 (Deloitte, 2018).

While there are many drivers behind this expansion, the basic impetus is either the need for market participants to position themselves early in a growing market segment or the need to ensure "portfolio coherence". The acquisition of Monsanto by Bayer and of Syngenta by ChemChina were focused, particularly, on the growing agrichemical market. Other recent acquisitions were directed at the growing healthcare and automotive markets.

Widespread social demand for sustainability requires the industry to elevate the attention given to environmental and related considerations. Current modest levels of attainment provide ample scope for innovative companies to seize competitive advantage. Major chemical companies and a number of start-ups are embracing new business opportunities in this area. Their efforts range from the introduction of technologies that utilise alternative feedstocks to material recycling and efficient waste management.

For example, Total has established a joint venture with Corbion that aims to produce a biodegradable polymer made from renewable feedstock. One pilot plant has been built in Thailand and another two are planned. Borealis regards the recycling of polyolefins as a strategic objective and acquired MTM plastics, which specialises in the production of polyolefin recyclate from mixed, post-consumer, plastic waste.

Some start-ups are trying to commercialise processes to convert carbon dioxide (CO_2) to chemical products and plastic waste to oil products. There is also growing interest from financial investors in the opportunities in a sustainable chemical value chain. Between 2010 and 2015, venture capital investments for material recycling increased five-fold, to around USD 200 million in 2015.

The majority of these initiatives aim to accomplish major changes in plastic waste collection and sorting, based on advanced data analytics and robotics (Lux Research, 2016).

However, since the end of the first clean technology surge in 2011, alternative chemical feedstock start-ups have struggled to attract funding, leading to an annual average reduction of about 25% in the overall level of funding over the period (Cleantech Group, 2018). This may reflect the difficulty of scaling up enzymatic conversion technologies sufficiently quickly to appeal to venture capital investors.

The chemicals industry is also uniquely positioned to offer a range of high-performance materials in support of the low-CO_2 transition in other industries, such as buildings, consumer goods and transportation. Enabling greater penetration of low-CO_2 technologies and contributing to energy efficiency improvements in other sectors creates new business opportunities for the chemical industry and benefits society as a whole. Widespread political adoption of the sustainability agenda means that over time, efforts to develop breakthrough technology and capture more value from material efficiency will need to become embedded in the method for value creation in most companies.

Policy matters in chemical supply chains

In industrial supply chains, comparative advantage in production stems partly from the prevailing economic and market conditions, but it can also depend on national or regional policy. Prices and preferences may all be influenced by policy makers and regulatory constraints are manifold. Whereas the policy measures deployed in end-use sectors, such as buildings or transport, often have a direct and traceable set of consequences. But in complex industrial supply chains – of which the chemical sector is a paramount example – cause and effect can be difficult to distinguish, at least until some time after the measure in question takes effect.

Impacts of policy behind the factory gate

A wide array of initiatives to promote industrial energy efficiency extend to the chemical industry. Important examples include policies and programmes that support or require the adoption of an **energy management system**, (such as that described by the International Organization for Standardization (ISO) 50001 standard), and sectoral or company-level targets and **minimum energy performance standards** (MEPS) for industrial equipment. An energy management system is a collection of procedures and practices to ensure the systematic planning, analysis, control, monitoring and improvement of energy use and efficiency.

For example, in Germany large energy-using companies, including chemical manufacturers, can obtain sizeable tax reductions by implementing an energy management system. In the United States, the voluntary Superior Energy Performance programme provides recognition, in the form of certification, for companies that implement ISO 50001 and achieve energy performance improvements. Adoption of ISO 50001 is also a component of industrial energy efficiency policies in Korea, Indonesia, Canada and Mexico and the European Union.

Policies that require companies or industry sectors to reach specified levels of energy efficiency or achieve a given level of energy intensity improvement, have been implemented in the People's Republic of China,[24] India and Japan. In its 11th Five Year Plan (2006-11) China set specific **energy performance improvement targets** for the top 1 000 energy-consuming enterprises. This programme was expanded in the 12th Five Year Plan (2011-16), with targets set for the top

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[24] Hereafter, "China".

10 000 energy consuming enterprises. The target for the chemical industry was to increase output (measured by value) by 8% a year while concurrently decreasing the energy intensity (measured by energy demand per unit of output in terms of value) of production by 18%.

In India, the Perform Achieve Trade (PAT) project requires designated industrial sectors and companies to achieve energy-saving targets and provides a trading mechanism that allows companies to trade certificated excess compliance with companies that have not met the targets (BEE, 2018). Fertiliser and chlor-alkali manufacturers were included in the first PAT cycle (2012-15); 22 companies in the chlor-alkali sector exceeding targeted savings (by 160%), while 29 fertiliser producers exceeded their target (by 70%). Combined, the two sectors achieved almost 1 million tonnes of oil equivalent (Mtoe) of energy savings, more than 10% of the annual process energy demand for primary chemicals production in India (BEE, 2018). The second PAT cycle (2016-19), again covers these two sectors with an increased number of companies required to meet targets. The list has been extended to include refineries, in which 18 industrial units have an energy-reduction target of 1.1 Mtoe.

In 2010, Japan amended its Act on the Rational Use of Energy to introduce mandatory energy efficiency thresholds in the form of performance benchmarks and to include an obligation to make annual energy efficiency improvements of 1%. Benchmarks are defined by reference to the performance of the top 10-20% of companies within each industrial sub-sector. Companies are required to meet performance targets, based on these benchmarks within the medium (five years) and long term (ten years). The policy extends to chemicals, manufacturing and oil refining.

The European Union's Energy Efficiency Directive contains a set of binding measures for member countries. These are aimed at providing a pathway to achieving the European Union targets of a 20% increase in energy efficiency by 2020, further increasing this to 30% by 2030 (both relative to business as usual projected energy use). Progress is tracked at the overall industry level – which includes the chemical sector – and has undergone a 19% reduction in energy intensity (energy input per unit of gross value added generated) between 2005 and 2015 in the European Union (European Union, 2012).

Electric motors are an important example of a conversion device used throughout the chemical industry, where they are used to power pumps, compressors, fans and a multitude of other industrial equipment. MEPS are applied to medium-sized electric motors in many major economies. However, due to the long operating life of electric motors, just over one-quarter of global electricity use related to such equipment is covered by MEPS. Across those countries with MEPS, if all motors were replaced by motors meeting the standard, that share would rise to over 50%, illustrating the broader scope of these policies (IEA, forthcoming).

Supportive interventions do not all stem from governments. For example, in 1985, the International Council of Chemical Associations launched Responsible Care. This is a voluntary commitment to improve and achieve excellence in environmental and health and safety performance. Responsible Care commits companies, national chemical industry associations and their partners to:

- continuously improve the environmental and health and safety knowledge and performance of technologies, processes and products over their life cycles, to avoid harm to people and the environment
- use resources efficiently and minimise waste
- report openly on performance, achievements and shortcomings
- listen, engage and work with people to understand and address their concerns and expectations

- co-operate with governments and organisations in the development and implementation of effective regulations and standards, and to meet or go beyond them
- provide help and advice to foster the responsible management of chemicals by all those who manage and use them along the product chain.

To date, there are 580 signatories to the Responsible Care Global Charter, covering 96% of the world's largest chemical companies (ICCA and Cefic, 2018).

Rational energy pricing

Energy costs contribute greatly to the overall costs faced by chemical producers. As we have seen, costs related to feedstock and process energy account for about 80% on average for naphtha-based steam cracking and around 60% on average for ethane-based steam cracking (on a levelised cost basis). Energy subsidies, which exist for a range of social and industrial reasons, many with no particular relevance to the chemical industry, can lead to wasteful use of energy and be detrimental to energy efficiency investments.

In the chemical industry, fossil fuel subsidies might also inhibit shifts towards feedstocks that are less carbon intensive or are renewable, if not designed effectively. While coal and natural gas can be used interchangeably as feedstock or fuel, oil products that are typically demanded for feedstock (e.g. naphtha and ethane) are rarely consumed solely as fuels, with liquefied petroleum gas (LPG) being an exception.

Global energy subsidies totalled USD 262 billion in 2016. They have been declining since 2012, through a combination of decreasing fuel prices and progress towards subsidy reform. Oil ranks second (USD 105 billion) and natural gas third (USD 49 billion) of global energy subsidies; coincidentally, these are the most consumed energy commodities in the chemical sector. Although most of these subsidies were designed to reduce prices for domestic, rather than industrial customers, fossil fuel subsidies can affect industrial fuel prices directly or indirectly. This depends on whether they are applied to exploration, refining and transformation, or consumption activities.

Natural gas subsidies, where applied to industrial applications, can inhibit efficient use of gas as a fuel in industrial activities generally, or as feedstock in the chemical sector. Iran, the Russian Federation[25] and the United Arab Emirates together account for around 60% of the global natural gas subsidies, while the Middle East and Russia are responsible, jointly, for about a third of the global natural gas demand for primary chemicals (including process energy and feedstock). Coal subsidies represent less than 1% of the global energy subsidies. The potential impact of subsidies on preventing shifts from coal to routes based on natural gas for primary chemicals production or on improving energy efficiency in coal-based chemical production is limited.

Oil subsidies, when applied to oil products consumed as fuels (e.g. fuel oil or gas oil), can promote wasteful consumption whenever they are used, including in the chemical sector. Saudi Arabia, Iran and China together account for almost half of global oil subsidies, while the Middle East and China make up 30% of global oil demand for primary chemicals. Saudi Arabia has announced its intention to phase out most fuel subsidies by 2020, (accompanied by measures to support industry with the transition). In China, oil price reform is progressing towards a market-oriented approach integrated with international market pricing. Early in 2015, the excise tax revenue from different Chinese refined oil products increased, including

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[25] Hereafter, "Russia".

naphtha (OECD, 2016a). Reforms on the oil consumption side in China are complemented by a reduction in the subsidies related to fossil fuel production, including the gradual removal of support for shale gas extraction.

Oil subsidies directly applied to oil products commonly used as chemical feedstock, such as ethane or naphtha, are rare. This is again because energy subsidies have typically targeted oil products that are generally demanded for household or transport-related applications, with the objective being to reduce energy poverty, ensure widespread access to energy and redistribute wealth.

Customers for LPG, however, come from both the domestic and the industrial sectors. While LPG is essential to facilitate clean cooking in remote areas and attracts subsidies primarily for this purpose, there can be some spill over to the industrial sectors. Nevertheless, most untargeted LPG subsidies have been removed or are due to be reformed, which reinforces the more general case for energy price subsidy reform.

Plastic waste management

The majority of the waste that arises from chemical-derived products relates to plastics. There are other important chemical products that must be disposed of carefully in order to avoid causing environmental damage, such as industrial solvents, paints and surfactants, but the bespoke policy measures relevant to these products are outside the scope of this report.

Where possible, the best waste management policy for plastics is to avoid waste generation in the first place. Where waste generation is unavoidable, well-designed products can reduce waste and costs. It is likely that recycling, incineration and landfill will continue to play a combined role in waste management options, but attention needs to be given to ensure best practice is pursued in each case.

Design codes and practices that make it easier for the materials in products to be extracted and sorted after use reduce the need for disposal and re-manufacture. Examples include the concept "design for disassembly", which was proposed to facilitate re-use and recycling (Talens Peiro, Ardent and Mathieux, 2017). The Eco-design Directive, developed by the European Commission, provides guidance on how to improve the environmental footprint of consumer products in the various phases of their life-cycle (European Union, 2009). Indicators that are evaluated under this directive cover energy and material efficiency indicators, such as recycled content and the waste generated when the product is disposed of. Such indicators help to assess the potential environmental damage of a product, taking account of its reusability or recyclability.

Codes and standards can also incentivise product designs that increase the likelihood that a material will be recycled (often more than once). Standards include those that foster the use of simple material mixes and facilitate the separation of different materials from waste. These features result in plastic resins that can be recovered at greater purity, which increases the economic incentive to recycle them for closely-related end-use applications (closed loop recycling). Alternatively, if the recycled resin is down-cycled to a lower-grade use that can tolerate a higher level of impurities, the likelihood of recycling such a resin a second time decreases, especially for uses with stringent specifications (e.g. food grade applications).

If the full costs of scrap collection, sorting, cleaning and secondary production are included, recycling plastics tends to be uneconomic without some form of government support. This support is most commonly provided in the form of **public waste collection and management services**. Many municipal governments and local councils across the world provide infrastructure and collection services to foster the separation of plastics at the point of disposal (through the use of dedicated bins and collection routines). This greatly reduces the cost of separation at a later stage in the waste stream. In certain regions these, and other means of government support, have delivered steadily increasing rates of recycling. In 2016, recycling overtook landfill as a destination for plastic waste for the first time in Europe, while landfill rates in Japan and Korea are below 10%.

Circular economy and resource efficiency strategies have been promoted by the European Commission, each of which includes aims for the prevention and reduction of waste. New measures have been announced recently in the framework of the Circular Economy Package, including a Europe-wide strategy for plastics, which has an objective that more than half of all plastic waste should be recycled by 2030 (European Union, 2018a). As long ago as 2001, Japan adopted a resource efficiency-conducive national policy framework, which was supported by legislative instruments for waste management (OECD, 2016b).

Box 6.1 • A vision for Europe’s new plastics economy

In January 2018, the European Commission announced a vision for Europe’s new plastics economy, as part of the new set of measures announced within the 2018 Circular Economy Package (European Union, 2018a). The European Strategy for plastics outlines the following commitments to be implemented:

- all plastic packaging used in the European market is to be cost-competitively reused or recycled by 2030
- more than half of plastic waste generated in Europe must be recycled
- plastic sorting and recycling capacity must be expanded four-fold by 2030, relative to 2015 levels, resulting in 200 000 new jobs
- some 10 million tonnes of recycled plastic is to be used for new products by 2025.

The key overarching policy objectives include reducing Europe’s dependence on imported fossil fuels, decreasing CO_2 emissions, mitigating other environmental effects, such as plastic leakage, and incentivising economic growth and job creation.

Extended producer responsibility policies may contain legal instruments that make producers accountable for collecting, sorting and processing products after use. This type of measure is already applied in Japan for home appliances, packaging and end-of-life vehicles (OECD, 2016b).

Green public procurement policies set criteria that require public purchasing to support environmental goals, stimulating innovation and demand for green products. To be effective, these programmes tend to rely upon environmental life-cycle assessment, a technique that is prone to boundary and allocation problems.

Landfill policies in place in several countries ban or tax waste that is sent to landfill. As of 2016, Korea, Switzerland, Austria, Germany, the Netherlands, Sweden, Denmark, Luxembourg, Belgium, Norway and Finland all had landfill restrictions in place. These appear to be associated with higher rates of waste-to-energy and recycling for plastic waste (Plastics Europe, 2017). In stark contrast, India is on course to provide new landfills the size of its second largest city, New Delhi, by 2050 (The Hindu, 2017). Like elsewhere in developing economies, this reflects strong population growth, increasing urbanisation and rising prosperity, all of which tend to result in larger quantities of plastic (and other) waste. Substantial investments in waste collection, recycling facilities and waste-to-energy plants are required to cope with this situation.

Regional asymmetries with respect to the generation of waste landfilling and other waste management measures have resulted in waste becoming a globally traded commodity. China’s commitment to ban post-consumer plastic waste imports as of 2018 will force exporting regions that previously relied on this relatively cheap outlet for considerable quantities of their plastic waste, to find alternatives. In the short term, this seems likely to have the unfortunate consequence of increasing landfilling, as reported in Australia (Hyam and Roe, 2018).

Stopping European plastic waste exports to China will result in an increase of almost 10% in the total plastic annual waste volume that needs to be managed domestically. If this were to be fully redirected to recycling (and it is not accounted as such already), as regulators propose, it would increase European plastic waste recycling by almost 30% (United Nations, 2018a).[26] The European Commission recently announced a target for plastic waste recycling to reach more than 50% by 2030 (European Union, 2018a).

Motivated largely by recent publicity about the devastating extent of plastic pollution, there have been calls to **ban the consumption of certain plastics**. These are particularly for single-use items and those for which substitutes exist (European Union, 2018b). In the United Kingdom, the private sector is preparing to go beyond current policy and legislative requirements. Forty businesses have signed the “UK Plastic Pact”, including some major trans-national consumer goods manufacturers and retailers. The pact comprises four targets to be achieved by 2025: 100% of plastic packaging must be reusable, recyclable or compostable; 70% must be effectively recycled or composted; average recycled content must reach 30%; and “problematic or unnecessary single-use packaging items” must be eliminated (WRAP, 2018). The signatories estimate that 80% of all plastic packaging for products sold in supermarkets will be covered by the pact.

At the European Union level, a tax on plastic consumption is proposed to encourage recycling, reduce waste and to raise revenue (Oettinger, 2018), though no details of the tax were included in the strategy for plastics adopted in January 2018 (European Union, 2018a). To mitigate the damage caused by the microplastics found in cosmetics, about 95 non-governmental organisations from around 40 countries and 119 manufacturers have joined forces to “beat the microbead” (Plastic Soup Foundation, 2018). This initiative encourages the expectation of progressive phase-out of this particularly pernicious source of water pollution.

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[26] Estimations based on 2016 statistics. It is unclear as to whether some countries already account for plastic waste exports as recycled, assuming they will be at their destination. Where this is the case, redirection will not result in any increase in recycling rates.

Top ten policy recommendations

Despite the substantial benefits petrochemical products provide to the world – including a growing number of applications in various cutting-edge, clean technologies – the production, use, and disposal of petrochemical products pose a variety of sustainability challenges that need to be addressed.

Few policies can be both global in scope and optimally efficient – local circumstances vary too much. However, the following ten recommendations warrant early and consistent attention from those intent on contributing to the chemical industry's transition to a more sustainable future. The ten are divided between *production* and *use and disposal*:

Production

1. **Directly stimulate investment in RD&D** of sustainable chemical production routes and limit associated risks. Unlock finance in areas with potential for sustainable returns, but with a low likelihood of attracting, under present circumstances, independent private investment.
2. **Establish and extend plant-level benchmarking schemes** through public-private co-operative frameworks, for energy performance, and CO_2 emission reductions targets, and incentivise their adoption through fiscal incentives.
3. **Pursue effective regulatory actions to reduce CO_2 emissions**. These need to include support to avoid the impact of asymmetric regional pricing pressures and targeted support to spur the creation of initial niche markets where necessary.
4. **Require industry to meet stringent air quality standards**, such as those of the World Health Organization, by developing and installing air pollution control technologies, fuel shifts, and improved fuel quality.
5. **Fuel and feedstock prices should reflect actual market value,** specifically those that delay investment in energy efficiency. Ensure that fuel subsidies designed to facilitate clean energy access (e.g. subsidies for liquefied petroleum gas for clean cooking) are precisely targeted and do not inhibit shifts towards alternative chemical feedstocks.

Use and disposal

1. **Reduce reliance on single-use plastics** other than for essential non-substitutable functions. Policy mechanisms include introducing deposit-return systems for reusable goods (e.g. beverage containers) or fiscal instruments (such as a revenue-neutral plastic consumption tax, the proceeds of which could be directed to preventing and mitigating plastic pollution).
2. **Improve waste management** practice around the world, both to increase recycling and to drastically reduce plastic waste leakage. Examples include prohibiting or implementing a tax on the disposal in landfills of all recoverable waste and improving the separation and collection of recyclables at source.
3. **Raise consumer awareness** about the multiple benefits of recycling consumer goods, the environmental ills associated with poor waste management, and the most effective policy interventions.
4. **Design products with disposal in mind** by incentivising designers and manufacturers downstream of chemical producers to adopt designs that optimise the use of materials, enable reuse, and facilitate closed-loop recycling.

5. **Extend producer responsibility** beyond production to appropriate aspects of the use and disposal of chemical products, for example, through systems that levy fees penalising the limited recyclability of a material and actions that complicate waste separation.

Keeping these policy strategies on course, monitoring, and evaluating their progress and effectively communicating their results require reliable, transparent, and timely data. A clear institutional framework defining responsibilities for stakeholders throughout the value chain – from chemical production through to the use and disposal of chemical products – will be a pre-requisite for ensuring cost-efficient, concerted action.

References

BEE (Bureau of Energy Efficiency) (2018), *The Perform Achieve and Trade (PAT) Cycle*, https://beeindia.gov.in/content/pat-cycle (accessed 6 June 2018).

Cleantech Group (2018), *i3 Database: The Innovation Network that Drives Sustainability*, www.cleantech.com/i3/ (accessed 6 June 2018).

Deloitte (2018), *2018 Global Chemical Industry Mergers and Acquisitions Outlook*, www2.deloitte.com/content/dam/Deloitte/global/Documents/Manufacturing/gx-global-chemical-report-2018.pdf.

European Union (2009), Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-related Products (recast), https://doi.org/10.1016/j.cirp.2012.03.121.

European Union (2012), *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency*, https://doi.org/10.3000/19770677.L_2012.315.eng.

European Union (2018a), *A European Strategy for Plastics in a Circular Economy*, http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy.pdf.

European Union (2018b), Directive 2009/172/EC of the European Parliament and of the Council on the Reduction of the Impact of Certain Plastic Products on the Environment, http://ec.europa.eu/environment/circular-economy/pdf/single-use_plastics_proposal.pdf.

Hyam, R. and I. Roe (2018), *Recycling Will Be Dumped by Councils Nationwide as Costs Blow Out, Government Association Says*, www.abc.net.au/news/2018-04-19/queensland-council-recycling-dump-to-start-nationwide-reaction/9673370 (accessed 6 June 2018).

ICCA (International Council of Chemical Associations) and Cefic (European Chemical Industry Council) (2018), *Responsible Care Global Charter*, www.icca-chem.org/responsible-care-global-charter/ (accessed 6 June 2018).

IEA (International Energy Agency) (forthcoming), *Energy Efficiency 2018*, OECD/IEA, Paris.

Lux Research (2016), Observing Trends from VC Investment Activities to Material Recycling Fields, Boston, MA.

OECD (Organisation for Economic Co-operation and Development) (2016a), *China's efforts to phase out and rationalise its inefficient fossil-fuel subsidies*, OECD/IEA, Paris (Chair of the peer review), Germany, Indonesia, US, IMF.

OECD (2016b), Policy Guidance on Resource Efficiency, OECD/IEA, Paris.

Oettinger, G. (2018), "A budget matching our ambitions" speech given at the conference "Shaping our Future", https://ec.europa.eu/commission/commissioners/2014-2019/oettinger/blog/budget-matching-our-ambitions-speech-given-conference-shaping-our-future-812018_en (accessed 6 June 2018).

Plastic Soup Foundation (2018), *Beat the Microbead*, www.beatthemicrobead.org/strategy/ (accessed 6 June 2018).

Plastics Europe (2017), *Plastics – the Facts 2017*, www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf.

Talens Peiro, L., F. Ardent and F. Mathieux (2017), *Design for Disassembly Criteria in EU Product Policies for a More Circular Economy*, https://ec.europa.eu/jrc/en/publication/design-disassembly-criteria-eu-product-policies-more-circular-economy-method-analyzing-battery-packs.

The Hindu (2017), "India needs New Delhi-sized landfills for waste by 2050: Report", www.thehindu.com/news/national/india-needs-new-delhi-size-landfills-for-waste-by-2050-report/article19144908.ece (accessed 6 June 2018).

United Nations (2018), *UN Comtrade Database*, https://comtrade.un.org/ (accessed 6 June 2018).

WRAP (Waste and Resources Action Programme) (2018), *The UK Plastics Pact*, www.wrap.org.uk/content/the-uk-plastics-pact (accessed 6 June 2018)

Acronyms, abbreviations and units of measure

Acronyms and abbreviations

BDH	bioethanol dehydration
BTX	benzene, toluene and mixed xylenes
CAPEX	capital expenditure
CCS	carbon capture and storage
CCU/S	carbon capture, utilisation and storage
COG	coke oven gas
CO_2	carbon dioxide
CTS	Clean Technology Scenario
GDP	gross domestic product
GHG	greenhouse gas
HDPE	high-density polyethylene
HVC	high-value chemicals
IEA	International Energy Agency
ISO	International Organization for Standardization
LDPE	low-density polyethylene
LPG	liquefied petroleum gas
LTO	light tight oil
MEPS	minimum energy performance standards
MTA	methanol to aromatics
MTO	methanol to olefins
NCC	naphtha catalytic cracking
NGL	natural gas liquid
NO	nitrogen oxide
NO_x	nitrogen oxides
NO_2	nitrogen dioxide
N_2O	nitrous oxide
OPEX	operational expenditure
PA	polyamide
PAT	Perform Achieve Trade
PBAT	polybutylene adipate terephthalate
PBS	polybutylene succinate
PCL	polycaprolactone
PE	polyethylene
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoate
PLA	polylactic acid
PDH	propane dehydrogenation
PM	particulate matter
$PM_{2.5}$	fine particulate matter (diameter less than 2.5 micrometres)
PM_{10}	coarse particulate matter (diameter between 2.5 and 10 micrometres)
PP	polypropylene
PS	polystyrene
PTT	polytrimethylene terephthalate
PVC	polyvinyl chloride
RTS	Reference Technology Scenario

SEC	specific energy consumption
SLCP	short-lived climate pollutant
SO_x	sulphur oxides
SO_2	sulphur dioxide
US	United States
USD	United States dollar
VOC	volatile organic compound

Units of measure

bcm	billion cubic metres
Bt	billion tonnes
EJ	exajoule
GJ	gigajoule
GJ/t	gigajoule per tonne
$GtCO_2$	gigatonnes of carbon dioxide
kg	kilogramme
kg/capita	kilogramme per capita
kWe	kilowatt electrical capacity
km^2	square kilometres
mb/d	million barrels per day
MBtu	million British thermal units
Mt	million tonnes
$MtCO_2$	million tonnes of carbon dioxide
$MtCO_2$-eq	million tonnes of carbon dioxide equivalent
$MtCO_2$/yr	million tonnes of carbon dioxide per year
Mtoe	million tonnes of oil equivalent
Mt/yr	million tonnes per year
MW	megawatt
MWh	megawatt hour
m^3	cubic metres
m^3/t	cubic metre per tonne
tCO_2	tonne of carbon dioxide
tCO_2/t	tonne of carbon dioxide per tonne
tHVC	tonne of high-value chemical
TWh	terawatt hour

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