MISSION POSSIBLE

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

ENERGY TRANSITIONS
COMMISSION

MISSION POSSIBLE

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

NOVEMBER 2018

The Energy Transitions Commission

The Energy Transitions Commission (ETC) brings together a diverse group of leaders from across the energy landscape: energy producers, energy users, equipment suppliers, investors, non-profit organizations and academics from the developed and developing world. Our aim is to accelerate change towards low-carbon energy systems that enable robust economic development and limit the rise in global temperature to well below 2˚C and as close as possible to 1.5˚C.

The ETC is co-chaired by Lord Adair Turner and Dr. Ajay Mathur. Our Commissioners are listed on the next page.

The *Mission Possible* report was developed by the Commissioners with the support of the ETC Secretariat, provided by SYSTEMIQ. It draws upon a set of analyses carried out by Material Economics, McKinsey & Company, University Maritime Advisory Services and SYSTEMIQ for and in partnership with the ETC, as well as a broader literature review.

Emerging findings were subject to a six-month consultation process through which we received inputs from nearly 200 experts from companies, industry initiatives, international organizations, non-governmental organizations and academia. We warmly thank them for their contributions.

This report constitutes a collective view of the Energy Transitions Commission. Members of the ETC endorse the general thrust of the arguments made in this report, but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century, but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organizations with different perspectives on and interests in the energy system should give decision-makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2˚C, and that many of the key actions to achieve these goals are clear and can be pursued without delay.

Learn more at:
www.energy-transitions.org
www.facebook.com/EnergyTransitionsCommission
www.linkedin.com/company/energy-transitions-commission
www.twitter.com/ETC_energy

Our Commissioners

Laurent Auguste
Senior Executive Vice President, Innovation and Markets, Veolia

Pierre-André de Chalendar
Chairman and CEO, Saint-Gobain

Dominic Emery
Vice President, Group Strategic Planning, BP

Will Gardiner
CEO, DRAX

Didier Holleaux
Executive Vice President, ENGIE

Chad Holliday
Chairman, Royal Dutch Shell

Gopi Katragadda
Chief Technology Officer and Innovation Head, Tata Sons

Zoe Knight
Managing Director and Group Head, Centre of Sustainable Finance, HSBC

Jules Kortenhorst
CEO, Rocky Mountain Institute

Rachel Kyte
Special Representative to the UN Secretary-General; CEO, Sustainable Energy For All

Mark Laabs
Managing Director, Modern Energy

Richard Lancaster
CEO, CLP Holdings Limited

Alex Laskey
Former President and Founder, OPower

Auke Lont
President and CEO, Statnett

Ajay Mathur
Director General, The Energy and Resources Institute; Co-Chair, Energy Transitions Commission

Arvid Moss
Executive Vice President, Energy and Corporate Business Development, Hydro

Philip New
CEO, Catapult Energy Systems

Nandita Parshad
Managing Director, Energy and Natural Resources, European Bank for Reconstruction and Development

Andreas Regnell
Senior Vice President, Strategic Development, Vattenfall

Mahendra Singhi
Managing Director and CEO, Dalmia Cement (Bharat) Limited

Andrew Steer
President and CEO, World Resources Institute

Nicholas Stern
Professor, London School of Economics

Nigel Topping
CEO, We Mean Business

Robert Trezona
Partner, Head of Cleantech, IP Group

Jean-Pascal Tricoire
Chairman and CEO, Schneider Electric

Laurence Tubiana
CEO, European Climate Foundation

Adair Turner
Chair, Energy Transitions Commission

Timothy Wirth
Vice Chair, United Nations Foundation

Lei Zhang
CEO, Envision Group

Changwen Zhao
Director General, Department of Industrial Economy, Development Research Center of the State Council of China

Cathy Zoi
CEO, EVgo

CONTENTS

Glossary

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

Basic Oxygen Furnace (BOF): Technology used in ore-based (virgin) steelmaking to reduce iron into steel. It usually relies on a coal input and produces CO_2 and other flue gases.

BECCS: A technology that combines bioenergy with carbon capture and storage to produce net negative carbon emissions

BEVs: Electric vehicles.

Business-as-usual scenario: A scenario for future patterns of activity which assumes that future trends will follow past trends and there will be no significant change in technology, economics, policies or behaviors, with regards to energy transitions

Carbon capture: Unless specified otherwise, we use the term "carbon capture" to refer to carbon capture on the back of energy and industrial processes, regardless of whether it is combined with carbon use or carbon storage. Direct air capture is excluded when using this terminology.

Carbon capture and storage (CCS): The term "carbon capture and storage" and the abbreviation "CCS" refer to the combination of carbon capture* on the back of fossil fuels, bioenergy and industrial processes, with carbon storage*. The use of carbon in CO_2-based products* is excluded from this terminology.

Carbon emissions / CO_2 emissions: We use these terms interchangeably to describe anthropogenic emissions of carbon dioxide emissions in the atmosphere.

Carbon offsets: Reductions in emissions of carbon dioxide or greenhouse gases made by a company, sector or economy to compensate for emissions made elsewhere in the economy. Legal disputes related to how to account for carbon emissions reductions from offsets which are traded internationally outside of regulated emissions trading schemes are not covered in this report.

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

Carbon storage: Underground storage of CO_2, for instance in depleted oil and gas reservoirs, saline formations, or deep coal beds. Natural carbon sinks* and the use of carbon in CO_2-based products* are excluded from this terminology.

Carbon use in CO_2-based products: This refers to the use of CO_2 in products developed via the conversion of CO_2 in which CO_2 is sequestered over the long-term (e.g. in concrete, aggregates, carbon fiber). CO_2-based products that only delay carbon emissions in the short-term are excluded when using this terminology (e.g. synthetic fuels).

Circular economy models: Economic models that ensure the recirculation of resources and materials in the economy, by recirculating a larger share of materials, reducing waste in production, light-weighting products and structures, extending the lifetimes of products, and deploying new business models based around sharing of cars, buildings, and more.

Combined Cycle Gas Turbine (CCGT): An assembly of heat engines that work in tandem from the same source of heat to convert it into mechanical energy to drive electric generators

Compressed Natural Gas (CNG): A gas mainly constituted by methane and compressed at a pressure of 200 to 248 bars, mainly used as a transport fuel

Direct air capture (DAC): The extraction of carbon dioxide from atmospheric air

Direct Reduced Iron (DRI): Technology used in ore-based (virgin) steelmaking to reduce iron into steel by removing oxygen from the iron ore without melting. It currently relies on a gas input and produces CO_2 and other flue gases. It could, in the future, rely on a hydrogen input.

Decarbonization technologies: We use the term "decarbonization technologies" to describe technologies that reduce anthropogenic carbon emissions by unit of product or service delivered through fuel/feedstock switch, process change or carbon capture. This does not necessarily entail a complete elimination of CO_2 use, since (i) the use of biomass or synthetic fuels can result in the release of CO_2, which would have been previously sequestered from the atmosphere through biomass growth or direct air capture, and (ii) CO_2 might still be embedded in the materials (e.g. in plastics). Energy efficiency technologies are excluded from this terminology.

Demand management: We use the term "demand management" to described practices and technologies that limit the growth – or even reduce – the demand for carbon-intensive products and services. This covers in particular materials efficiency, circularity and substitution in the heavy industry sectors, and logistics efficiency and modal shift in the heavy-duty transport sectors.

Development Finance Institutions (DFIs): Organizations that provide concessional finance to developing countries. DFIs include multilateral, regional and bilateral institutions.

Easier-to-abate sectors: Economic sectors with relatively lower abatement costs than harder-to-abate sectors. These include power, light-duty road transport, rail, pulp and paper, aluminum and other industries, buildings, agriculture, fishing, and other. They currently emit 23.9Gt of CO_2 out of 34.3Gt CO_2 from the energy and industrial system.

Electric Arc Furnace (EAF): Technology used in ore-based (virgin) steelmaking as well as scrap-based steelmaking to refine molten pig iron into steel

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

End-of-life emissions: CO_2 emissions released by a product at the point of use (for N-fertilizers) or when the product decomposes or is burnt at the end of its useful life (for plastics).

Energy and industrial system emissions: CO_2 emissions arising from the use of fossil fuels and from industrial processes

Energy efficiency: Energy consumption per unit of a given energy-based good or service

Energy productivity: Energy consumption per unit of GDP

Exajoule (EJ): 1EJ = 277.78TWh

FCEVs: Fuel-cell electric vehicles

Final energy consumption: All energy supplied to the final consumer for all energy uses. This indicator is usually disaggregated into the final end-use sectors: industry, transport, households, services and agriculture.

Greenhouse gases (GHG): Gases that trap heat in the atmosphere. In 2010, global emissions consisted of carbon dioxide (76%), methane (16%), nitrous oxide (6%) and fluorinated gases (2%). Fossil fuels use generates 75% of total greenhouse gas emissions (IPCC, 2014).

Harder-to-abate sectors: Economic sectors with relatively higher abatement costs than the rest of the economy. These include heavy industry sectors (cement, steel, chemicals) and heavy-duty transport (heavy-duty road transport, shipping, aviation). They currently emit 10.3Gt of CO_2 out of 34.3Gt CO_2 from the energy and industrial system.

HDVs/Heavy-duty road transport/Heavy road transport: Heavy-duty vehicles have a gross vehicle weight rating above 4,500 kg, such as most trucks and buses.

Illustrative pathways: Throughout this report, the ETC presents quantifications whose aim is to identify likely orders of magnitude that can inform policy and investment, rather than develop a scenario and suggest that precise prediction is possible. In particular, the ETC's illustrative pathways assess the implications for the energy system of an illustrative mix of supply-side and demand-side decarbonization solutions by mid-century. These pathways are described on p.102-103.

Land use system emissions: CO_2 emissions arising from land use change, in particular deforestation, and from the management of forest, cropland and grazing land. The global land use system is currently emitting CO_2 (as well as other greenhouse gases), but may, in the future, absorb more CO_2 than it emits, delivering negative CO_2 emissions, thanks to reforestation, afforestation, revegetation and changes in land use management practices.

LDVs/Light-duty road transport/Light road transport: Light-duty vehicles have a gross vehicle weight rating of below 4,500 kg, such as individual passenger vehicles.

Liquefied Natural Gas (LPG): Natural gas that has been cooled down to liquid form for ease and safety of non-pressurized storage or transport

Low-carbon energy/power system: We use this term to refer to an energy or power system that emits an amount of CO_2 that is compatible with or lower than the requirements of a 2˚C scenario.

Mid-century: We use this term to indicate the decade 2050-2060. Developed countries could reach net-zero CO_2 emissions from the energy and industrial system by 2050, while developing countries could reach this objective closer to 2060.

Multilateral Development Banks (MDBs): International financial entities that aim at financing large-scale projects and programs on a regional or national level such as the International Monetary Fund or the World Bank.

Natural carbon sinks: A natural reservoir that stores more CO_2 than it emits. Forests, plants, soils and oceans are natural carbon sinks.

Nationally Determined Contributions (NDCs): The NDCs are national strategies to reduce greenhouse gas emissions submitted by individual countries prior to the 2015 United Nations international climate change conference in Paris (COP21). These plans are updated every five years, starting from 2020 onwards.

Near-total-variable renewable power system: We use this term to refer to a power system where 85-90% of power supply is provided by variable renewable energies (solar and wind), while 10-15% is provided by dispatchable/peaking capacity, which can be hydro, biomass plants or fossil fuels plants (combined with carbon capture to reach a zero-carbon power system).

Net-zero-carbon-emissions economy/Net-zero-carbon economy/Net-zero economy: We use these terms interchangeably to describe an economy in which any remaining anthropogenic CO_2 emissions is compensated by negative emissions from the land use system or BECCS.

Net-zero-carbon/Net-zero emissions within the sector: We use these terms interchangeably to describe the situation in which a specific economic sector releases no CO_2 emissions, either because it does not produce any or because it captures the CO_2 it produces to use or store. In this situation, there should be almost no use of offsets* from other sectors, which should be used only to compensate for remaining emissions from leakages at the carbon capture level or for uncontrollable end-of-life emissions.

Paris Agreement: International treaty that aims to limit the rise in global temperatures to well below 2˚C and as close as possible to 1.5˚C above pre-industrial levels. The agreement was concluded at the 2015 United Nations international climate change conference in Paris (COP21) and is a replacement of the 1997 Kyoto Protocol.

Paris objective: We use this term to refer to the objective set in the Paris Agreement to limit the rise in global temperatures to well below 2˚C and as close as possible to 1.5˚C above pre-industrial levels.

Primary energy consumption: Crude energy directly used at the source or supplied to users without transformation, that is, energy that has not yet been subjected to any conversion or transformation process.

Process emissions: CO_2 and other greenhouse gases emissions generated as consequence of a chemical reaction occurring during an industrial process

Sharing economy models: Economic models in which individuals are able to borrow or rent assets owned by someone else, thereby increasing utilization of underutilized assets.

Steam methane reforming (SMR): A process in which methane from natural gas is heated and reacts with steam to produce hydrogen. The SMR process generally produces to CO_2 streams, one from process emissions, which is relatively pure, and one from the combustion of gas to produce heat, which has a lower CO_2 concentration.

Synfuels: Hydrocarbon liquid fuels produced synthesizing hydrogen from electrolysis and CO_2. Synfuels can be zero-carbon if the electricity input is zero-carbon and the CO_2 from direct air capture. Also known as "power-to-fuels" and "electrofuels".

Terawatt hours (TWh): 1 EJ = 277.78 TWh

Well below 2˚C pathway: A pathway for future patterns of activity which would limit total greenhouse gases emissions by 2100 to a significantly lower level that those assumed in 2˚C scenarios, therefore increasing the probability that warming will not exceed 2˚C above preindustrial levels and remain closer to 1.5˚C.

Zero-carbon energy sources: We use this term to refer to renewables (including solar, wind, hydro, geothermal energy), sustainable biomass, nuclear, and fossil fuels if and when their use can be decarbonized through carbon capture.

MISSION

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

POSSIBLE

REPORT SUMMARY

GLOBAL WARMING

WELL BELOW 2°C

MISSION POSSIBLE

To limit global warming to well below 2°C and as close as possible to 1.5°C, the world must reach net-zero CO₂ emissions by mid-century.

CARBON EMISSIONS

NET-ZERO CO$_2$ BY MID-CENTURY

THE BIGGEST CHALLENGE IN MEETING THE PARIS AGREEMENT LIES IN THE MAJOR HARDER-TO-ABATE SECTORS

HEAVY INDUSTRY

CEMENT

STEEL

PLASTICS

HEAVY-DUTY TRANSPORT

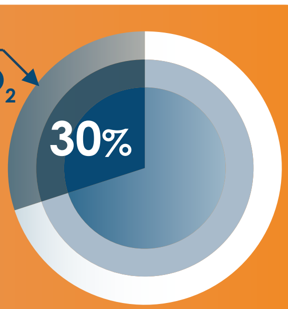
HEAVY ROAD TRANSPORT

SHIPPING

AVIATION

10GtCO$_2$

of total annual carbon emissions from energy and industry...



...and their share of remaining emissions will grow as other sectors, like power, buildings and light-duty transport get decarbonized.

REACHING NET-ZERO CO$_2$ EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY IS POSSIBLE

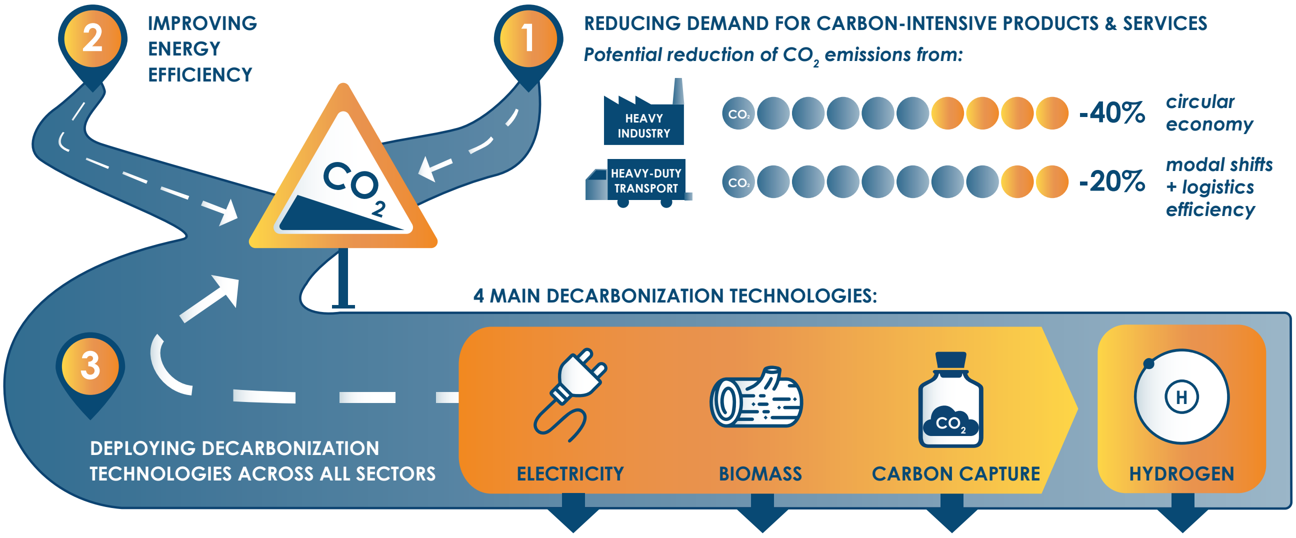
TECHNICALLY

Technologies are commercially ready or at research phase.

ECONOMICALLY

It will cost less than 0.5% of global GDP.

THERE ARE THREE MAIN ROUTES TO DECARBONIZATION



1 REDUCING DEMAND FOR CARBON-INTENSIVE PRODUCTS & SERVICES

Potential reduction of CO$_2$ emissions from:

HEAVY INDUSTRY	-40%	*circular economy*
HEAVY-DUTY TRANSPORT	-20%	*modal shifts + logistics efficiency*

2 IMPROVING ENERGY EFFICIENCY

3 DEPLOYING DECARBONIZATION TECHNOLOGIES ACROSS ALL SECTORS

4 MAIN DECARBONIZATION TECHNOLOGIES:

ELECTRICITY	BIOMASS	CARBON CAPTURE	HYDROGEN
massive electrification, leading to a power demand increase by 4-6x	*prioritized and tightly regulated use, progressively focused on aviation and plastics feedstock*	*combined with use or storage: essential but limited role (5-8 GtCO$_2$ per annum)*	*major role, leading to a 7-11x demand increase, achievable through three production routes*

The Paris climate agreement committed the world to **limit global warming to well below 2°C and keep it as close as possible to 1.5°C above preindustrial levels.** The latest IPCC report[1] has warned the world of the major negative impacts on humanity and the planet of a rise in global temperatures of 1.5°C, and the even more dramatic consequences of 2°C global warming. It therefore urges the world to aim for 1.5°C and recommends achieving net-zero CO_2 emissions globally by 2050.

The Energy Transitions Commission (ETC) – a coalition of business, finance and civil society leaders from across the spectrum of energy producing and using industries – supports the objective of limiting global warming ideally to 1.5°C and, at the very least, well below 2°C.

To achieve even the 2°C goal, and to have any chance of reaching the aspired 1.5°C limit, **it is essential for energy and industrial systems to achieve net-zero CO_2 emissions within themselves** – i.e. without permanently relying on offsets from the land use sector. The ETC strongly believes that **this is achievable by 2050 in developed economies and 2060 in developing economies[2].**

This is an imperative, but also a major opportunity. As the New Climate Economy has demonstrated, the **new economic model** required to avoid harmful climate change will also drive rapid technological innovation, increase resource productivity, create jobs in new industries and deliver local environmental benefits which increase quality of life.

Action over the next decade will be vital, both to deliver the early emissions reductions needed to limit the growing stock of CO_2 in the atmosphere, and to make it possible to reach net-zero emissions from the energy and industrial systems by mid-century.

Achieving net-zero CO_2 emissions from the energy and industrial systems will require **rapid improvements in energy efficiency** combined with **the rapid decarbonization of power and the gradual electrification of as much of the economy as possible[3]**, mainly light-duty road transport, manufacturing, and a significant part of residential cooking, heating and cooling. In the Energy Transitions Commission's first report – *Better Energy, Greater Prosperity* – published in April 2017, we focused on these challenges. In particular, we demonstrated that dramatic reductions in the cost of renewable electricity generation and of energy storage options now make it possible to plan for cost-competitive power systems which are nearly entirely dependent on wind and solar (e.g. at 85-90%)[4].

However, to reach a fully decarbonized economy, we must also **reduce and eventually eliminate emissions from what we have labelled the "harder-to-abate" sectors in heavy industry (in particular cement, steel and chemicals) and heavy-duty transport (heavy-duty road transport, shipping and aviation)**. These sectors currently account for 10Gt (30%) of total global CO_2 emissions, but, on current trends, their emissions could account for 16Gt by 2050 and a growing share of remaining emissions as the rest of the economy decarbonizes[5]. To date, many national strategies – as set out in Nationally Determined Contributions (NDCs) to the Paris agreement – focus little attention on these sectors.

Over the last year, the ETC has therefore focused on defining a path to net-zero CO_2 emissions in the harder-to-abate sectors[6]. The good news is that **this is technically possible by mid-century at a cost to the economy of less than 0.5% of global GDP** with a minor impact on consumer living standards. The technologies required to achieve this decarbonization already exist: several still need to reach commercial viability; but we do not need to assume fundamental and currently unknown research breakthroughs to be confident that net-zero carbon emissions can be reached. Moreover, **the cost of decarbonization can be very significantly reduced** by making better use of carbon-intensive materials (through greater materials efficiency and recycling) and by constraining demand growth for carbon-intensive transport (through greater logistics efficiency and modal shift).

However, **this vital and technically possible transition will not be achieved unless policymakers, investors and businesses jointly take immediate and forceful action** to transform economic systems.

This report therefore describes in turn:
A. Why reaching net-zero CO_2 emissions from harder-to-abate sectors is technically and economically feasible (p.16);
B. How to manage the transition to net-zero CO_2 emissions in heavy industry and heavy-duty transport (p.28);
C. What policymakers, investors, businesses and consumers must do to accelerate change (p.32).

[1] IPCC (2018), *Global warming of 1.5˚C*

[2] If the world is to be net-zero CO_2 emissions by mid-century, negative emissions from the land use sector will therefore be needed during the transition period to compensate for remaining emissions from the energy and industrial systems in the 2050s.

[3] The pace of electrification will need to be adapted to the pace of power decarbonization, as explained on page 23.

[4] Energy Transitions Commission (2017), *Better Energy, Greater Prosperity*

[5] IEA (2017), *Energy Technology Perspectives*

[6] Throughout this report, the ETC presents quantifications whose aim is to identify likely orders of magnitude that can inform policy and investment, rather than develop a scenario and suggest that precise prediction is possible. In particular, the ETC's illustrative pathway assesses the implications for the energy system of an illustrative mix of supply-side and demand-side decarbonization solutions by mid-century.

A. MISSION POSSIBLE: REACHING NET-ZERO CO_2 EMISSIONS FROM HARDER-TO-ABATE SECTORS IS TECHNICALLY AND ECONOMICALLY FEASIBLE

It is technically possible to decarbonize all the harder-to-abate sectors by mid-century at a total cost of well less than 0.5% of global GDP. Three complementary sets of actions are required:

- **Limiting demand growth** – which can greatly reduce the cost of industrial decarbonization and, to a lower extent, of heavy-duty transport decarbonization;
- **Improving energy efficiency** – which can enable early progress in emissions reduction and reduce eventual decarbonization costs;
- **Applying decarbonization technologies**[7] – which will be essential to eventually achieving net-zero CO_2 emissions from the energy and industrial systems.

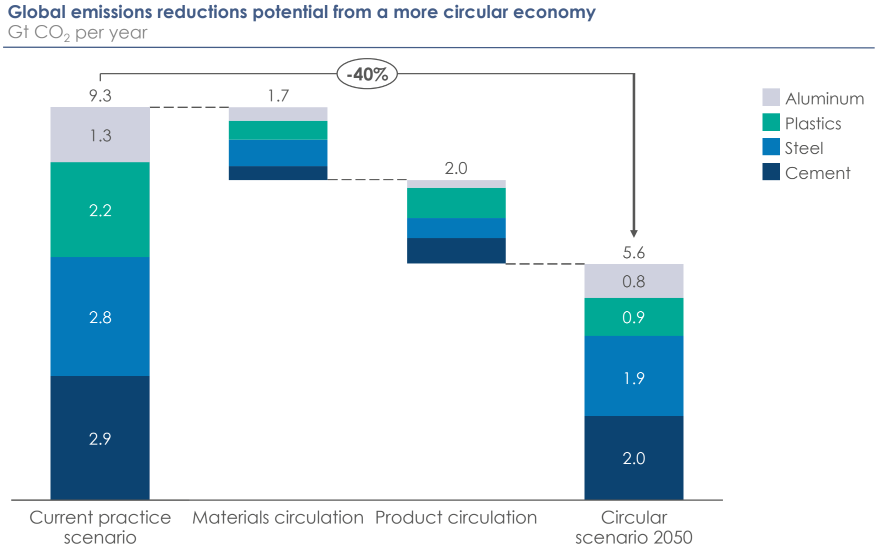
REACHING NET-ZERO CO_2 EMISSIONS FROM HEAVY INDUSTRY

Demand management through materials efficiency and circularity

A more circular economy can reduce CO_2 emissions from four major industry sectors (plastics, steel, aluminum and cement) by 40% globally, and by 56% in developed economies like Europe by 2050[8] [Exhibit 1]. This entails two major developments: (i) making better use of existing stocks of materials through greater and better recycling and reuse and (ii) reducing the materials requirements in key value chains (e.g. transport, buildings, consumer goods, etc.) through improved product design, longer product lifetime, and new service-based and sharing business models (e.g. car sharing).

- **Primary plastics production could be reduced by 56%** versus business as usual, through more extensive mechanical and chemical recycling, and reduced use of plastics in key value chains.
- **Primary steel production could be cut by 37%** versus business as usual levels, through reduced losses across the value chain, reduced downgrading in the recycling process, greater reuse of steel-based products, and a shift to new car-sharing systems.

A more circular economy can cut emissions from the harder-to-abate sectors in industry by 40% by 2050



Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 1

---

[7] We use the term "decarbonization technologies" to describe technologies that reduce anthropogenic carbon emissions by unit of product or service delivered through fuel/feedstock switch, process change or carbon capture. This does not entail a complete elimination of CO_2 use. First, the use of biomass or synthetic fuels can result in the release of CO_2 previously sequestered from the atmosphere through biomass growth or direct air capture. Second, CO_2 might still be embedded in the materials (e.g. in plastics). We exclude energy efficiency technologies from the scope of "decarbonization technologies", as they are considered separately.

[8] Material Economics analysis for the Energy Transitions Commission (2018)

- **Primary aluminum production could be cut by 40%** through the same mix of approaches applied in steel.
- In cement, recycling opportunities are more limited, but **improved building design could reduce total demand by 34%.**

Capturing these opportunities will require major changes to product design and to relationships between companies operating at different points in value chains. Strong policies are required to create incentives for these changes.

Energy efficiency

In the industrial sectors, opportunities for energy efficiency improvement within existing processes (through advanced production techniques or the application of digital technologies) can enable short-term emissions reductions. They are unlikely to exceed **15-20% of energy consumption,** but will be essential to reduce emissions from existing, long-lived industrial assets, in particular in developing countries.

Decarbonization technologies

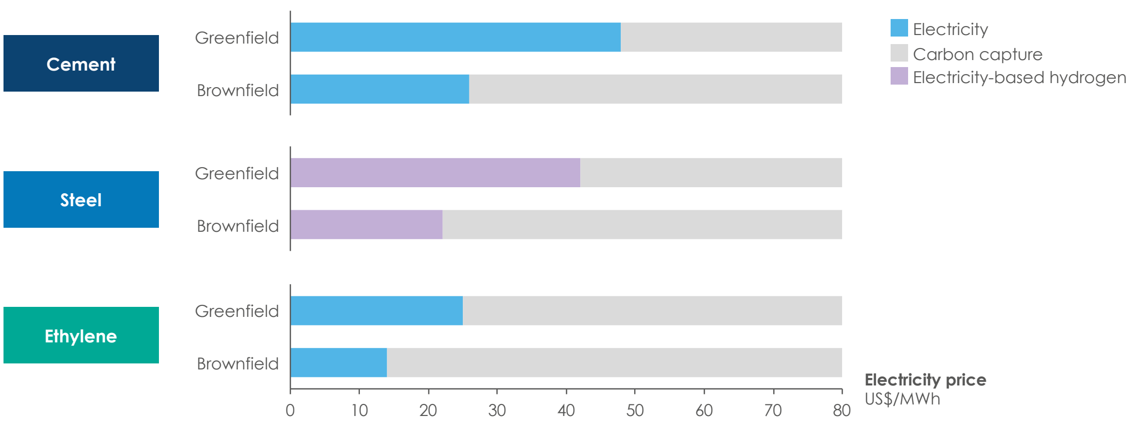
In each industrial sector, there are four main pathways to the decarbonization of production:

- Using **hydrogen as a heat source or as a reduction agent,** in the case of steel and chemicals production, with zero-carbon hydrogen derived from electrolysis (which will likely be the predominant route in the long term) or near-zero-carbon hydrogen derived from steam methane reforming (SMR) with carbon capture[9];
- **Direct electrification of industrial processes**, in particular the generation of high temperature heat;
- **The use of biomass as an energy source for heat production**, as a reduction agent in steel production or as a feedstock in particular for plastics production;
- **Carbon capture**, combined with either use or underground storage.

In each of the industrial sectors, the most cost-effective route to decarbonization will likely **vary by specific locations depending on local resources.** In particular, the choice between the electricity-based routes and either biomass or carbon capture options will be strongly influenced by the price at which zero-carbon electricity is available locally[10] [Exhibit 2].

Whether electricity-based decarbonization is cheaper than a carbon capture route will be strongly driven by the electricity price

Cheapest supply-side decarbonization route for primary production depending on electricity price
US$/MWh



Note: Biomass may be lower cost in some geographies but is not considered as a priority option due to limited availability
Source: McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 2

---

[9] Zero-carbon hydrogen could also theoretically come from biomethane reforming, although this route is unlikely to play a major role given constraints on sustainable biomass supply.

[10] Exhibit 2 only presents the trade-off between the electricity-based route and carbon capture at different electricity prices. The cost of carbon capture, when combined with underground storage, may vary depending on location. Biomass may be lower cost in some geographies, but is not considered as a priority option due to limited availability.

Regardless of the route, our analysis makes us confident that it will be possible to decarbonize the harder-to-abate industrial sectors at costs per tonne of CO_2 saved of US$60 or less for steel, US$130 or less in cement, and US$300 or less in the case of plastics (ethylene production).

REACHING NET-ZERO CO_2 EMISSIONS FROM HEAVY-DUTY TRANSPORT

Demand management through logistics efficiency and modal shifts

Opportunities to reduce demand growth are more limited in the transport sectors than in the industrial sectors, as freight transport is driven by global economic growth and passenger transport by higher mobility demand in emerging economies. Nonetheless, **a combination of greater logistics efficiency and modal shifts** – from trucking to rail and shipping, and from short-haul aviation to high-speed rail – **might still deliver up to 20% reduction in CO_2 emissions** [Exhibit 3].

Energy efficiency

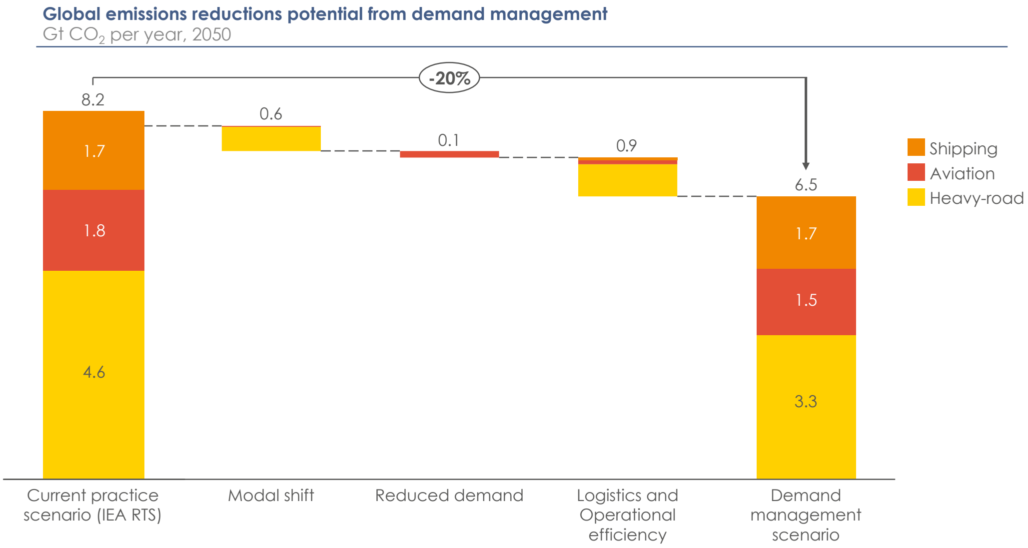
There are significant opportunities to **improve energy efficiency by 35-40% in the transport sectors** without radical changes in technology, and potentially more with technology breakthroughs. This potential will be particularly important in shipping and aviation, given the long lifetime of planes and ships: potential energy efficiency improvements in engine and vessel/airframe design could very significantly reduce the cost of switching to a new fuel.

Decarbonization technologies

The predominant route to full decarbonization and the costs incurred will likely be significantly different for heavy road transport than for shipping and aviation [Exhibit 4].

- **In heavy road transport, electric drivetrains will almost certainly eventually dominate** given their efficiency advantage over internal combustion engines, with energy storage either in battery or hydrogen form. Electric trucks are likely to become cost-competitive with diesel or gasoline vehicles during the 2020s. As a result, any role for biofuels and natural gas will and should be only transitional.

Demand management can cut emissions from the harder-to-abate sectors in transport by 20% by 2050



Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 3

- **In both shipping and aviation, electric engines using battery or hydrogen energy storage will likely play a role in short-distance transport.** But, unless and until there is a major breakthrough in battery density, **long-distance aviation will probably rely either on bio jet fuel or synthetic jet fuel, while long-distance shipping will likely use ammonia or (to a lower extent) biodiesels**[11] in existing engines. Since these fuels will likely be more expensive than existing fossil fuels, decarbonization costs could be US$115-230 per tonne for aviation and US$150-350 for shipping, although technological progress and economies of scale could reduce these costs over time.

MINIMAL COSTS TO THE ECONOMY AND TO CONSUMERS

Cost to the global economy

Estimated marginal costs of abatement, based on already proven decarbonization technologies, vary greatly by sector; but, in most of the harder-to abate sectors, they are significant [Exhibit 5].

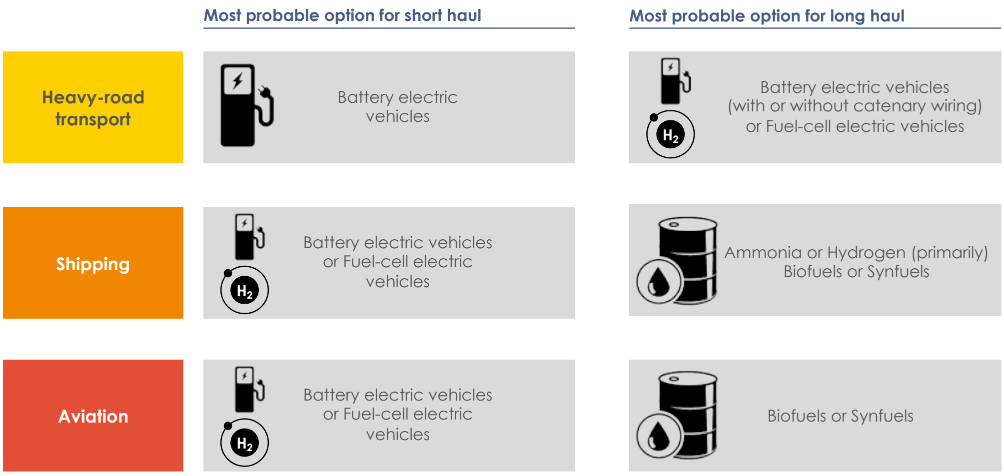
Even with these costs, and even if demand grows in line with business-as-usual forecasts, the maximum additional cost of decarbonized heavy industry and heavy-duty transport would only be **0.5% of global GDP by mid-century** [Exhibit 6]. The cost of running a net-zero-CO_2-emissions economy would be well less than 1% of GDP.

These costs are dominated by four sectors. Within industry, **cement** will be relatively costly to decarbonize because of process emissions, but so too will **plastics**, given the need to eliminate both production and end-of-life emissions. Within transport, **aviation and shipping** will be relatively costly to decarbonize, whereas shifting to battery electric or hydrogen fuel-cell trucks is likely to entail minimum costs given the inherent energy efficiency advantage of electric engines[12].

These decarbonization costs could be significantly reduced by three factors:

- **Lower renewable energy costs:** If zero-carbon electricity was available at US$20/MWh across the world (instead of US$40/MWh), decarbonizing heavy industry would cost 25% less. Similarly, the cost of decarbonizing shipping and aviation would fall by 55% if the additional cost of biofuels or synfuels could be brought down to US$0.30 per litre (instead of US$0.60

Electric drivetrains will dominate in heavy-road transport and short-haul shipping and aviation



	Most probable option for short haul	Most probable option for long haul
Heavy-road transport	Battery electric vehicles	Battery electric vehicles (with or without catenary wiring) or Fuel-cell electric vehicles
Shipping	Battery electric vehicles or Fuel-cell electric vehicles	Ammonia or Hydrogen (primarily) Biofuels or Synfuels
Aviation	Battery electric vehicles or Fuel-cell electric vehicles	Biofuels or Synfuels

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 4

---

[11] Given constraints on the sustainable supply of biomass, bioenergy use should indeed be limited in sectors where alternative low-carbon fuels exist.

[12] BEVs and FCEVs will, however, demand infrastructure investment addressed later in this report.

per litre). Overall, lower renewable energy prices could reduce the total cost to the global economy from 0.45% to 0.24% of global GDP.

- **Demand management:** Greater recycling and reuse of materials within a more circular economy, combined with logistics efficiency and modal shifts in transport sectors, could reduce the decarbonization costs for harder-to-abate sectors by 40-45%, bringing them down to 0.15-0.25% of global GDP.
- **Future technological development:** History tells us that learning curve and economies of scale effects often reduce technology costs by more than anticipated, and that new technologies emerge which could not be anticipated in advance. If this occurred in the future, the cost of decarbonization could be dramatically reduced. For instance, the cost of decarbonizing cement could be far lower if learning curve and scale bring down the cost of carbon capture, and the cost of decarbonizing aviation and shipping would be far lower if dramatic battery density improvements allowed a greater role for electrification.

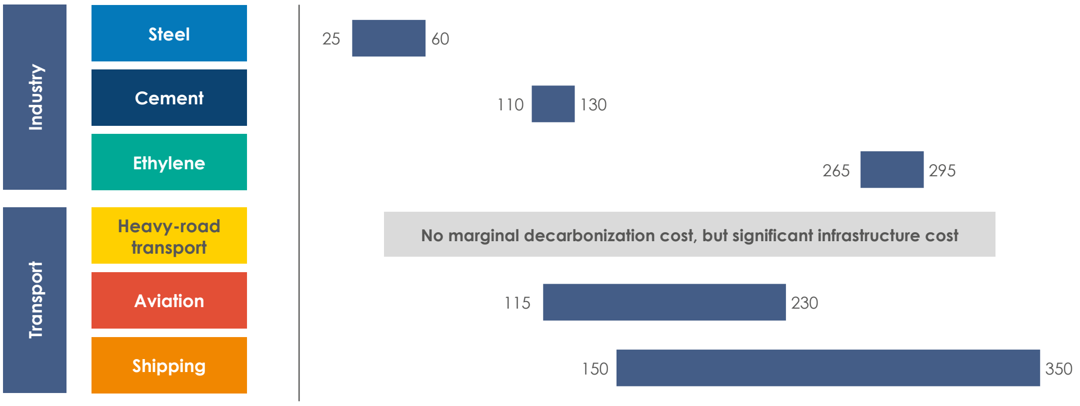
Analysis of total capital investment needs further confirms that **decarbonization is achievable at an affordable cost.**

- In the **industrial sectors**, total incremental capital investment from 2015 to 2050 could amount to US$5.5 to US$8.4 trillion[13], representing about 0.1% of aggregate GDP over that period and **less than 0.5% of probable global savings and investments.**
- In **heavy-road transport**, European Commission estimates suggest that the investments required for recharging or hydrogen refueling infrastructure would be **less than 5% of business-as-usual investment in transport infrastructure**[14].
- In the **aviation and shipping sectors**, if decarbonization is achieved primarily via the use of zero-carbon fuels in existing engines, **no major incremental capital investment would be needed**.

Investments in infrastructure and industrial assets required to transition heavy industry and heavy-duty transport to net-zero CO_2 emissions are therefore not large compared to global savings and investment, and **there is no reason to believe that shortage of finance will constrain the path to net-zero CO_2 emissions if adapted financing mechanisms are developed**.

Costs of supply-side decarbonization vary greatly by sectors

Supply-side abatement costs by sector in low-cost and high-cost scenarios
US$/tonne CO_2



Source: Industry: McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* / Shipping: UMAS analysis for the Energy Transitions Commission (2018) / Other transport sectors: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 5

---

[13] McKinsey and Company (2018), *Decarbonization of the industrial sectors: the next frontier*

[14] European Environment Agency (2018)

Cost to end consumers

The impact of decarbonization on prices faced by end consumers will vary by sector, but will overall be small [Exhibit 7]. Decarbonizing steel is unlikely to add more than US$180 to the price of a car, while using zero-emissions plastics would increase the price of a litre of soft drinks by less than US$0.01. **The most significant cost to end consumer would be in aviation:** if biofuels or synthetic fuels remain significantly more expensive than conventional jet fuel, zero-carbon international flights may require a 10-20% increase in ticket prices. Since expenditure on international aviation accounts for less than 3% of global household consumption, however, the total impact of this on living standards would still be very slight.

Intermediate product costs

Even if the impact on end-product prices is small, **price implications at the intermediate product level could be significant.** For instance, producing zero-carbon steel may cost 20% more per tonne than conventional steel. Some companies may find it difficult to finance upfront investments in low-carbon technologies, in particular if this entails writing off existing assets before the end of their useful life. In addition, where intermediate products are internationally traded, unilateral imposition of domestic carbon prices or regulation could produce harmful competitiveness effects, and international carbon prices or regulations are therefore ideal [Exhibit 8].

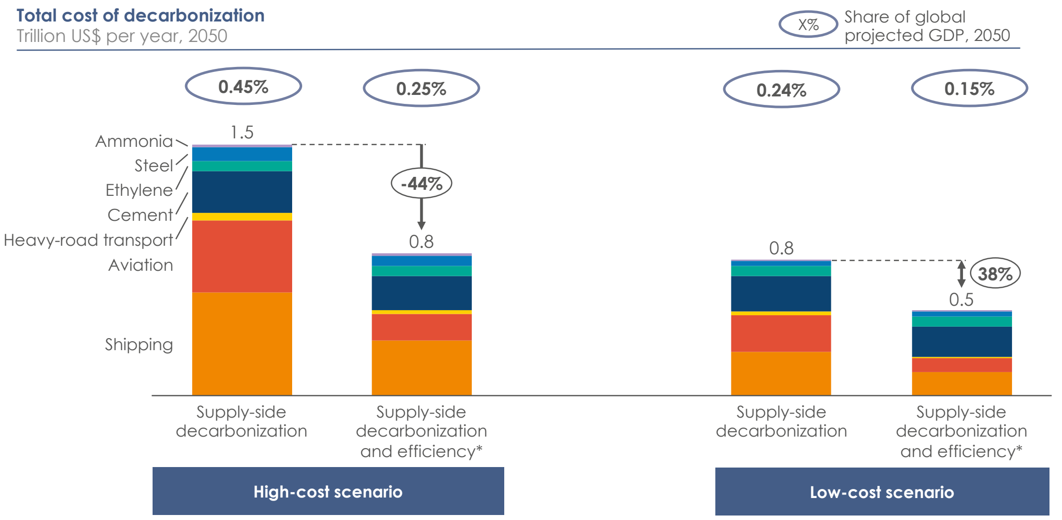
Key implications for policymakers:

- Carbon prices will be required and can be withstood by consumers, but should be carefully designed to avoid international competitiveness effects.
- Harder-to-abate sectors should benefit from public support to innovation and investment.
- Driving energy efficiency, materials efficiency and circularity, and demand management in transport – alongside decarbonization technologies – is essential to reduce the overall cost to the economy.

A PORTFOLIO OF SUPPLY-SIDE DECARBONIZATION TECHNOLOGIES

It is neither possible nor necessary to determine in advance the precise balance between the four main routes to supply-side decarbonization – electricity, bioenergy, carbon capture, and hydrogen – that will be needed to achieve net-zero CO_2 emissions from harder-to-abate sectors.

Decarbonizing harder-to-abate sectors would cost significantly less if pursuing energy efficiency improvement and demand management opportunities



Note: The term "efficiency" covers energy efficiency, materials efficiency, materials circularity, and demand management in transport.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) based on McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* and Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 6

The optimal balance will vary by region in light of different natural resource endowments (solar, wind and hydro resources; sustainable biomass resources; availability of underground carbon storage) and will evolve over time following uncertain technological and cost trends.

Public policy should therefore focus primarily on creating strong incentives for decarbonization, while leaving it to markets to determine the most cost-effective route forward per sector. But it is possible to **define some almost certain features of the path to net-zero CO_2 emissions,** which carry implications for public policy and private investment priorities.

A major role for hydrogen

Hydrogen is highly likely to play a major, cost-effective role in the decarbonization of several of the harder-to-abate sectors, and may also be important in residential heat and flexibility provision in the power system. Achieving a net-zero-CO_2-emissions economy will therefore require **an increase in global hydrogen production from 60 Mt per annum today to something like 425-650 Mt by mid-century**, even if hydrogen fuel-cell vehicles play only a small role in the light-duty transport sector.

It is therefore essential to foster the large-scale and cost-effective production of zero-carbon hydrogen via one of three routes:

- **Electrolysis using zero-carbon electricity:** This will be increasingly cost-effective as renewable electricity prices fall and as electrolysis equipment costs decline. If 50% of future hydrogen demand were met by electrolysis, the total volume of electrolysis production would increase 100 times from today's level creating enormous potential for cost reduction through economies of scale and learning curve effects.
- **The application of carbon capture to steam methane reforming, and the subsequent storage or use of the captured CO_2:** This may be one of the most cost-effective forms of carbon capture given the high purity of the CO_2 stream produced from the chemical reaction, if energy inputs to the process are electrified. For hydrogen from SMR plus CCS to really be near-zero-carbon, however, carbon leakage in the capture process, as well as methane emissions throughout the gas value chain, would have to be brought down to a minimum. If 50% of future hydrogen demand were met using SMR with carbon capture on chemical reaction, the related carbon sequestration needs would amount to 2-3Gt.

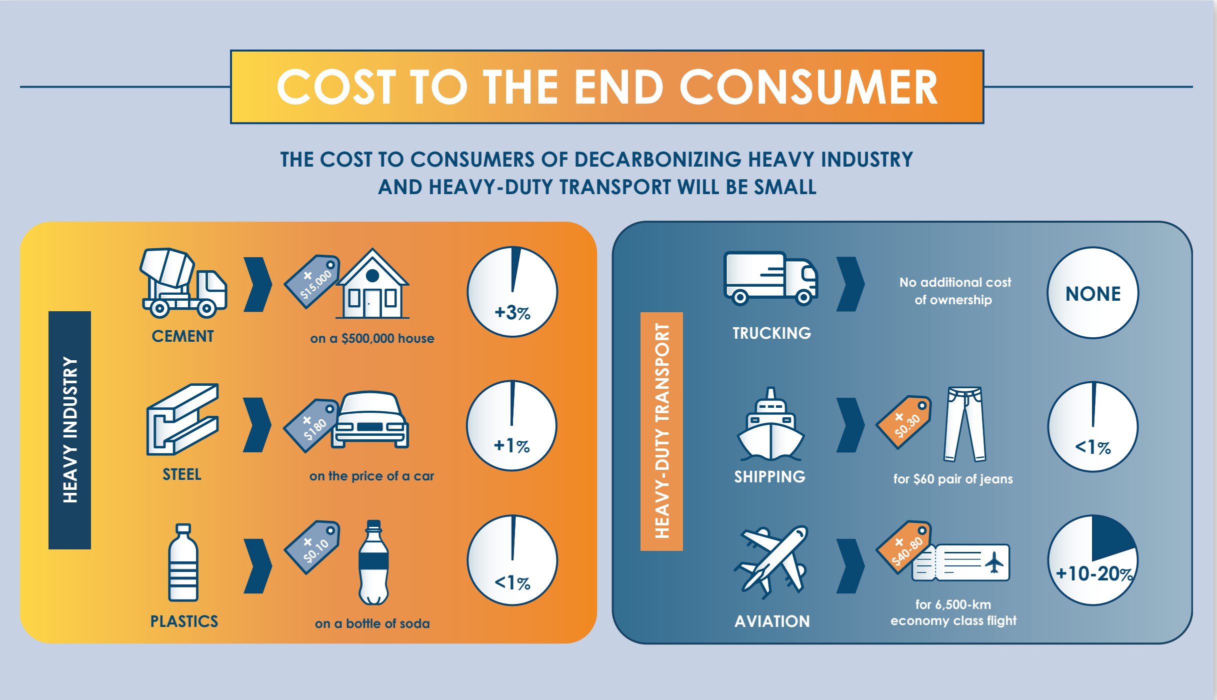


Exhibit 7

- **Biomethane reforming:** SMR could also be made zero-carbon if biogas were used rather than natural gas, but is unlikely to play a major role, given other higher priority demands on limited sustainable biomass resources.

Key implications for policymakers:

- Electrolysis cost reduction is a key innovation priority, targeting capital costs of US$250/kW.
- CCS infrastructure needs to be developed to enable production of near-zero-carbon hydrogen from SMR plus CCS.
- Further reduction in fuel-cell costs and hydrogen tanks are also key priorities.
- International trade in hydrogen or ammonia is likely to play a key role, potentially requiring significant infrastructure investment.

Vital and massive electrification

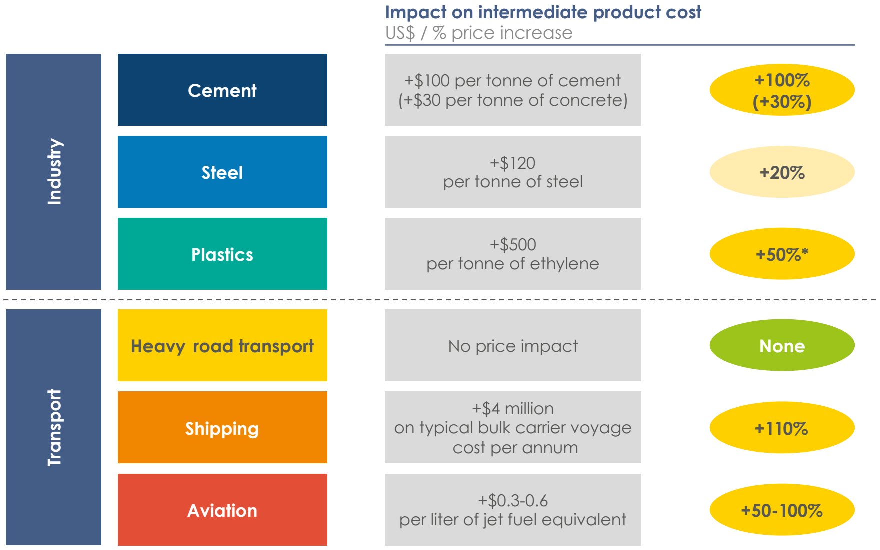
In any feasible path to a net-zero-carbon economy, electricity's share of total final energy demand will rise from today's 20% to over 60% by 2060. As a result, total global electricity generation must grow from about 20,000 TWh today to 85-115,000 TWh by mid-century while switching for high-carbon to zero-carbon power sources.

Strong policies to improve energy efficiency, increase materials efficiency and circularity, and manage demand for heavy-duty transport could reduce this requirement by a useful 25% – or more in developed economies. Given the scale of the investment challenge, it is vital to maximize these opportunities.

But **a very rapid expansion of zero-carbon electricity will still be required.** Our analysis suggests that this expansion, while challenging, is technically and economically feasible:

- **Renewable electricity is increasingly cost-competitive with fossil-fuel-based power.** It will be possible, within 15 years, to run electricity systems in which 85-90% of power demand is met by a mix of wind and solar, combined with batteries for short-term back-up and with the remaining 10-15% met by dispatchable peak generation capacity (e.g. dispatchable hydro, biomass or fossil fuels with carbon capture). Dramatic reductions in the cost of renewable electricity and of batteries will make it possible to operate such a power system at an all-in cost of US$55/MWh in most geographies, and below US$35/MWh in the most favorable locations by 2035, especially if appropriate market design is in place[15] [Exhibit 9]. This is lower than today's conventional electricity costs.

Decarbonization of the harder-to-abate sectors would have a significant impact on the price of intermediate products



		Impact on intermediate product cost US$ / % price increase	
Industry	Cement	+$100 per tonne of cement (+$30 per tonne of concrete)	+100% (+30%)
	Steel	+$120 per tonne of steel	+20%
	Plastics	+$500 per tonne of ethylene	+50%*
Transport	Heavy road transport	No price impact	None
	Shipping	+$4 million on typical bulk carrier voyage cost per annum	+110%
	Aviation	+$0.3-0.6 per liter of jet fuel equivalent	+50-100%

*Assuming an initial price of US$1000/tonne for ethylene, although the price of ethylene is very volatile.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 8

---

[15] SYSTEMIQ analysis for the Energy Transitions Commission (2018), based on Climate Policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

- **At the aggregate global level, there is easily sufficient land to support renewable electricity generation on the scale required, but with large regional variations.** In favorable geographies like north-west China, mid-west US and the Middle East, renewable electricity could be produced at low cost in quantities exceeding local demand. But less favorable locations, with high population density or less favorable renewable resources, may need to draw on zero-carbon power sources that are less land-intensive and have higher capacity factors (e.g. nuclear or fossil fuels with carbon capture) or on imports of power (via long-distance transmission lines or in the form of hydrogen or ammonia).
- **A rapid increase in the pace of renewables deployment is needed.** To meet power demand of 100,000 TWh by 2050 with 90% renewable power, the deployment rate of solar and wind would need to increase by more than 10% per year (i.e. double every 7 years). This will also require a strengthening of power grids.

If electrification occurs before adequate power decarbonization, with electricity still produced mainly from fossil fuels, CO_2 emissions could increase in the short term. Our analysis suggests that, in developed economies where the carbon intensity of electricity is below 750gCO_2 per kWh, this danger is limited both in surface transport and in many industrial applications, but much lower carbon intensities are required before a switch to hydrogen, ammonia and synfuels, or to electric heating, will reduce emissions. By contrast, immediate electrification in some coal-dependent developing economies – for instance in India where the carbon intensity of electricity is above 1000gCO_2 per kWh – could result in significant carbon emissions. **Rapid progress towards power decarbonization is therefore essential, combined with careful coordination of the pace of power decarbonization and electrification.**

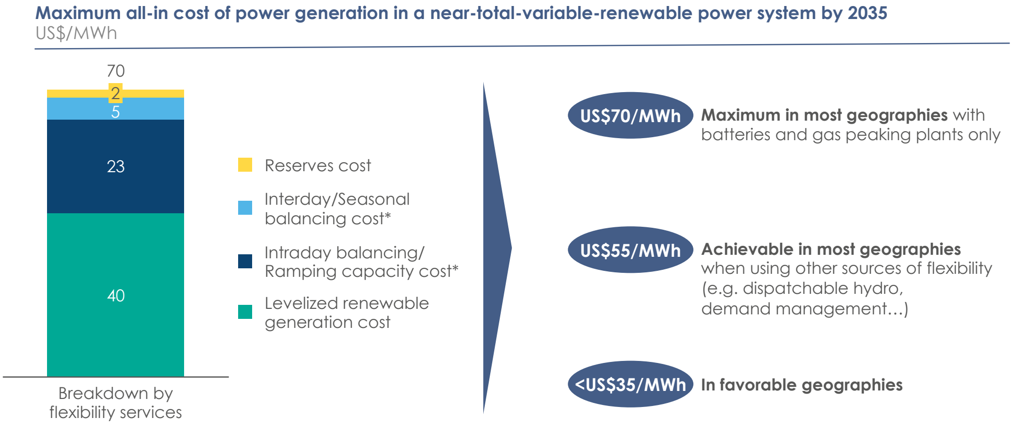
Key implications for policymakers:

- Power decarbonization policies should plan for very significant increases in power demand, accelerating renewable power deployment.
- National decarbonization plans, as described for instance in the NDCs, should set out an integrated vision for power decarbonization and electrification, ensuring that increased power demand will be met by zero-carbon power[16].

A prioritized and tightly regulated use of biomass

Biomass – whether used as a source of energy for heat production, as a reduction agent in steel production, or as a feedstock in chemicals production – could in principle play a role in the

Low-cost, low-carbon electricity is likely to be available in most geographies, with electricity below $35/MWh produced in most favorable locations



Note: Based on German resource and load profile / *Considers only two flexibility technologies: CCGT & Lithium-ion batteries / Levelized renewable energy generation cost includes all energy potentially produced, including amount curtailed or stored/shifted.
Source: Adapted from Climate Policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

Exhibit 9

---

[16] Or in the NECPs of EU member states.

decarbonization of each of the harder-to-abate sectors. When used in power, heat or industry, it could be combined with carbon capture, and potentially generate negative emissions. Timber could also offer an alternative low-carbon building material.

However, **the use of biomass must be constrained by limits on the available supply of truly sustainable biomass,** given competition for land use. This requires that biomass comes from sources or land that would not otherwise provide food or carbon storage, and that its use is compatible with biodiversity and ecosystem conservation imperatives, in particular, the need to avoid deforestation. Moreover, bioenergy typically produces less than 1% of the energy that solar power can produce per hectare, making electricity-based solutions more effective where available and technically feasible.

Estimates of sustainable biomass supply vary widely, but analysis suggests that **70EJ per annum of sustainable biomass for energy and feedstock would certainly be available by mid-century,** when accounting for 10-15EJ from municipal waste, 46-95EJ from agricultural wastes and processing residues, and 15-30EJ of wood harvesting residues[17]. This estimate excludes any biomass production from dedicated energy crops whether in the form of oil plants (e.g. soya) or forest crops (e.g. fast-growing willow or poplar).

The key uncertainties relate to the supply of lignocellulosic material which could be sustainably harvested from forest crops (through a large-scale reforestation program, focused on degraded land in tropical countries), as well as to the availability of winter cover crops and algae-based products. Several factors could decrease the amount of sustainable biomass available for energy, in particular reduced crop yields due to climate change.

A sustainable supply of 70EJ (or even 100EJ) would be insufficient to meet all the potential sectoral claims on biomass from the energy, industry and transport sectors. **Its use must therefore be focused on sectors where alternative decarbonization routes are least available:**

- **The highest priority sector appears to be aviation,** where a zero-carbon equivalent of jet fuel is essential to decarbonize long-haul flights. A maximum of 42EJ of biomass would be required for complete decarbonization. This could be lowered if synfuels are used, as well as through energy efficiency and demand management.
- **The second highest priority sector is likely to be plastics,** where bio-feedstock is essential to compensate for end-of-life emissions, unless end-of-life plastics are recycled or securely landfilled. Bio-feedstock could not entirely substitute for fossil fuels: 28EJ of biomass supply would be required to cover only 30% of feedstock needs. The strategy for plastics decarbonization must therefore combine an as complete as possible shift towards a circular model, with carbon sequestration – in the form of solid plastics placed in permanent, secure and leak-proof storage – and an as limited as possible use of bio-feedstock to compensate for inevitable losses in the value chain.
- If not constrained by tight sustainability criteria, however, **the biggest demands for biomass** could emerge not in the harder-to-abate sectors considered in this report, but **in residential heating and in electricity generation** (where it could create negative emissions if combined with carbon capture and sequestration)[18]. It is therefore essential to minimize this need, especially in the power sector, by driving maximum progress of renewables, energy storage technologies and smart demand management.
- By contrast, **biofuels/biomass are not essential to drive the decarbonization of heavy road transport, shipping, and other industrial sectors,** where other routes to decarbonization are available.

When used, **biomass, biogas and biofuels are highly likely to be more expensive than fossil fuels**. Carbon prices and regulations will therefore be essential and appropriate to make them economic. Biomass-based solutions may also be more expensive than alternative decarbonization routes like electrification or hydrogen in some applications, where they would then naturally be driven out of the market.

---

[17] IEA (2017), Technology roadmap: *Delivering Sustainable Bioenergy*

[18] The ETC's illustrative pathway suggests up to 28EJ of biomass input if biogas plays a significant role in residential heating, and as much as 34EJ if biomass-based power generation provides only 4% of global electricity supply to help meet peak generation needs.

Key implications for policymakers:

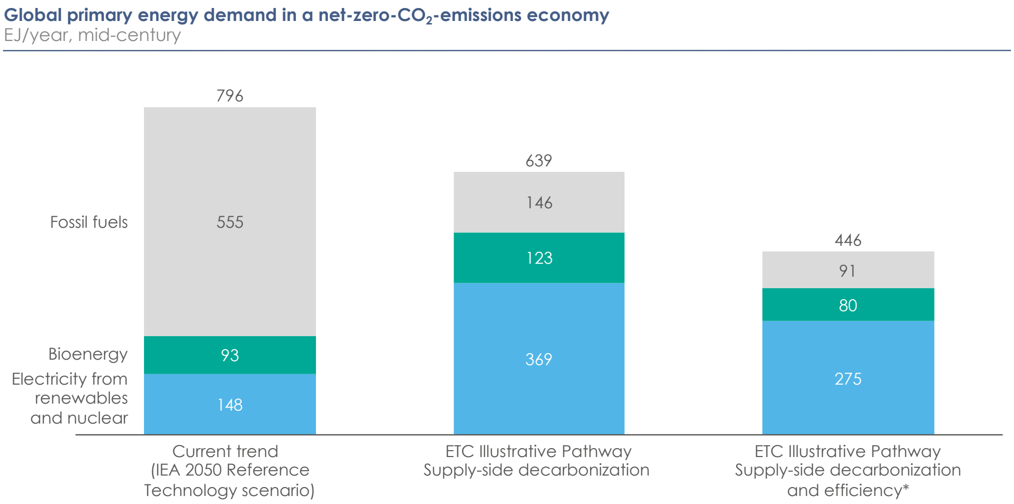
- Tight regulations on biomass sustainability are vital. This will likely exclude energy crops, which often compete with agriculture and ecosystem services, with some local exceptions like winter cover crops in temperate climates.
- The development and cost reduction of truly sustainable bio jet fuels for aviation and bio-feedstock for plastics is a high priority for innovation support.
- Public support to biomass development should transition away from non-priority sectors to high-priority sectors, except when local conditions provide a clearly sustainable supply for a larger portfolio of applications.
- It is essential to develop non-biomass-based peak generation capacity and energy storage options for power and residential heating.
- Improved efficiency in the biorefinery process is key to enable greater bioenergy and bio-feedstock use from a given level of primary supply.

An essential, but limited, role for carbon capture

Dramatic reductions in the cost of renewables over the last 10 years mean that carbon capture is **likely to play a relatively small role in the power sector,** potentially providing dispatchable low-carbon electricity to complement variable renewables. But achieving net-zero CO_2 emissions in the harder-to-abate industrial sectors will probably be impossible, and certainly more expensive, without a role for carbon capture and sequestration: it is likely to be the **only route to achieve total decarbonization of cement production** (unless a breakthrough in cement chemistries eliminates process emissions) and, in some locations, is likely to be the most cost-effective route to decarbonization of steel, chemicals, and hydrogen production.

But there is **no current consensus about the necessary scale of carbon capture.** Several scenarios for achieving the Paris climate objectives assume that, by 2100, carbon capture and sequestration could account for 18Gt per annum of emission reductions (or more), with its application to biomass-based processes producing significant negative emissions. There are concerns that these huge volume assumptions are used to justify continued large-scale fossil fuel production use. In addition, fears are sometimes expressed that underground carbon storage is unsafe or not permanently effective.

Electricity from renewables and nuclear could account for ~60% of primary energy demand



Note: The term "efficiency" covers energy efficiency, materials efficiency, materials circularity, and demand management in transport
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018); IEA (2017), *Energy Technology Perspectives*

Exhibit 10

It is therefore vital to achieve some consensus around the required role for carbon capture, as well as the respective roles of carbon storage and carbon use in CO_2-based products. The ETC's judgement is that:

- A net-zero-carbon economy can be achieved without the very large quantities of carbon capture (e.g. 18Gt per year) assumed in some models, but **a more modest scale of carbon capture (e.g. around 5-8Gt per year)** is highly likely to be a necessary and cost-effective part of an overall decarbonization strategy.
- **Around 1-2Gt of the CO_2 captured annually could then probably be used in CO_2-based products that enable long-term storage,** with the greatest opportunities lying in concrete, aggregates and carbon fiber. This implies a potential synergy between carbon capture in cement plants and use within concrete production.
- **Some storage is however likely to be required** – 3-7Gt of CO_2 storage per annum – and best expert opinion – including from the IPCC – suggests that carbon storage can be safe and adequately secure provided it is effectively regulated[19].
- **Achieving these volumes of carbon capture by mid-century would require a step change in the pace of deployment,** which will not occur unless governments play an active role in (i) building social acceptance of carbon transport and storage on the back of independent scientific evidence of their safety, (ii) making carbon capture and storage economically viable through carbon pricing, and (iii) planning and regulating the deployment of carbon transport and storage infrastructure. These conditions are not yet met today. Immediate and forceful collective action from policymakers and industries is needed to meet them in the next 10 years.

Key implications for policymakers:

- Commercial-scale carbon capture and carbon use technologies, in particular in the cement-concrete value chain, should be a key innovation priority.
- A carbon price will be vital to support any form of carbon capture and sequestration.
- For underground carbon storage to be part of the portfolio of solutions, governments need to:
  - Regulate carbon transport and storage sufficiently tightly to achieve social acceptance;
  - Plan and support the deployment of carbon transport and storage infrastructure.
- If underground carbon storage is not developed, governments would need to:
  - Plan for an even faster deployment of renewables and electricity-based solutions for industry;
  - Bring to market low-carbon materials to substitute for cement;
  - Bring to market carbon dioxide destruction technologies to treat remaining carbon emissions.

Optimal supply-side path to a net-zero-carbon economy

The optimal path to a net-zero-carbon economy will require use of all the decarbonization levers. Within the overall balance, **electrification will play the greatest role, accounting for roughly 65% of final energy demand by mid-century and with electricity also used to produce a significant share of hydrogen.** Around 85-90% of electricity will in turn be derived from renewables or other zero-carbon sources, with no more than 10-15% from biomass or fossil fuels with carbon capture. Primary energy demand would be significantly lower if pursuing opportunities for energy efficiency, materials efficiency/circularity and demand management in transport. [Exhibit 10]

The optimal balance will however vary significantly by location, given wide variations in relevant natural resource endowments:

- **Large differences in solar and wind resources** mean that, while some countries could meet well over 65% of final energy demand from locally produced cheap renewable electricity, others will need to rely on other zero-carbon power sources or on power imports. The cost of renewable generation will also vary widely.
- **Biomass resources per capita and costs also vary greatly by region,** which will likely trigger international trade of biorefined products for aviation and plastics, and very different levels of biomass use by geography in other (localized) sectors of the economy, such as heat and power.
- **In the case of underground carbon storage, huge regional variations in the known scale of available storage capacity in part reflect limitations to current knowledge in various geographies** (in particular Africa). But, once a comprehensive survey is complete, available storage capacity is likely to vary greatly between regions.

---

[19] IPCC (2005), *Carbon Dioxide Capture and Storage*; IPCC (2014), *Mitigation of climate change*

B. THE PATH TO NET-ZERO: MANAGING THE TRANSITION TO NET-ZERO-CO_2-EMISSIONS INDUSTRY AND TRANSPORT

Our analysis shows that all harder-to-abate sectors could achieve net-zero CO_2 emissions by mid-century at low cost to the global economy and to the end consumer. But the path to net-zero matters as well as the end point. It is therefore essential to:

- **Recognize the complexities which determine the feasible pace of transition;**
- **Reduce the scale of the decarbonization challenge through energy efficiency improvement and demand management;**
- **Determine an appropriate role for transitional solutions,** in particular unabated gas as a transition fuel and offset purchase as a transitional abatement strategy.

TECHNICAL, ECONOMIC AND INSTITUTIONAL CHALLENGES BY SECTOR

Three categories of transition challenges are important: technical, economic and institutional challenges.

Technical challenges:

- **Many of the relevant technologies are not yet commercially ready.** While electric trucks could be cost-competitive by 2030, cement kiln electrification may not be commercially ready till a decade later. Hydrogen-based industrial processes also require significant development. **Accelerating development and scaling deployment of key technologies is therefore vital.**
- **Reaching zero lifecycle emissions from plastics constitutes a significant challenge,** as it requires eliminating end-of-life as well as production emissions. Limits to sustainable biomass supply will likely make it impossible to entirely substitute fossil fuels by bio-feedstock. It will therefore be essential to manage the existing and future fossil-fuels-based plastics stock through **mechanical and chemical recycling, as well as secured end-of-life storage for solid plastic.**
- In most cases, **carbon capture technologies will capture about 80-90% of the CO_2 stream,** with the remaining 10-20% still released into the atmosphere. The development of capture technologies with higher capture rates should be a priority, but some level of negative emissions from land use or BECCS will probably be required to compensate for these residual emissions.

Economic challenges:

- Since most decarbonization routes will entail a net cost, **market forces alone will not drive progress;** and strong policies – combining regulations and support – must create incentives for rapid decarbonization.
- A particular difficulty is to **create strong enough financial incentives today** to trigger the search for optimal decarbonization pathways **without imposing a disproportionate burden** on sectors for which full decarbonization technologies are not yet available.
- **In heavy industry, very long asset lives will delay the deployment of new technologies,** unless there are strong policy incentives for early asset write-offs. In steel, for instance, a switch from blast furnace reduction to hydrogen-based direct reduction may require scrapping of existing plant before end of useful life.
- **High upfront investment costs may act as a barrier to progress** even where carbon prices make a shift to zero-carbon technologies in theory economic, in particular in sectors or companies facing low margins. Direct public investment support (for instance through loan guarantees or repayable advances) may therefore be required.
- Although beneficial on an aggregate scale, the transition to a zero-carbon economy will inevitably create winners and losers, impacting local economic development and employment in some regions. Moreover, the impact on end consumer prices, although limited, might have a greater impact on lower-income households, especially in developing countries. **Policy should anticipate and compensate for these distributional effects through just transition strategies.**

Institutional challenges:

- **Current innovation systems are poorly connected,** with little coordination between public and private R&D, and a lack of international forums to carry an innovation agenda focused on harder-to-abate sectors.

- In sectors exposed to international competition, **domestic carbon prices or regulations could produce harmful effects on competitiveness and movement of production location.** This implies the need for international policy coordination, or alternatively the use of downstream rather than upstream taxes, border tax adjustments, or free allocation within emissions trading schemes or compensation schemes (combined with increasingly ambitious benchmark technology standards).
- **Some industries, like shipping or construction, are so fragmented that incentives are split.** Even cost-effective efficiency technologies and circular practices are not easily deployed. Innovative policy should strengthen incentives, for instance regulations imposed at port level or obligations for materials recycling.

Implications for industry and heavy-duty transport

Given these technical, economic and institutional barriers, transition paths will vary significantly by sector:

- **In the industrial sectors, progress to full decarbonization will inevitably take several decades.** Public policy must therefore provide strong incentives for long-term change, established well in advance, whether via carbon pricing, regulations, or financial support. Proactive action from industries over the next decade would reduce costs of subsequent decarbonization efforts.
- In the **transport sectors**, transition paths are less complicated:
  - In heavy road transport, considerably shorter asset lives could allow **rapid decarbonization of truck fleets** (e.g. over 15 years rather than 30) once alternative vehicles (whether battery electric or hydrogen fuel-cell) become cost-competitive at point of new purchase.
  - **In long-distance shipping and aviation**, the fact that the likely route to full decarbonization entails the **use of zero-carbon fuels within existing engines** means that the longevity of shipping and aviation engines is not a constraint on the pace of transition, which will instead be determined by the relative costs of zero-carbon versus conventional fuels[20].

REDUCING THE DECARBONIZATION CHALLENGE THROUGH EFFICIENCY IMPROVEMENT AND DEMAND MANAGEMENT

Given the time required to achieve supply-side decarbonization, especially in industry, **efficiency improvement and demand side reductions are essential not only to deliver short-term emissions reductions, but to decrease the cost of long-term decarbonization** by reducing the volume of primary industrial production or mobility services to which supply-side decarbonization technologies need to be applied [Exhibit 11].

Energy efficiency improvements will be particularly important in shipping and aviation, where lower fuel consumption per kilometer could reduce the penalty cost of using zero-carbon fuels and reduce claims on a limited sustainable supply of biofuels.

The potential for demand management differs between the transport and industrial sectors:

- **In the transport sectors, the biggest potential lies in modal shift** from road to rail for freight and from plane to high-speed rail for short-haul passenger trips, as well as logistics efficiency, but total available potential is unlikely to exceed 20%.
- **In industry, however, greater materials efficiency and circularity could reduce CO_2 emissions by 40% globally** – and by more than 55% in developed economies – by 2050, with greatest opportunities lying in the plastics and metals supply chains.

Most of the technologies required to achieve this demand-side reduction potential are already available. Their deployment at scale will likely drive cost reductions, for instance in recycling industries. But **major changes in product design, industry practice and regulation will be essential** to seize the opportunity.

- **Improved materials circularity cannot occur without more coordination between different companies along the manufacturing, automotive and buildings value chains.** High-quality recycling indeed requires new approaches to product design as well as to end-of-life dismantling and materials separation, which will not occur unless required

---

[20] Although some retrofitting will be needed in shipping to adapt fuel handling and storage equipment to the use of ammonia or hydrogen.

by regulation, in particular through extended producer responsibility.

- **Improved logistics efficiency will also rely on greater coordination between companies,** facilitated by big data computing, while **driving modal shifts will require improving public transport infrastructure,** in particular railways, and creating financial incentives to change for both passenger and freight.

LEVERAGING TRANSITIONAL SOLUTIONS: GAS AND OFFSETS

The appropriate use of these solutions will vary by sector depending on when the end-state solution will be commercially available. Transitional solutions are therefore **particularly appropriate in heavy industry, where many zero-carbon solutions are not yet market ready;** whereas they are likely to play **a smaller role in transport**, given the relative ease of transition to either electric vehicles (in trucking) or biofuels and synfuels (in shipping and aviation).

Gas as a transition fuel

Since **gas combustion can produce about 50% less emissions than coal** – if and only if methane emissions are tightly controlled –, switching from coal to gas within otherwise largely unchanged production processes/equipment could in principle achieve significant short-term emissions reductions. **Switching from oil to gas would deliver more limited reductions (5-20%).** However, the climate benefits can be reduced significantly or even disappear if methane leakages in the gas value chain are above 1-3% (depending on applications).

- **In industry, there could be significant potential to switch from coal to gas,** in industries where coal is still used as a heat source (e.g. cement) and in countries where coal is still used as a feedstock in chemicals production (e.g. China). However, this potential could be constrained by limited domestic gas supplies, particularly in China and India.
- **In transport, the optimal role of gas is more limited.** There may be a limited transition role for CNG in trucking and LNG in shipping, if these technologies can be retrofitted on existing vehicles now and replaced, respectively, by electric vehicles and by zero-carbon fuels in the next 10-15 years and the related infrastructure repurposed or written off[21].

The optimal path to net-zero CO_2 emissions might entail a roughly flat or even slightly rising gas production by 2040, provided that:

- **Strong policies ensure that methane emissions (from flaring, venting and leaking) across the whole production and use chain reaches sufficiently low levels** (0.2% for upstream leakage and below 1% when jointly considering upstream, midstream and downstream emissions) prior to any expansion of gas use;
- Pre-announced strategies ensure that gas-using sectors will eventually:
    - **Switch to biogas** – while taking into account constraints on sustainable biomass availability which, in turn, will put pressure on prices;
    - **Apply carbon capture and sequestration** to existing gas-fired production processes;
    - **Move beyond natural gas to electricity, hydrogen, or bioenergy,** which implies the need to plan in advance for either writing off gas infrastructure and equipment prior to end of useful life or repurposing them for hydrogen.

Indeed, it is clear that **unabated gas consumption would need to rapidly fall beyond 2040** to be compatible with the Paris objectives.

The appropriate role of offsets

Since the marginal cost of decarbonization varies greatly among the harder-to-abate sectors and across the whole economy, **the early stages of sectoral paths to net-zero could allow for the purchase of offsets from other sectors of the economy or from the land use sector**[22]. These schemes (sometimes labelled "market-based measures") will also create incentives to search for longer-term decarbonization solutions by facing sectors with a marginal price of carbon.

In addition, the purchase of offsets from the land use sector could provide a valuable source of financing to support investment in more sustainable land use, for instance preventing deforestation and facilitating reforestation.

But any reliance on offset purchases must be strictly controlled and clearly time-limited:

- **Offsets purchased from other energy-using sectors must only occur within the framework of emissions trading schemes whose total volumes are tightly capped and declining at a pace**

---

[21] In addition, natural gas may play a transitional role in residential heating, alongside greater electrification, and could subsequently be substituted by biogas or hydrogen. However, the ETC has not analyzed this issue in detail.

[22] Legal disputes related to how to account for carbon emissions reductions from offsets which are traded internationally outside of regulated emissions trading schemes are not covered in this report.

compatible with the Paris climate objective. This implies that by mid-century there will be almost no remaining potential for such purchases.

- Land use offsets should also ideally play only a transitional role, given **limits to the total possible scale of natural carbon sequestration.** Land use offsets must also be subject to extremely tight regulation to ensure that the purchase of offsets truly does result in incremental carbon emissions reductions, and to avoid adverse effects of biodiversity.

However, our analysis suggests that, while the energy and industrial systems can get very close to net-zero by 2060, there may be small residual emissions (around 2Gt per annum) which would be very expensive to eliminate. A small long-term role for negative emissions from land use or BECCS may therefore be required.

But, given constraints on long-term negative emissions, sectoral strategies can only claim to be compatible with the Paris climate agreement if they aim for as close as possible to net-zero CO_2 emissions within the sector by mid-century.

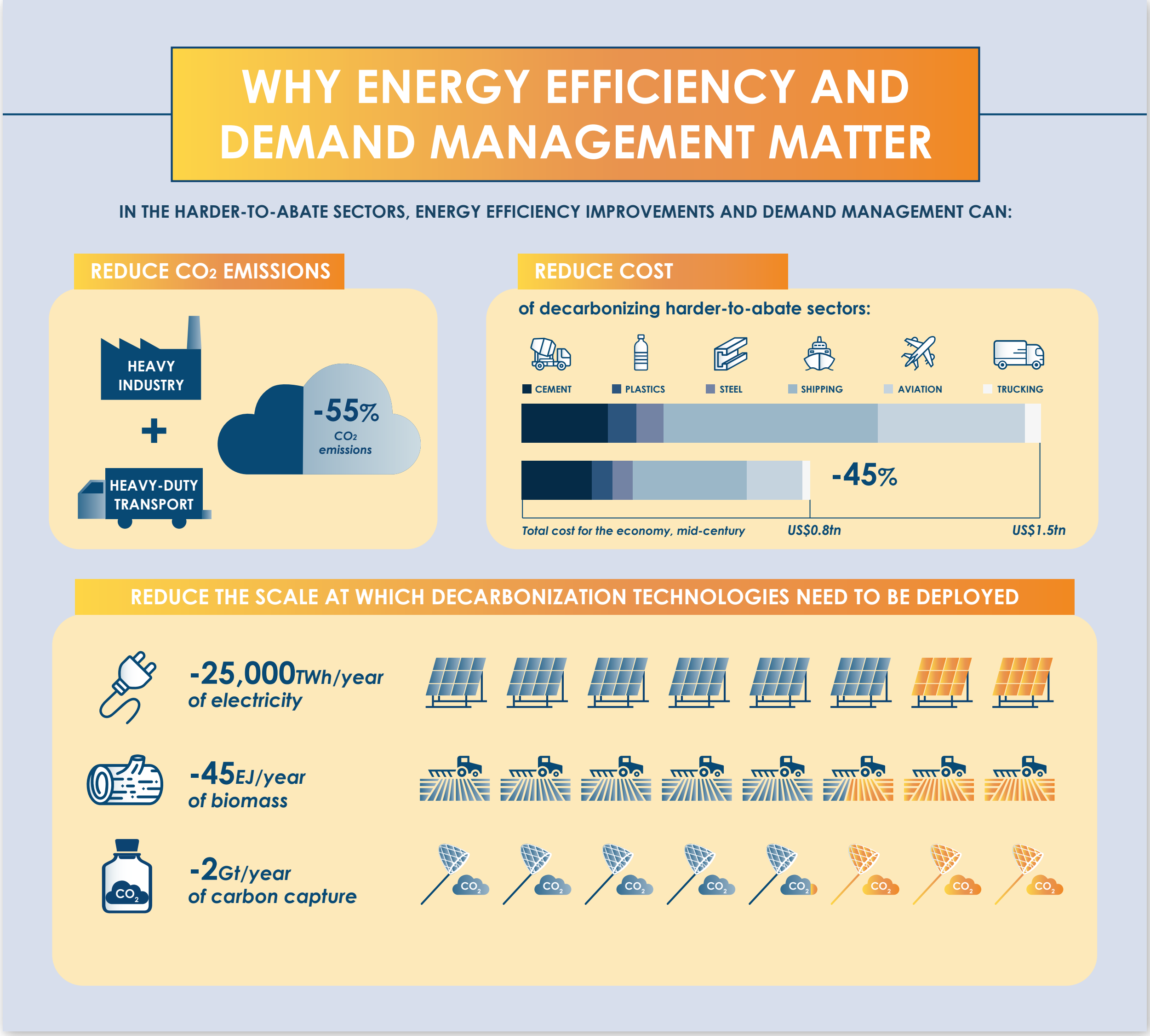


Exhibit 11

C. ACTION: WHAT POLICYMAKERS, INVESTORS, BUSINESSES AND CONSUMERS CAN (AND SHOULD) DO

DRIVING PROGRESS THROUGH INNOVATION

Complete decarbonization of all the harder-to-abate sectors **could be achieved using technologies already under development**. But many of them are still not market-ready, nor have been deployed at commercial scale. In addition, **future unpredictable technological breakthroughs** will almost certainly, some time over the next decades, allow different and cheaper routes to decarbonization. Both private investment and public policy support are required to drive incremental innovation and maximize the likelihood of more fundamental breakthroughs.

Enabling greater efficiency and circularity

Achieving the potential for energy efficiency as well as materials efficiency and circularity will require innovation in three major areas:

- **Product design** to enable:
  - Increased energy efficiency – e.g. improved design of air frames and ships;
  - Use of new low-carbon fuels – e.g. radical redesign of air frames to enable the use of hydrogen;
  - Improve materials efficiency and circularity – e.g. conceiving buildings, vehicles or packaging in a way that reduces over-specification of materials and facilitates end-of-life dismantling, sorting and recycling of materials;
- **Improving materials processing systems,** in particular:
  - New manufacturing or construction techniques that reduce waste from production;
  - New high-strength materials that reduce the materials input required;
  - Materials traceability systems, enabled by digital technologies;
  - Automated sorting systems, enabling advanced separation of materials;
  - Methods to separate the constituents of composite materials (such as textiles);
  - Improved metallurgy, to remove impurities from scrap metals and produce high-quality metals from mixed scrap;
- **New business models relying on longer product lifetimes** (through design, maintenance, higher-quality materials, re-manufacturing and re-use) and more intensive use (through sharing or increased occupancy levels).

Enabling electrification of transport and industry

In the transport sectors the crucial challenge is further to reduce the cost and improve the performance of batteries:

- Massive private investments now flowing into the currently dominant lithium-ion technology make it highly likely that **battery prices will fall to meet be BNEF's projection of US$100 per kWh** (for cells plus pack) by 2025 – and probably before.
- **Improvements in energy density, charging speed and battery life will then become more important than further cost reductions.** Battery density improvement of 2 to 3 times would make battery electric vehicles dominant even for long-distance surface transport and improvement of 5 to 10 times would be required to make electrification feasible for long-distance shipping and aviation. These will require more fundamental changes in battery chemistry.

In the industrial sectors, the key challenge is to **develop electric cement kilns and electric furnaces.** Alongside these, fundamental research should explore the potential for more **radical breakthroughs in electrochemistry,** in both the steel and chemicals industry.

Driving down the cost of hydrogen production and use

Given the major role that hydrogen will almost certainly play, it is crucial to reduce the cost of hydrogen production and use, aiming in particular:

- To radically **reduce the cost of electrolysis equipment**, achieving US$250 per kW by the mid-2020s versus US$1000 per kW today;
- To **reduce the cost of steam methane reforming plus carbon capture;**
- To **reduce the cost of fuel-cells** from around US$100 per kW today to less than US$80 per kW by 2025 for medium duty vehicles and of hydrogen tanks from $15 per kW today to less than $9 per kW by 2025.

Revolutionizing the chemicals industry through biochemistry and synthetic chemistry

While emissions from industrial processes can be eliminated via electrification, biomass combustion, or carbon capture and sequestration, **the more difficult technical challenge is to address end-**

of-life emissions produced in multiple dispersed locations and in particular those resulting from the remaining use of liquid hydrocarbon fuels (in aviation and shipping), plastics and fertilizers (which produce both CO_2 and N_2O emissions).

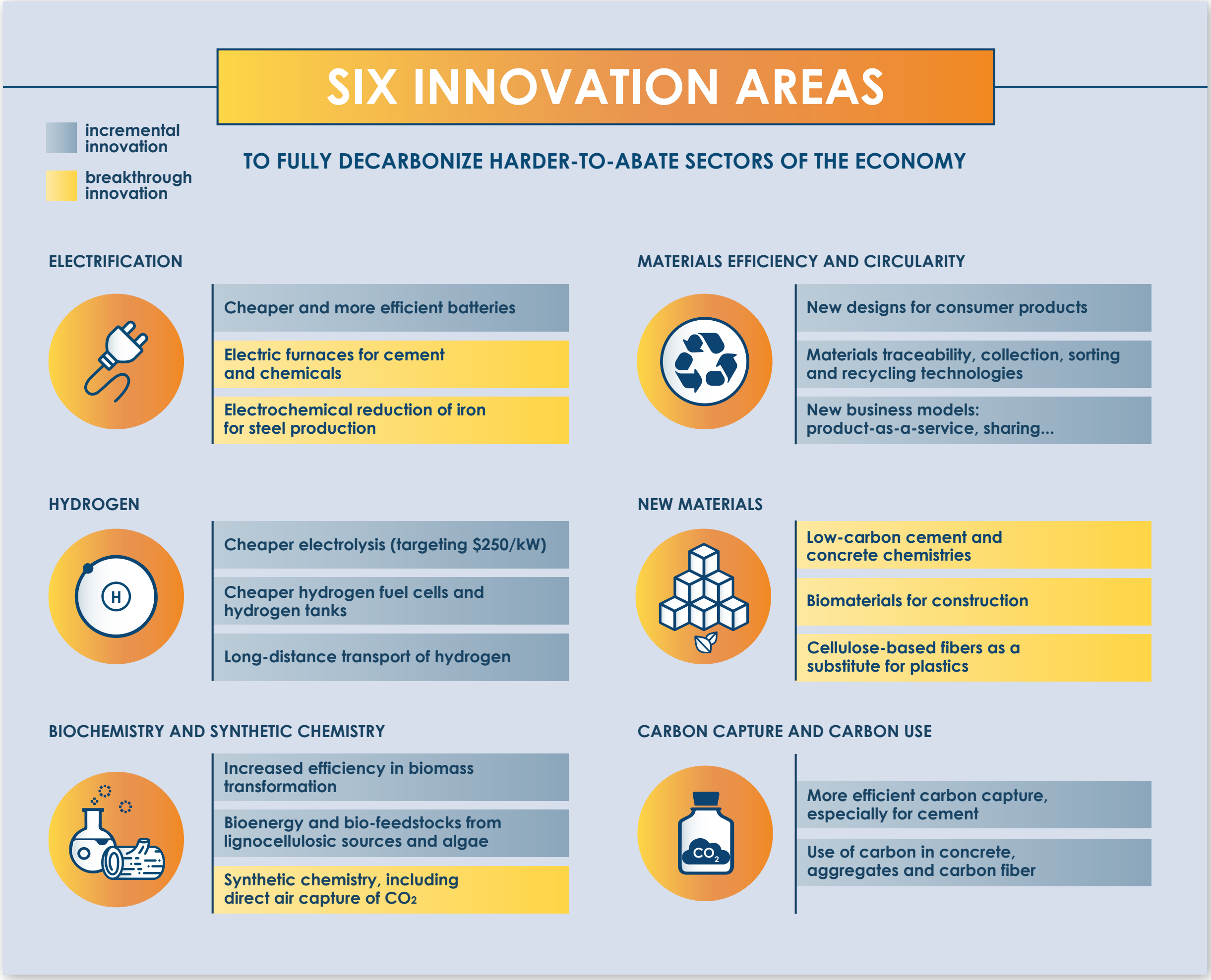
This makes four areas of innovation vital:

- **Biochemistry,** where the key challenge is to enable the development of liquid fuels or feedstocks for plastics production, while minimizing the use of biomass sources which compete with food production and threaten biodiversity, through:
  - Biochemical technologies which can enable the exploitation of lignocellulosic sources,
  - Genetic engineering of crops which can grow on arid land or sea water, including algae,
  - Increased efficiency of biorefinery processes;
- **Synthetic chemistry,** where the two key innovation challenges are:
  - To reduce the cost of direct air capture of CO_2 (DAC),
  - To find effective routes to produce aromatics used in plastics;
- **Hybrid chemical routes** – i.e. combining bio and synthetic chemistries;
- **Chemical recycling of plastics** to limit the need for new bio and synthetic feedstock.

Developing new materials

There is significant potential to substitute less carbon-intensive materials for carbon-intensive ones, for instance:

- In the buildings sector, **using timber or pozzolan-based concrete to substitute for Portland cement;**
- In packaging, textiles and manufacturing, **using cellulose-based fibers to substitute for plastics** (and for bio-based plastics, which would require a much greater biomass input than direct fiber use).



SIX INNOVATION AREAS

TO FULLY DECARBONIZE HARDER-TO-ABATE SECTORS OF THE ECONOMY

▨ incremental innovation

🟨 breakthrough innovation

ELECTRIFICATION
- ▨ Cheaper and more efficient batteries
- 🟨 Electric furnaces for cement and chemicals
- 🟨 Electrochemical reduction of iron for steel production

MATERIALS EFFICIENCY AND CIRCULARITY
- ▨ New designs for consumer products
- ▨ Materials traceability, collection, sorting and recycling technologies
- ▨ New business models: product-as-a-service, sharing...

HYDROGEN
- ▨ Cheaper electrolysis (targeting $250/kW)
- ▨ Cheaper hydrogen fuel cells and hydrogen tanks
- ▨ Long-distance transport of hydrogen

NEW MATERIALS
- 🟨 Low-carbon cement and concrete chemistries
- 🟨 Biomaterials for construction
- 🟨 Cellulose-based fibers as a substitute for plastics

BIOCHEMISTRY AND SYNTHETIC CHEMISTRY
- ▨ Increased efficiency in biomass transformation
- ▨ Bioenergy and bio-feedstocks from lignocellulosic sources and algae
- 🟨 Synthetic chemistry, including direct air capture of CO_2

CARBON CAPTURE AND CARBON USE
- ▨ More efficient carbon capture, especially for cement
- ▨ Use of carbon in concrete, aggregates and carbon fiber

Exhibit 12

CARBON PRICING

ADEQUATE CARBON PRICES MUST PLAY A CENTRAL ROLE IN DRIVING DECARBONIZATION OF THE HARDER-TO-ABATE SECTORS

Internal agreements covering all sectors are ideal and should be pursued.

CO_2

Governments can make progress without delay through efficient and pragmatic approaches to carbon pricing.

EFFICIENT AND PRAGMATIC APPROACHES TO CARBON PRICING

DEFINED IN ADVANCE

Setting a long-term signal driving investment decisions through taxes or floor prices, rather than through fluctuating prices in a trading scheme.

DIFFERENTIATED

Different by sector, because higher prices are needed to trigger change in shipping than in steel.

DOMESTIC

On products that are not internationally traded (e.g. cement), but not on internationally-traded products (e.g. steel).

DOWNSTREAM

On the lifecycle carbon emissions of consumer products rather than on production processes (e.g. taxing the carbon content of packaging).

INDICATIVE SUPPLY-SIDE ABATEMENT COST (US$/TONNE CO_2)

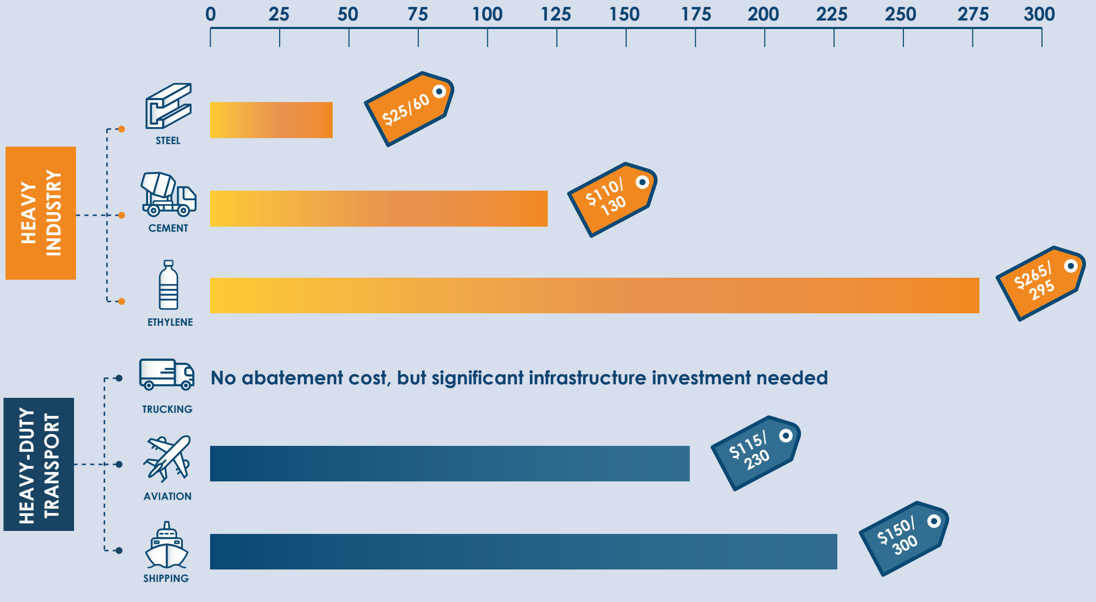


Exhibit 13

Driving down the cost of carbon capture and carbon use technologies

The key challenge with carbon capture and use is not a fundamental technological one, but rather a question of how to achieve sufficiently large-scale deployment to drive economies of scale and learning curve effects.

DRIVING PROGRESS THROUGH POLICY

Since there are multiple routes to the decarbonization of harder-to-abate sectors, **policy should aim to unleash a market-driven search for the optimal solution, while also ensuring focused support for those aspects of the transition which are certain to be needed.** Four complementary sets of policies are required to drive progress.

Efficient and pragmatic approaches to carbon pricing

Adequate carbon prices must play a central role, simultaneously incentivizing improved energy efficiency, supply-side decarbonization, and demand reduction.

Existing carbon pricing schemes, like the EU-ETS, have begun to play a role in driving down carbon emissions, but three challenges have limited their effectiveness to date:

- The danger that if international agreement cannot be achieved, imposing carbon taxes in one country could result in **shifts in the production location of internationally traded goods and services** (e.g. steel and aluminum), which has often led to exceptions within carbon pricing schemes, including the EU-ETS;
- **Very different marginal abatement costs by sector,** which, together with high emissions caps, mean that the resulting prices may be far too low to provoke change in the higher-cost sectors (e.g. aviation);
- The uncertainty on long-term prices in emissions trading systems, which do not provide a sufficiently strong long-term price signal to spur technology development.

It is essential to overcome these challenges. International agreements covering all sectors remain ideal and it is vital to pursue them. However, policymakers should also recognize that, if the ideal is not possible, there is still an opportunity to make progress by strengthening existing emissions trading schemes and by developing complementary, imperfect but still useful, approaches that might be [Exhibit 13]:

- **Defined in advance,** with specific taxes or floor prices in some cases providing greater certainty and thus more powerful incentives than can be achieved through fluctuating prices;
- **Differentiated by sector to reflect different marginal abatement costs and technology readiness,** with for instance far higher carbon price applied in shipping and aviation than to the materials-producing industrial sectors;
- **Domestic/regional,** with for instance a significant carbon price applied to cement (where competition is primarily domestic) even while not applied at the same level to steel, (using free allocation within emissions trading schemes or compensation schemes to avoid carbon leakage dangers (with allocations/compensations combined with increasingly ambitious benchmark technology standards so as to provide incentives for innovation and investment);
- **Downstream,** i.e. applied to the lifecycle carbon emissions of consumer products rather than production processes, as is the case with excise duties on gasoline and diesel, which are effectively subject to a carbon tax whatever the location of crude oil production and refining.

Such approaches to carbon pricing would need to be designed to limit risks of carbon leakage between sectors and between regions, and might require new systems to ensure the traceability of lifecycle carbon emissions. They should ideally build up towards a globally consistent carbon pricing framework.

Mandates and regulations

In addition to carbon pricing, specific regulatory mandates could and should include:

- **Energy efficiency regulation,** which has been a key driver of improvements in automobile and appliance efficiency, and which is already being applied by the IMO to drive improvements in the energy efficiency of new ships;
- **Tightly defined sustainability standards** for low-carbon fuels (including bioenergy and hydrogen), based on robust lifecycle carbon accounting and assessment of other environmental impacts;
- **Green fuel mandates** which could require airlines and ship operators to use a rising percentage of zero-carbon fuels;

- **Regulations which ban the sale of diesel or gasoline ICE trucks**, beyond given future dates, and/or ban their use in major cities;
- **Labelling – and regulations on – embedded carbon in products,** ensuring traceability of the source, carbon intensity and recycled content of materials used in consumer products (e.g. cars or appliances);
- **Standards on materials efficiency,** especially in infrastructure, buildings and key consumer products;
- **Regulations to drive the circular economy,** in particular by enforcing end-of-life product recycling responsibility and requiring product designs which make recycling possible.

Public support for infrastructure development

Most of the investments required to build a net-zero-carbon economy will be made by the private sector. But active public policy coordination or direct investment support may be required in:

- **Long-distance power transmission** to support high penetration of variable renewables;
- **Vehicle charging and refueling infrastructure** along road networks as well as in ports and potentially airports (if hydrogen and ammonia use develops);
- **Railway infrastructure,** especially high-speed rail connections on a regional level, to enable greater modal shift;
- **Port and pipeline infrastructure** to drive the development of domestic and international trade in new fuels such as hydrogen and ammonia;
- **Carbon transport and storage networks**, where governments have a key role to play in imposing tight regulatory standards, and in planning and approving the routing of pipelines.

Public support for research, development and deployment of new technologies

The optimal public policy role in driving technological progress will differ depending on the market readiness of different technologies:

- **Deploying proven technologies at commercial scale:** Here most of the investment must come from the private sector, but governments could accelerate progress by facilitating financing (for instance via loan guarantees or reimbursable advances) and by using public procurement to create demand for low-carbon products and services.
- **Bringing technologies under development to commercial readiness:** A combination of public and private innovation funding will be required to accelerate the process to bring technologies to market, in particular to fund pilot projects.
- **Fostering radical technology game changers:** Public funding should provide direct support for specific areas of research, in particular via target-driven programs which define specific quantitative objectives 10-15 years ahead and stand willing to support multiple R&D efforts that could deliver the objectives.

DRIVING PROGRESS THROUGH PRIVATE SECTOR ACTION

Private sector action will also be vital to achieve full decarbonization of harder-to-abate sectors.

Industry associations in harder-to-abate sectors

Many industry associations in key industrial sectors and in heavy-duty transport (especially shipping and aviation) are already aiming to achieve significant carbon reductions by mid-century. These efforts could be further strengthened by:

- **Developing roadmaps to net-zero carbon emissions by mid-century,** including clear specification of how transitional solutions such as offsets or use of unabated natural gas will be phased out over time;
- **Developing cross-sectoral initiatives to develop demand for low/zero-carbon products** (e.g. partnership between airlines, airports and travel agencies to develop a zero-carbon flight offer) and to support materials circularity (e.g. partnership between steel producers and manufacturers to improve collection rates and quality of steel scrap);
- **Using their lobbying capacity to advocate ambitious international agreements on carbon pricing.**

Companies in harder-to-abate sectors

In parallel, **leading industry companies have already started to prepare for a low-carbon transition,** with some companies committing to science-based targets and a few making bolder commitments to net-zero carbon emissions. We hope that an increasing number of companies will continue to:

- **Invest in R&D projects, especially pilot plants,** focused on key innovation priorities outlined above;
- **Develop partnerships which can deliver greater materials efficiency and circularity;**

- **Develop regional partnerships in industrial clusters**, to support infrastructure development and industrial symbiosis;
- **Base their long-term business strategy and shareholder reporting on tightened science-based targets,** which aim to net-zero carbon emissions by mid-century.

Major buyers of materials and mobility services

Major buyers – in particular businesses and public procurement services – can accelerate change in the harder-to-abate sectors by creating demand for "green" materials and mobility services, initially at a premium price. Initiatives could include:

- **The expansion of the EV100 commitment** (commitment to 100% electric vehicles) taken by businesses and cities to electric trucks and buses (BEVs or FCEVs);
- **A commitment to low-lifecycle-carbon-emissions materials for commercial and industrial buildings,** completing existing operational energy efficiency targets;
- **A commitment to green flights purchase** as an alternative to buying offsets to compensate for business air travel.

Consumers

With the exception of aviation and some subsectors of shipping and heavy-road transport (i.e. buses), **harder-to-abate sectors are not directly exposed to consumer pressure**. However, materials and freight transport are essential to the delivery of key end consumer products. **Adequate labelling of lifecycle and embedded carbon intensity of products** (e.g. cars, appliances) and services (e.g. flights) could create traceability and be a powerful tool for consumer awareness. It could also facilitate the creation of a "green offer" at a premium price, given that the cost impact of decarbonization on end consumers is relatively small.

Public and private investors

New investment opportunities will arise both in low-carbon infrastructure, and in companies that take advantage of low-carbon innovation in materials, products and business models. Investors could help accelerate decarbonization by:

- **Better evaluating climate-related risks and opportunities** focusing not only on energy, but also on the industry and transport sectors;
- **Developing clear plans to shift their investment portfolios through time,** increasing investment in low-carbon infrastructure, technologies and companies, and cutting investments in potentially stranded assets;
- **Developing a range of "green investment" products with different risk-return profiles,** with the support of development banks to facilitate sustainable infrastructure investment in developing countries (through policy development, public investment and private capital mobilization via blended finance).

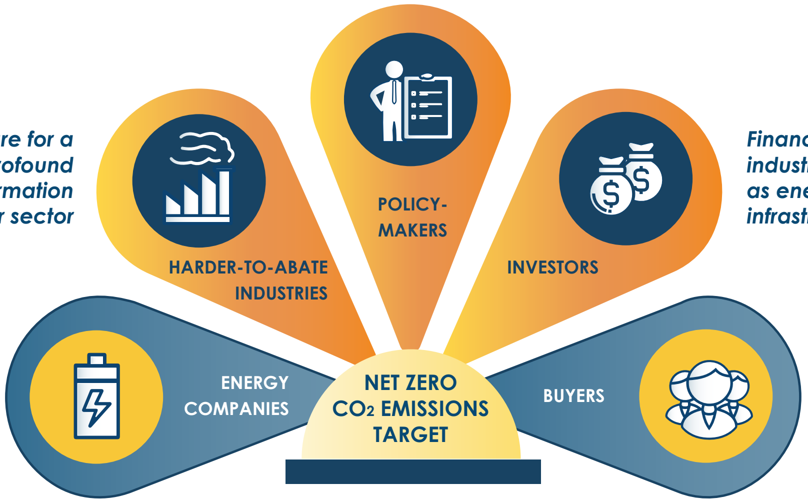
WINNING THE CLIMATE WAR

The Energy Transitions Commission believes it is possible to achieve the near-total decarbonization of the harder-to-abate sectors of the economy by mid-century, significantly increasing the chance of limiting global warming to 1.5˚C. Succeeding in that historic endeavor would not only limit the harmful impact of climate change; it would also drive prosperity, through rapid technological innovation and job creation in new industries, and deliver important local environmental benefits. National and local governments, businesses, investors and consumers should therefore take the actions needed to achieve this objective.

WINNING THE CLIMATE WAR

With immediate collective action, reaching net-zero CO_2 emissions from harder-to-abate sectors of the economy – in heavy industry and heavy-duty transport – is technically and economically feasible.

OUR RESPECTIVE RESPONSIBILITIES



POLICY-MAKERS: *Drive and support a green industry revolution*

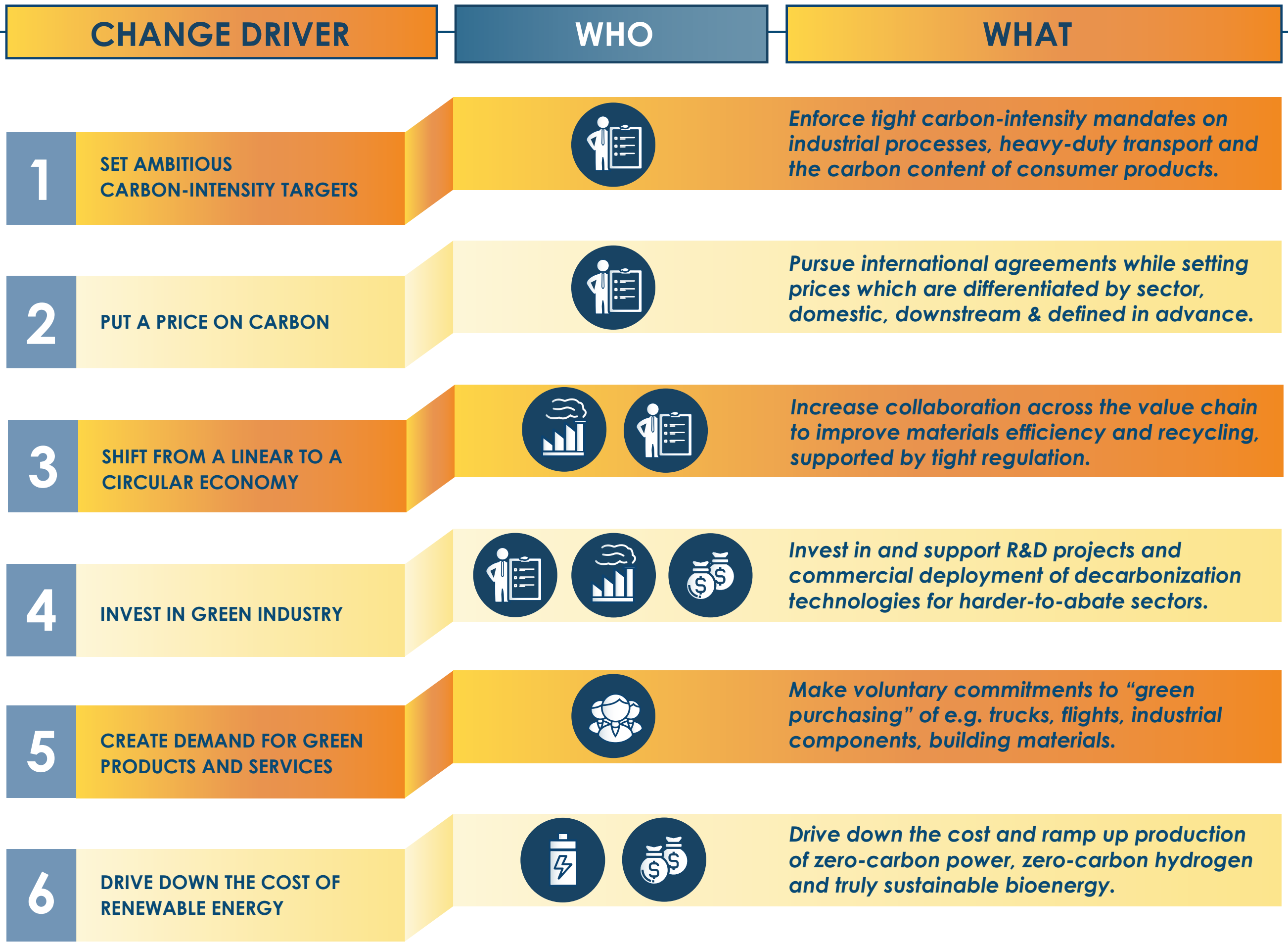
HARDER-TO-ABATE INDUSTRIES: *Prepare for a profound transformation of their sector*

INVESTORS: *Finance low-carbon industrial assets as well as energy and transport infrastructure*

ENERGY COMPANIES: *Produce low-cost, zero-carbon energy*

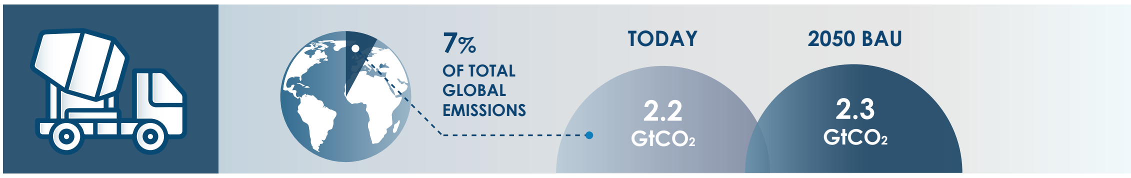
BUYERS: *Businesses, public procurement services and end consumers: create demand for zero-emissions materials and mobility*

NET ZERO CO_2 EMISSIONS TARGET



CHANGE DRIVER	WHO	WHAT
1 SET AMBITIOUS CARBON-INTENSITY TARGETS		*Enforce tight carbon-intensity mandates on industrial processes, heavy-duty transport and the carbon content of consumer products.*
2 PUT A PRICE ON CARBON		*Pursue international agreements while setting prices which are differentiated by sector, domestic, downstream & defined in advance.*
3 SHIFT FROM A LINEAR TO A CIRCULAR ECONOMY		*Increase collaboration across the value chain to improve materials efficiency and recycling, supported by tight regulation.*
4 INVEST IN GREEN INDUSTRY		*Invest in and support R&D projects and commercial deployment of decarbonization technologies for harder-to-abate sectors.*
5 CREATE DEMAND FOR GREEN PRODUCTS AND SERVICES		*Make voluntary commitments to "green purchasing" of e.g. trucks, flights, industrial components, building materials.*
6 DRIVE DOWN THE COST OF RENEWABLE ENERGY		*Drive down the cost and ramp up production of zero-carbon power, zero-carbon hydrogen and truly sustainable bioenergy.*

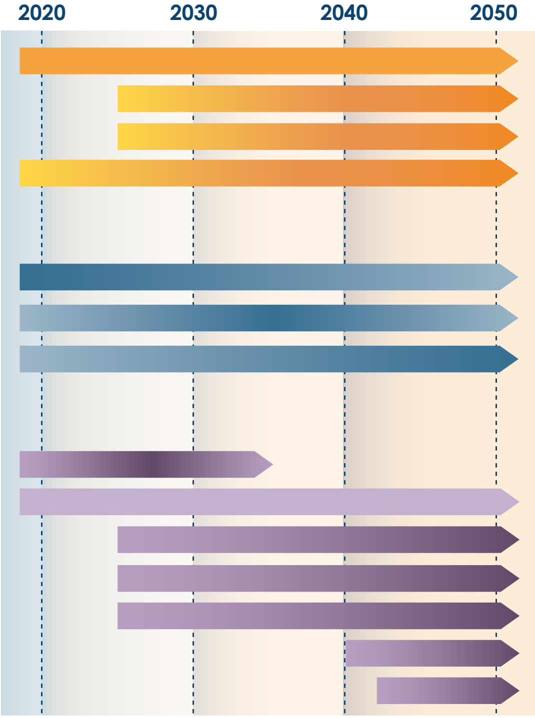
HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM CEMENT



REACHING NET-ZERO CO_2 EMISSIONS FROM CEMENT IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Designing buildings more efficiently	-34%
	Recycling un-hydrated cement	
	Reusing concrete	
	Substituting concrete with timber	UNCERTAIN
2 ENERGY EFFICIENCY	Switch to dry kilns	-10%
	Multistage cyclone heaters	
	Decrease of clinker-to-cement ratio	
3 DECARBONIZATION TECHNOLOGIES	Gas (transition fuel)	-50%
	Biomass/waste for heat generation (localized)	-100%
	Carbon capture on production and process emissions	-90%
	Belite clinker	-10%
	Pozzolan-based concrete	-70%
	Cement-less concrete	-100%
	Kiln electrification	-100%

TECHNOLOGY APPLICABILITY / AVAILIBILITY OVER TIME



MAXIMUM DECARBONIZATION COST

COST PER TONNE OF CO_2
CO_2
+$110/130

B2B COST
+$100
+100%
PER TONNE OF CEMENT

COST TO END CONSUMER
+$15,000
+3%
ON A $500K HOUSE

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR...

INNOVATION

- Pilot new industrial processes producing a purer CO_2 stream and reducing the cost of carbon capture
- Develop low-carbon heat technologies (e.g. hydrogen or electric kiln furnaces) to commercially feasible scale
- Develop new construction materials, including new cement and concrete chemistries

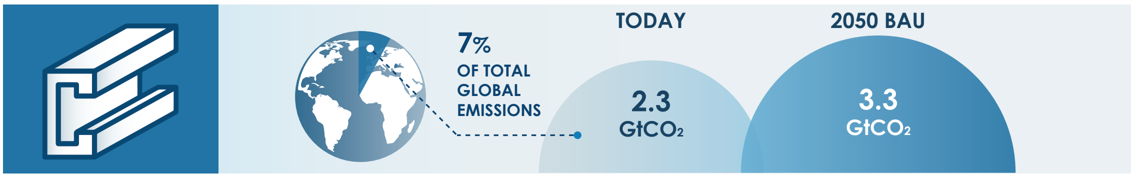
POLICY

- Set a domestic/regional carbon price of $100 per tonne of CO_2
- Use public procurement of buildings and infrastructure to create initial demand for low-carbon construction materials
- Strengthen existing building standards to include embedded carbon intensity targets and shift from materials specification to performance specification

INDUSTRY/BUSINESSES

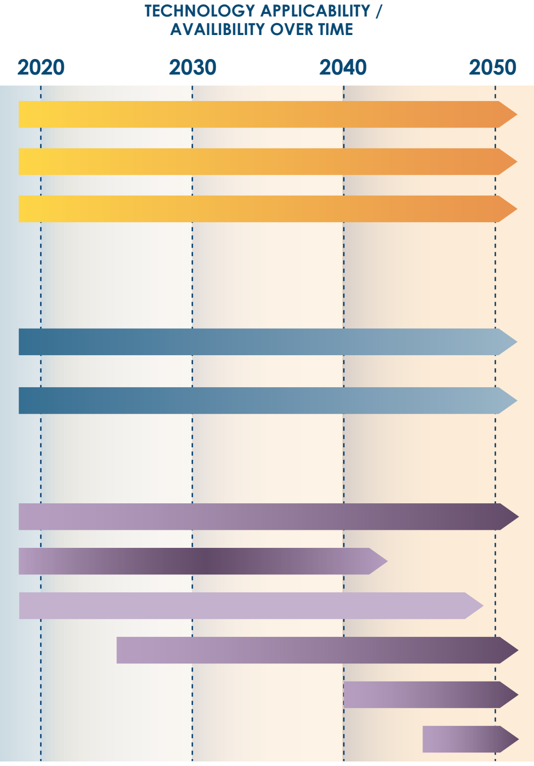
- Cement producers: invest in R&D and pilot carbon capture at commercial scale
- Construction industry: increase materials efficiency in buildings and address the barriers to higher recycling rates
- Construction industry, building buyers and occupiers: commit to "green buildings" defined as low operational and embedded carbon emissions

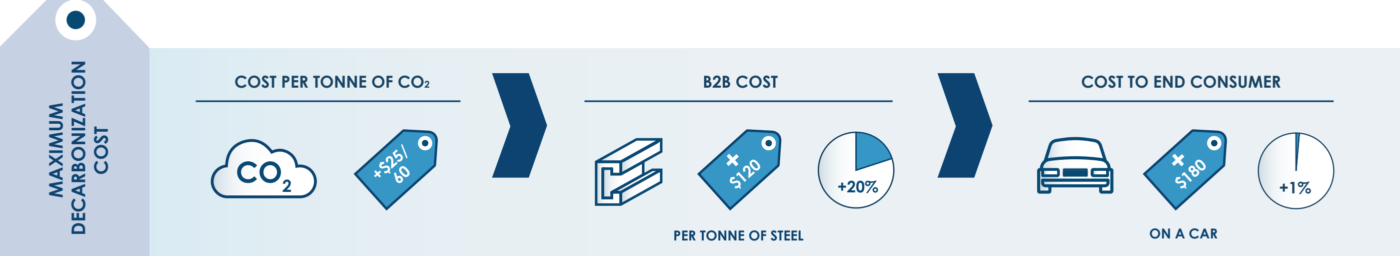
HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM STEEL



REACHING NET-ZERO CO_2 EMISSIONS FROM STEEL IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Greater and better scrap recycling Redesigning products for materials efficiency and circularity More intensive use of steel-based products (e.g, sharing)	-38%
2 ENERGY EFFICIENCY	Use high-pressure gas leaving the furnace to power other equipment Coke dry quenching	-15/20%
3 DECARBONIZATION TECHNOLOGIES	Scrap-based EAF	-100%
	Gas-based DRI (transition fuel)	-50%
	Charcoal in BF/BOF (localized)	-100%
	Carbon capture	-90%
	Hydrogen-based DRI	-100%
	Electrolysis of iron	-100%





TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR…

INNOVATION

- Develop and pilot hydrogen-based DRI
- Develop and pilot new technologies to reduce cost of carbon capture on BF-BOF
- Develop metallurgy to enable higher-quality and higher-value recycling of steel

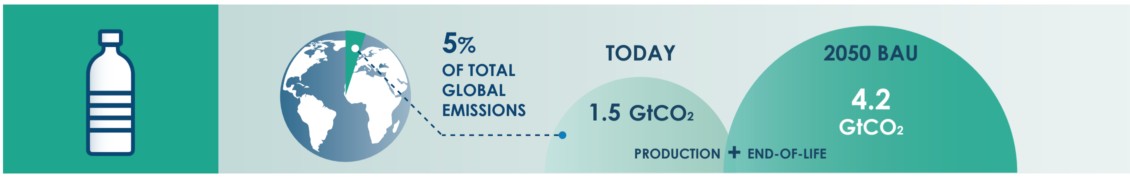
POLICY

- Coalition of governments: agree on a carbon tax on steel production reaching $50-70 by 2030
- Create and progressively tighten regulations on the embedded carbon intensity of steel-based produced, like cars
- Commit to 100% “green steel” in all publicly-funded infrastructure and buildings by 2040

INDUSTRY/BUSINESSES

- Steel industry: support “green steel” standards design and implementation
- Automotive industry: take commitments today on “green steel” purchase targets by 2040
- Steel producers and users: initiate collaborative projects between producers and users to increase and improve quality of steel recycling

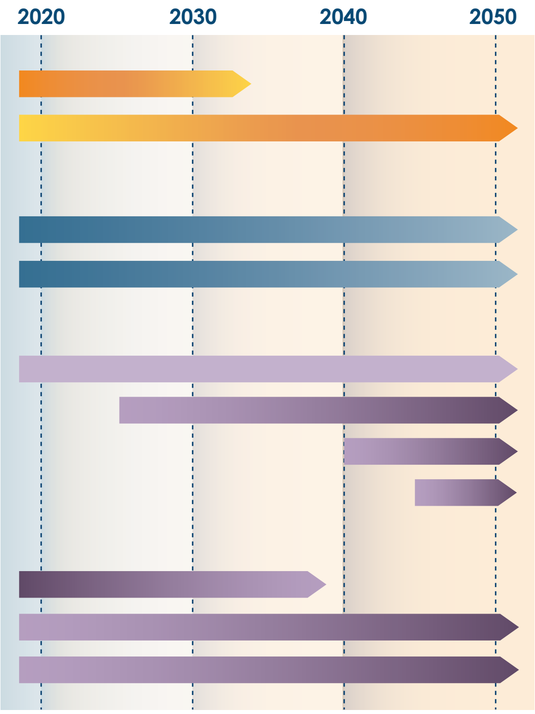
HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM PLASTICS



REACHING NET-ZERO CO_2 EMISSIONS FROM PLASTICS IS POSSIBLE BY COMBINING 4 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Banning of key single-use items	-56% OF LIFECYCLE EMISSIONS
	Chemical and mechanical recycling	
2 ENERGY EFFICIENCY	Energy efficiency improvements in monomer production	-15/20% OF PRODUCTION EMISSIONS
	Naphtha catalytic craking	
3 PRODUCTION DECARBONIZATION	Biomass/waste for heat generation (localized)	-100%
	Carbon capture	-90%
	Furnace electrification	-100%
	New electrochemical processes	-100% OF PRODUCTION EMISSIONS
4 FEEDSTOCK DECARBONIZATION	Switch from coal to gas	-50%
	Use of recycled plastics	-50%
	Use of bio or synthetic feedstock	-100% OF END-OF-LIFE EMISSIONS

TECHNOLOGY APPLICABILITY / AVAILIBILITY OVER TIME



MAXIMUM DECARBONIZATION COST

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR…

INNOVATION

- Develop higher-quality and higher-volume mechanical and chemical recycling
- Develop low-carbon high heat options for pyrolysis furnaces
- Develop sustainable bio or synthetic feedstock

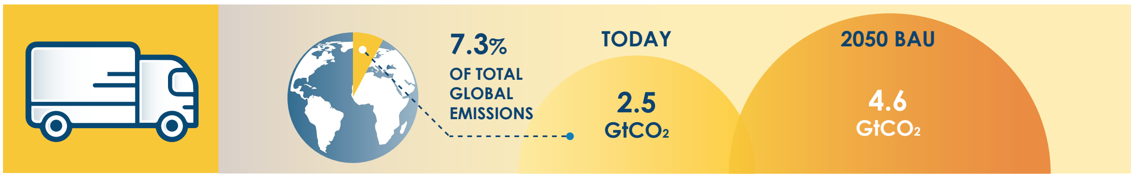
POLICY

- Impose and gradually tighten embedded carbon intensity standards on packaging, appliances and other manufactured products
- Enforce new regulations on product recyclability and/or on extended producer responsibility
- Create carbon taxes on plastics incineration at least as high as landfilling taxes

INDUSTRY/BUSINESSES

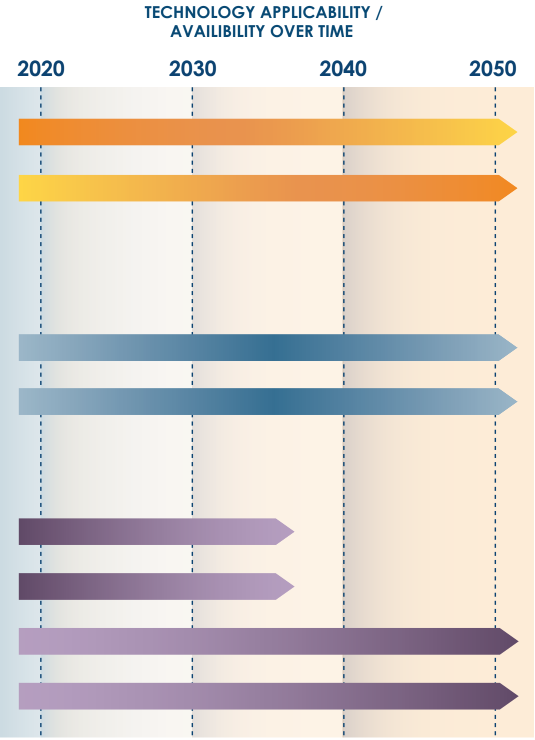
- Plastics producers and users: increase collaboration across the value chain from product design to end-of-life mangement to increase circularity
- Manufacturers: take commitments on recyclability and recycled content in plastics products
- Plastics industry: anticipate policy changes and seize opportunities of growing recycling market

HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM HEAVY ROAD TRANSPORT



REACHING NET-ZERO CO_2 EMISSIONS FROM HEAVY ROAD TRANSPORT IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Logistics and operational efficiency Modal shift to rail or shipping	-30%
2 ENERGY EFFICIENCY	Improvements in engine efficiency Improvements in aerodynamics and tyre design	-30/45%
3 DECARBONIZATION TECHNOLOGIES	Liquified natural gas (transition fuel)	-5%
	Biofuels (transition fuel)	-100%
	Hydrogen fuel-cell vehicles	-100%
	Electric battery vehicles (with or without catenary wining)	-100%



MAXIMUM DECARBONIZATION COST

COST PER TONNE OF CO_2

CO_2 +$10/20

DUE TO INFRASTRUCTURE COSTS EXCLUSIVELY

B2B COST

+$0 NONE

ON COST OF OWNERSHIP

COST TO END CONSUMER

+$0 NONE

ON PRODUCTS MOVED BY TRUCK

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR…

INNOVATION

- Improve battery density and charging speed
- Reduce the cost of electrolysis
- Reduce the cost and improve the efficiency of hydrogen fuel-cells and hydrogen tanks

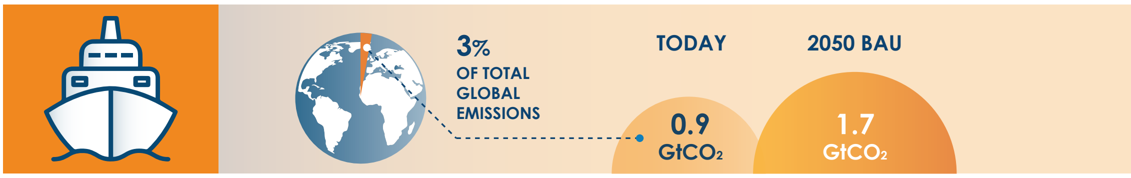
POLICY

- Decarbonize power and strengthen power distribution networks
- Support infrastructure deployment in high-speed charging, hydrogen refueling and overhead wiring
- Cities: commit to 100% zero-carbon bus fleets by 2035

INDUSTRY/BUSINESSES

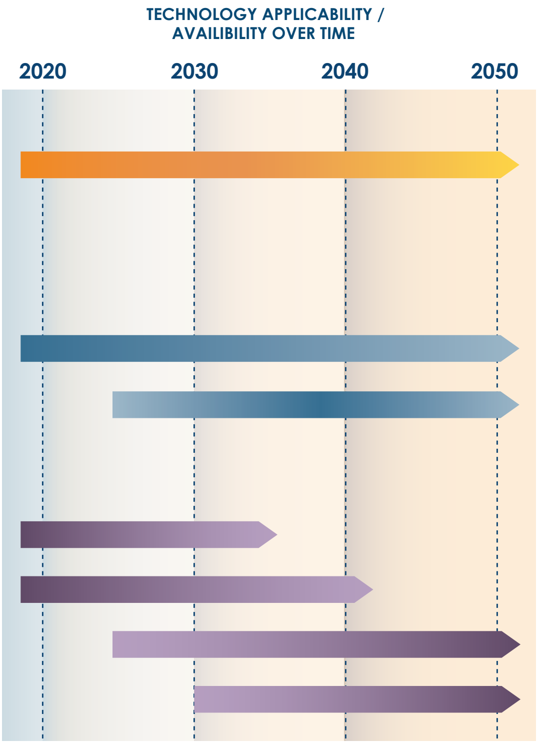
- Fleet owners and operators: adopt best practices and technologies for energy efficiency and logistics efficiency
- Major logistics companies and retailers: commit to 100% zero-carbon trucking
- Automotive and energy companies: develop high-speed charging and hydrogen refueling infrastructure on major freight roads

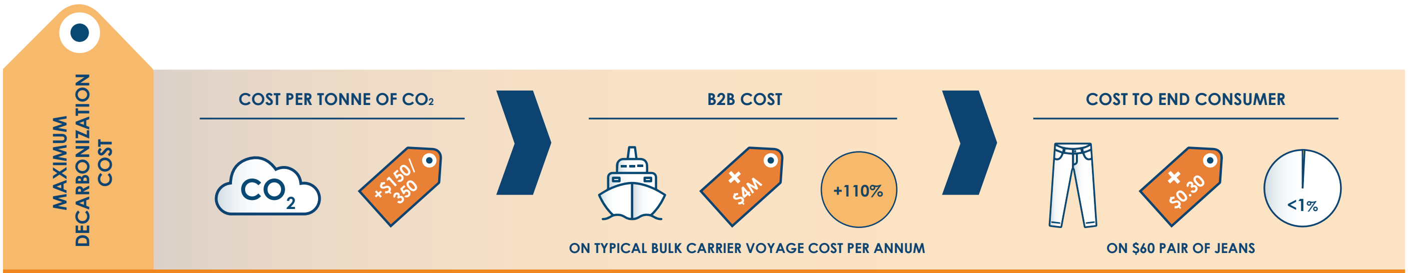
HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM SHIPPING



REACHING NET-ZERO CO_2 EMISSIONS FROM SHIPPING IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Fleet management and voyage plan optimization	-5%
2 ENERGY EFFICIENCY	Machinery efficiency and wind assistance Ship design, hull and propulsion efficiency	-30/55%
3 DECARBONIZATION TECHNOLOGIES	Gas (transition fuel)	-10%
	Biodiesel (transition fuel)	-100%
	Electric battery or hydrogen fuel-cell (short-distance transport)	-100%
	Ammonia or hydrogen in combustion engine	-100%




MAXIMUM DECARBONIZATION COST

COST PER TONNE OF CO_2

B2B COST

ON TYPICAL BULK CARRIER VOYAGE COST PER ANNUM

COST TO END CONSUMER

ON $60 PAIR OF JEANS

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR…

INNOVATION

- Improve energy efficiency of ship, equipment and design
- Reduce the cost of green ammonia (by reducing the cost of electrolysis)
- Reduce the cost and grow the supply of biofuels produced from truly sustainable biomass

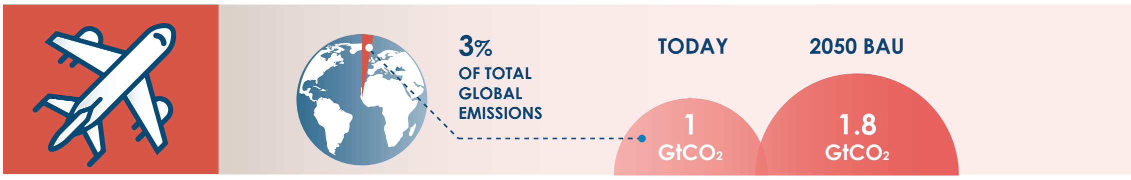
POLICY

- IMO: develop a detailed international roadmap to reach zero CO_2 emissions by mid-century
- IMO: tighten the Energy Efficiency Design standards for new built ships, and set Operational Efficiency standards for the existing fleet
- IMO or coalition of governments: enforce a carbon tax on HFO and/or a "green fuel" mandate

INDUSTRY/BUSINESSES

- Ship owners: invest in available energy efficiency technologies and in R&D and early deployment of decarbonization technologies
- Ports: Develop supply of low-carbon fuels and adapted fuel storage for hydrogen or ammonia
- Global logistics companies: commit to increasingly tight carbon intensity targets for freight transport

HOW TO REACH NET-ZERO CO₂ EMISSIONS FROM AVIATION



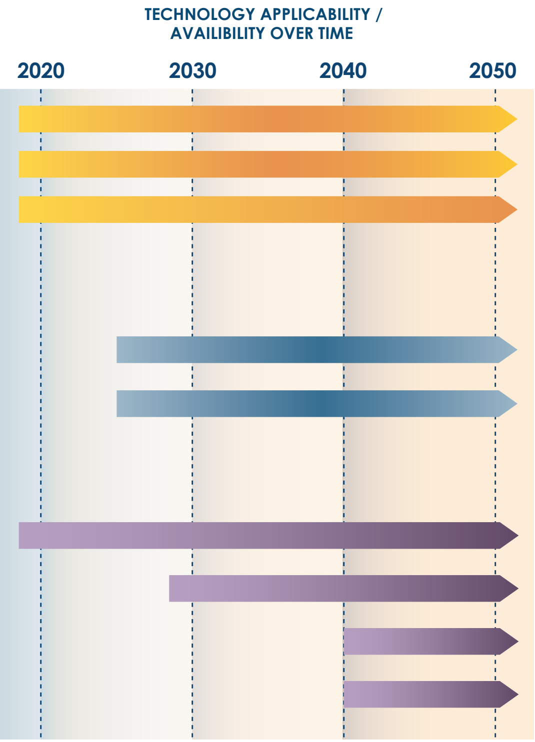
3% OF TOTAL GLOBAL EMISSIONS

TODAY: 1 GtCO₂

2050 BAU: 1.8 GtCO₂

REACHING NET-ZERO CO₂ EMISSIONS FROM AVIATION IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO₂ EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Better Air Traffic Management (ATM)	-15%
	Load factors improvement	
	Modal shift to high-speed rail	
2 ENERGY EFFICIENCY	Thermodynamic efficiency of new engines	-30/45%
	Aircraft design	
3 DECARBONIZATION TECHNOLOGIES	Biofuels	-100%
	Synfuels	-100%
	Hydrogen (short-distance transport)	-100%
	Electric battery (short-distance transport)	-100%



MAXIMUM DECARBONIZATION COST

COST PER TONNE OF CO₂: +$115/230

B2B COST: +$0.30/0.60, +50/100% ON A LITRE OF JET FUEL

COST TO END CONSUMER: +$40/80, +10/20% FOR A LONG-DISTANCE ECONOMY FLIGHT

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR…

INNOVATION

- Improve airframe and engine efficiency
- Drive down the cost of sustainable biofuels
- Drive down the cost of synthetic fuels

POLICY

- Create a "green fuel" mandate imposing an increasing percentage of zero-carbon fuels reaching 100% by 2050
- Create fuel taxes of about US$100 per tonne of CO2 applied at full rate to domestic flights and with reduced rates to international flights
- Tighten sustainability standards on biofuels, based on lifecycle carbon analyses and assessments of other environmental impacts

INDUSTRY/BUSINESSES

- IATA: increase ambitions of IATA roadmap to aim for zero emissions by mid-century
- Airport and airlines: create a coalition to secure a large-scale supply of cost-competitive sustainable biofuels
- Airlines: develop a "green flight" offer at a premium price in coordination with major travel agencies and corporate consumers of air travel

An introduction to the harder-to-abate sectors

The Paris climate agreement committed the world to **limit global warming to well below 2°C and keep it as close as possible to 1.5°C above preindustrial levels**. The latest IPCC report[1] has warned the world of the major negative impacts of a rise in global temperatures of 1.5°C, and the even more dramatic consequences of 2°C global warming. It therefore urges the world to aim for maximum warming of 1.5°C above pre-industrial levels and recommends achieving net-zero CO_2 emissions globally by 2050.

The Energy Transitions Commission (ETC) – a coalition of business, finance and civil society leaders from across the spectrum of energy producing and using industries – supports the ideal objective of limiting global warming to 1.5°C and, at the very least, well below 2°C.

Achieving this will require that **the energy and industrial system reaches net-zero CO_2 emissions in themselves** – i.e. without permanently relying on the purchase of offsets from the land use sector. This will be a major challenge, but will also deliver major economic opportunities, driving technological innovation and resource productivity improvements, creating jobs in new industries, and delivering major local environmental benefits[2]. We believe that **this is achievable by 2050 in developed economies and 2060 in developing economies[3]**.

The good news, indeed, is that one crucial element in the transition to a zero-carbon economy is now clearly achievable and at a much lower cost than seemed possible a decade ago: **we know that we can decarbonize electricity generation at an affordable cost by the early 2030s.** As the ETC's first report *Better Energy, Greater Prosperity*[4] set out, decreasing costs of both renewable generation and flexible back-up resources (in particular batteries) make it reasonable to assume that power systems relying almost entirely on variable renewable sources will increasingly be able to deliver 24/7 electricity at a price fully competitive with fossil fuels.

In most geographies, 85-90% of power demand could be met by a mix of wind and solar, combined with batteries for short-term back-up, with the remaining 10-15% met by dispatchable peak generation capacity, which could be dispatchable hydro, biomass or fossil fuels with carbon capture. Developments in costs since we produced *Better Energy, Greater Prosperity* have increased our confidence that such power systems could be operated at a maximum all-in cost of US$70/MWh (if relying only on batteries and gas peaking plants for back-up), going down to US$55/MWh in most geographies (when using multiple sources of flexibility), and below US$35/MWh in the most favorable locations. **The key priority is therefore to drive the decarbonization of power systems as rapidly as possible**, bringing down the costs still further, and to gradually electrify as much of the economy as possible, at a pace compatible with the pace of power decarbonization to avoid any risk of increased carbon emissions from premature electrification.

The *Better Energy, Greater Prosperity* report indeed also demonstrated that:

- **Rapid electrification of new sectors of the economy can expand the benefits of clean power.** 10-20% of global fossil fuels consumption could be displaced by the electrification of light-duty road transport, manufacturing and part of residential cooking, heating and cooling. Electric cars, in particular, are rapidly becoming cost-competitive. They could dominate new sales as early as 2030 and replace almost entirely the ICE fleet by 2040.
- **A revolution in the pace of energy productivity improvement can be achieved by mid-century.** Developed economies can halve their final energy consumption and developing economies can continue to grow economically without proportional increases in final energy consumption. This will require a combination of energy efficiency measures across the buildings, transport and industry sectors, and of structural reforms decoupling economic growth from the consumption of energy-consuming products and services, through smart urban planning, new mobility systems and circular business models.

But, as we reduce CO_2 emissions from the "easier-to-abate" sectors of the economy, it will become **increasingly important to tackle the "harder-to-abate" sectors in heavy industry and heavy-duty transport.** Otherwise, emissions from these sectors will make it impossible to achieve net-zero emissions by mid-century.

---

[1] IPCC (2018), *Global warming of 1.5˚C*

[2] New Climate Economy (2018), *Unlocking the Inclusive Growth Story of the 21st Century*

[3] If the world is to be net-zero CO_2 emissions by mid-century, negative emissions from the land use sector will therefore be needed during the transition period to compensate for remaining emissions from the energy and industrial system in the 2050s.

[4] Energy Transitions Commission (2017), *Better Energy, Greater Prosperity*

Over the last year, the Energy Transitions Commission has therefore focused on whether it is feasible to decarbonize these sectors within themselves (i.e. without buying offsets from other sectors), how and at what cost.

- In transport, we have covered **heavy road transport (trucks and buses), shipping and aviation.**
- In industry, we have focused on the most important heavy industry sectors – **cement, steel, plastics** – while also touching on chemicals, aluminum and other industries.

This report draws upon a set of analyses carried out for and in partnership with the ETC by the following **knowledge partners**:

- **Material Economics**, who analyzed how far we can reduce demand for carbon-intensive materials via a shift to a more circular economy[5];
- **McKinsey & Company**, who conducted a detailed analysis of the options to achieve supply-side decarbonization of major industrial sectors[6];
- **University Maritime Advisory Services**, who modelled different pathways and cost scenarios for the decarbonization of shipping; and
- **SYSTEMIQ**, who drove the integrated cross-sectoral analysis of the implications of the decarbonization of harder-to-abate sectors for the energy system.

In addition, we have drawn on multiple reports and roadmaps, referenced throughout this report. We have also benefitted from **inputs from nearly two hundred experts** from companies, industry initiatives, international organizations, non-governmental organizations and academia, who have participated to expert workshops to discuss preliminary conclusions and provided rich feedback on nine consultation papers (covering six main harder-to-abate sectors and three cross-cutting technologies) throughout a 6-month consultation process. We warmly thank all contributors and are particularly grateful to experts from the International Energy Agency (IEA) for fruitful exchanges.

---

[5] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*

[6] McKinsey and Company (2018), *Decarbonization of the industrial sectors: the next frontier*

This report integrates sectoral findings into **a system-wide vision** of a feasible pathway to net-zero CO_2 emissions from the energy and industrial system, and draws implications for public and private decision-makers. Inevitably, this requires simplification of very complex issues and trade-offs, and the indicative quantification of possible future developments whose precise pattern is inherently uncertain. Our aim in these quantifications is to **identify likely orders of magnitude** that can inform policy and investment, rather than develop a scenario and suggest that precise prediction is possible.

Overall, we conclude that **it is technically possible to decarbonize each of the harder-to-abate sectors at an affordable cost to consumers and to the overall economy.** In the industrial sectors, there is significant potential to reduce demand below a scenario through more efficient use of materials and greater recycling. In the transport sectors, estimated potential for slowing demand growth is more limited. But, across all sectors, it is technically possible to deliver materials or mobility services without emitting CO_2.

This report therefore describes in turn:

A. Why reaching net-zero CO_2 emissions from the harder-to-abate sectors is technically and economically feasible:

- Our **key sectoral findings** are summarized in Chapters 2 and 3. Sectoral appendices lay out assumptions and analyses in more details.
- Chapter 4 then pulls together the **implications for the cost of decarbonization** in terms of cost per tonne of CO_2, prices of end products and services, and total cost to the economy as a percentage of GDP. The overall conclusion is that it would be possible to achieve net-zero emissions in the harder-to-abate sectors of the economy by mid-century – by 2050 in developed economies and 2060 in developing economies – at a cost of less than 0.5% of global GDP.

B. How to transition to zero CO_2 emissions in heavy industry, heavy-duty transport and what the implications are for the energy system:

- In Chapter 5, we set out the radical changes in business value chains and the forceful public policies which would be required to achieve **a shift to a more circular economy**.
- Chapter 6 considers whether there are **any fundamental resource supply constraints** which would make achieving a zero-carbon economy impossible, and concludes that there are no insurmountable obstacles to achieve net-zero emissions through a portfolio of decarbonization technologies.
- Even if the end point is feasible, however, there are important **issues relating to the feasible pace of change and the optimal process of transition**, which are covered in Chapter 7.

C. What policymakers, investors, businesses and consumers can and should do to accelerate change:

- Chapter 8 proposes **an innovation agenda** for the decarbonization of harder-to-abate sectors, considering both how to make already known technologies commercially viable and how the picture might change if a variety of fundamental breakthroughs (for example, a step change in battery density) were achieved.
- While transition to a zero-carbon economy – including in the harder-to-abate sectors – is feasible, it will not be achieved without strong **policy action**, supported by large-scale industry investment. Chapter 9 discusses key policy choices and priorities, while Chapter 10 sets out the **implications for business and for finance** given the major opportunities created and investments required.

1

Targeting net-zero emissions by 2050-2060 in the harder-to-abate sectors

The Energy Transitions Commission believes that **harder-to-abate sectors can achieve net-zero CO_2 emissions within themselves around mid-century,** with the developed world achieving this objective by 2050 and the developing world by 2060[1]. This target is both achievable and compatible with the Paris agreement objectives.

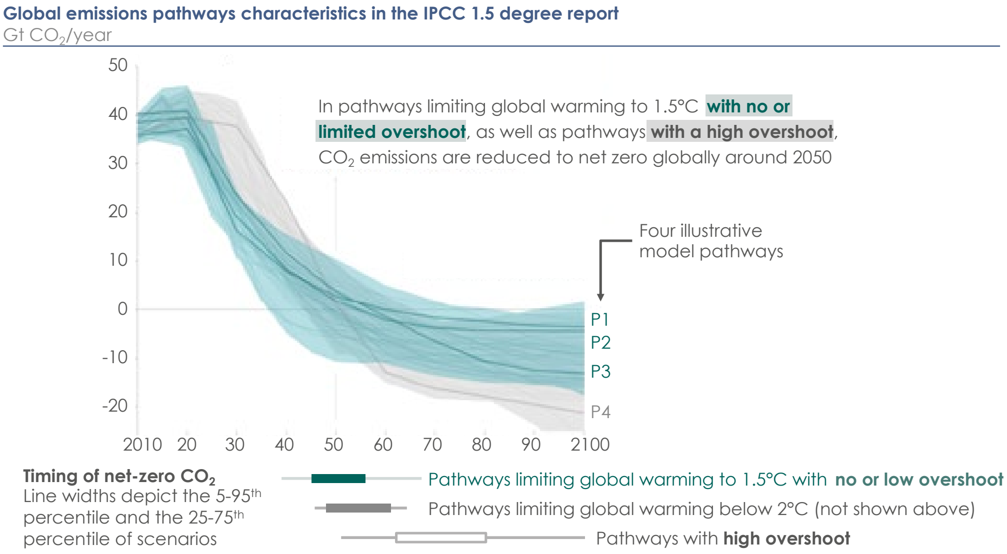
(I) OVERALL CLIMATE AND EMISSIONS OBJECTIVE

The Paris climate agreement committed the world to limit global warming to well below 2°C and to keep it as close as possible to 1.5°C above preindustrial levels. The latest IPCC report[2] has warned the world of the major negative impacts on humanity and the planet of a rise in global temperatures of 1.5°C and the even more dramatic consequences of 2°C global warming. **It therefore urges the world to treat a limit of 1.5°C as the objective.** The Energy Transitions Commission supports this ideal objective, and believes that it is absolutely essential to at least achieve a well below 2°C trajectory.

The implications of this objective for the acceptable level of CO_2 emissions arising from the use of fossil fuels and industrial processes (which we label "energy and industrial system emissions" in the rest of this report) are complex and depend on multiple assumptions.

Total acceptable CO_2 emissions (including those derived from land use changes as well as energy and industrial system) are in part dependent on the emission levels from important non-CO_2 gases (in particular methane and nitrous oxide), which are likely to fall, but at an uncertain rate. There are, in turn, an infinite number of different year-by-year CO_2 emission scenarios which could be compatible with meeting the 1.5˚C target. Higher emissions in early years might be acceptable if negative emissions can be generated in later years, either by land use changes (e.g. increasing the extent of forestation), or by using carbon capture and sequestration to capture emissions generated from bioenergy (BECCS). However, all four indicative scenarios presented in the IPCC report show **total CO_2 emissions reaching net-zero sometime between 2050 and 2060** [Exhibit 1.1]. If significant negative emissions cannot in fact be achieved, the date for achieving net-zero would have to be earlier still.

CO_2 emissions are reduced to net-zero globally by around 2050 in global emissions pathways for 1.5 °C from IPCC



In pathways limiting global warming to 1.5°C **with no or limited overshoot**, as well as pathways **with a high overshoot**, CO_2 emissions are reduced to net zero globally around 2050

Source: IPCC (2018), *Global Warming of 1.5°C*

Exhibit 1.1

---

[1] See definition of "net-zero CO_2 emissions within themselves" in the Glossary.

[2] Intergovernmental Panel on Climate Change (2018), *Special Report on Global Warming of 1.5°C*

Given the overall objective of achieving **net-zero** emissions globally by the early 2050s, **the acceptable level of emissions from the energy and industrial systems depends on whether we can safely assume that emissions from land use can be turned negative in the late 21st century.** At present, land use change results in significant positive emissions. But almost all scenarios compatible with the Paris agreement rely on the fact that these positive emissions can be eliminated, and some suggest that significant negative emissions can be achieved at some future date. This would require a profound change in food and land use system. The ETC view, however, is that we do not need to rely on high levels of negative emissions from the food and land use system, since **it is possible, with determined action, to achieve close to net-zero emissions from the energy and industrial systems by mid-century.** Our analysis indeed suggests that the energy and industrial systems, including the harder-to-abate sectors of the economy, can get very close to net-zero carbon emissions within themselves by 2050 in developed economies and by 2060 in developing economies.

Beyond those dates, **there may be small residual emissions (around 2Gt per annum)** which would be very expensive to eliminate, particularly some end-of-life emissions from chemicals (plastics and fertilizers) and the last 10-20% of industrial emissions which cannot be captured in a cost-effective way. A small long-term role for negative emissions from land use or BECCS may therefore be required.

(II) EMISSIONS FROM HEAVY INDUSTRY AND HEAVY-DUTY TRANSPORT

In 2017, the harder-to-abate sectors which we consider accounted for **about 32% of total energy system CO_2 emissions** – representing 10.7Gt out of 34Gt. For completion, one should add 0.7Gt of end-of-life emissions from the plastics sector[3], 0.5Gt of end-of-life emissions from the ammonia (fertilizer) sector[4], as well as 140Mt of non-CO_2 emissions (for the whole industry and transport sectors)[5] [Exhibit 1.2].

IT IS POSSIBLE TO ACHIEVE CLOSE TO NET-ZERO CO_2 EMISSIONS FROM ENERGY AND INDUSTRY.

The share of the harder-to-abate sectors in remaining emissions will increase over the next decades as electricity generation is increasingly decarbonized, and as clean electrification is increasingly applied to sectors – in particular light-duty road transport and buildings – where it is more straightforward and less costly than in the harder-to-abate sectors.

Estimates of how rapidly the harder-to-abate sectors grow in importance vary with assumptions about the pace of energy efficiency improvement and of overall emissions reductions included in different scenarios. But an indication of the **rising importance of the harder-to-abate sectors** can be illustrated by two IEA scenarios. The IEA's reference technology scenario (RTS) suggests that emissions from the harder-to-abate sectors could grow from 31% of total energy system emissions today to 40% by 2050, while the IEA's 2°C scenario suggests an **increase to 61% by 2050**[6] [Exhibit 1.3].

It is therefore essential to develop strategies which will drive down emissions from harder-to-abate sectors. This will require moderation of the increase in carbon emissions, which would happen under a business-as-usual scenario (both in absolute terms and as a percentage of total) during the 2020s, followed by absolute reductions from the 2030s to mid-century.

As Chapter 4 will show, the costs of decarbonization will almost certainly vary significantly between the harder-to-abate sectors and, in general, will be higher than in the easier-to-abate sectors, in particular power generation. The cost-effective path to overall energy and industrial system decarbonization could therefore involve emissions credit trading between sectors. **But it is essential to drive all harder-to-abate sectors to as close to net-zero emissions in themselves as possible by mid-century.** Chapters 2 and 3 clarify whether this is technically feasible.

---

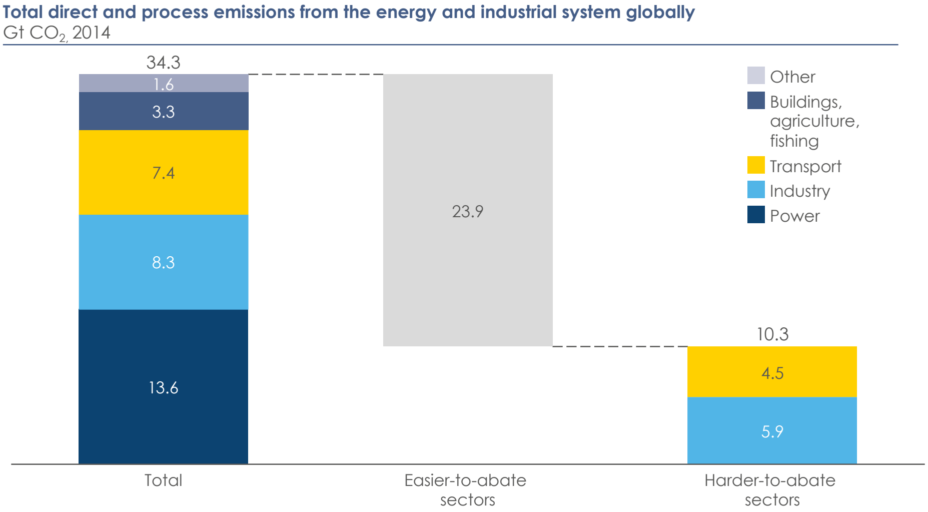
[3] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

[4] Brown T. (2016), ammoniaindustry.com

[5] IEA (2017), *World Energy Outlook*. Includes SO_2, NOX and PM2,5 emissions from all energy activities for the industry and transport sectors.

[6] *IEA (2017), Energy Technology Perspectives*

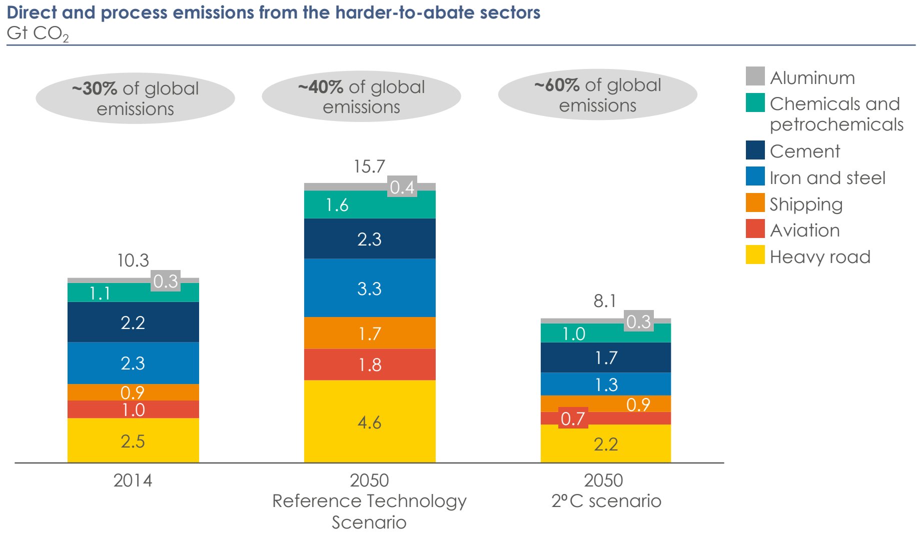
Emissions from the harder-to-abate sectors of the economy represent ~30% of emissions from the energy and industrial system today



Note: Easier-to-abate sectors include rail and light-duty road transport, pulp and paper, aluminum and other industries, power, buildings, agriculture, fishing, other.
Source: IEA (2017), *Energy Technology Perspectives*

Exhibit 1.2

With no action, emissions from harder-to-abate sectors could increase by 50% by mid-century



Source: IEA (2017), *Energy Technology Perspectives*

Exhibit 1.3

2

The road to net-zero carbon: Heavy industry

Industry in total accounts for 25% of total energy use and 18% of global CO_2 emissions today[1]. Of this, 190EJ of energy and 2.8Gt of CO_2 emissions come from a broad swathe of manufacturing industries within which electricity for machine drive dominates. As a result, these sectors will substantially decarbonize as and when electricity becomes low-carbon.

The greatest decarbonization challenge lies within those sectors where industrial processes require high-temperature heat and/or where the process of chemical transformation involves emission of CO_2 (called "process emissions"). The most important sectors are **cement, iron and steel, and chemicals** – which together account for 5.6Gt CO_2 emissions today[2]. We have therefore focused our analysis on these three sectors and, within chemicals, on the production of plastics. We have carried out more limited work on other chemicals (in particular ammonia) and aluminum.

For each of the sectors, we find that **it will be technically feasible to decarbonize production by mid-century** at costs which would not impose unacceptable burdens on the economy or end consumers. These costs could, moreover, be significantly reduced by grasping the major opportunities to moderate growth in demand for virgin materials through greater materials efficiency and circularity, as well as the more limited opportunities for greater energy efficiency in industrial processes, especially in developing economies.

This chapter covers in turn:

i. Demand projections, and the potential to moderate demand via greater materials efficiency, recycling and reuse within a more circular economy;
ii. The potential for energy efficiency improvement;
iii. Decarbonization technologies to drive the decarbonization of materials production as well as end-of-life emissions (for plastics);
iv. Transition complexities and options, including the potential role of natural gas.

Detailed analyses of the cement, steel and plastic sectors are set out in Appendices 2-4.

(I) DEMAND OUTLOOKS AND CIRCULAR ECONOMY OPPORTUNITIES

Exhibits 2.1 to 2.3 set out base case projections for demand for cement, steel and plastics, globally and by major countries. In each case, **economic growth is likely to drive very significant increases in total demand, particularly in emerging economies.**

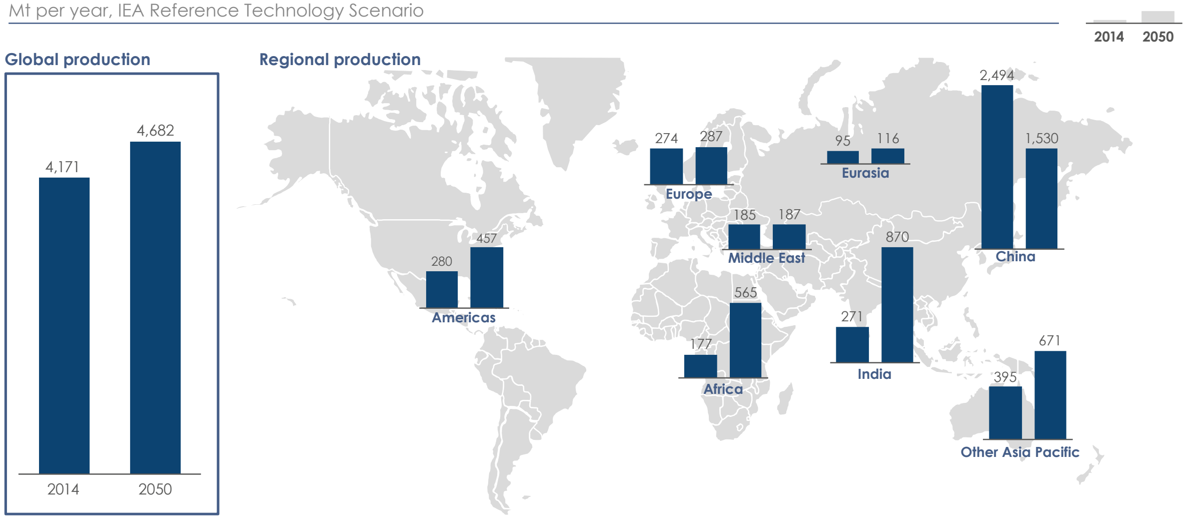
- **Cement demand** is currently flat in many developed countries where extensive built environments already exist and will likely fall from extremely high levels in China as the long construction boom slows down. But **rapid growth is likely in India, Southeast Asia and Africa**[3]. Different analyses can present a more aggressive demand increase than the global 4.7Gt by 2050 calculated by the IEA[4]. For instance, if demand were closely correlated with GDP growth, it could rise to 6.3Gt by 2050[5].
- **Steel demand** is ultimately driven by the stock of steel per capita required to support good standards of living. In advanced economies, the stock of steel per capita typically stabilizes at about 12-13 tonnes per capita. In China, it is now over 5 tonnes per capita, growing fast, and may reach maturity within a decade. In India and Africa, it stands below 1 tonne per capita[6]. As a result, **a high percentage of steel demand from developed economies could be met with scrap-based recycled steel, while increasing stocks in some developing economies will require significant virgin production.** China is the dominant steel producer in the world today (with nearly 50% of global total production[7]), but the key drivers of future demand will be in India and Africa.
- **Plastics demand under a business-as-usual scenario could grow enormously** from 320Mt today to over 800Mt by 2050 and even 1,350Mt by 2100, with China initially accounting for a significant share of the growth, but other emerging economies subsequently becoming more important[8].

---

[1] IEA (2017), *Energy Technology Perspectives*
[2] IEA (2017), *Energy Technology Perspectives*
[3] IEA-CSI (2018), *Technology Roadmap - Low-carbon transition in the cement industry*
[4] IEA (2017), *Energy Technology Perspectives*
[5] Material Economics analysis for the Energy Transitions Commission (2018)
[6] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*
[7] IEA (2017), *Energy Technology Perspectives*
[8] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*

Global annual cement production is expected to increase by 12% by mid-century

Global cement production
Mt per year, IEA Reference Technology Scenario

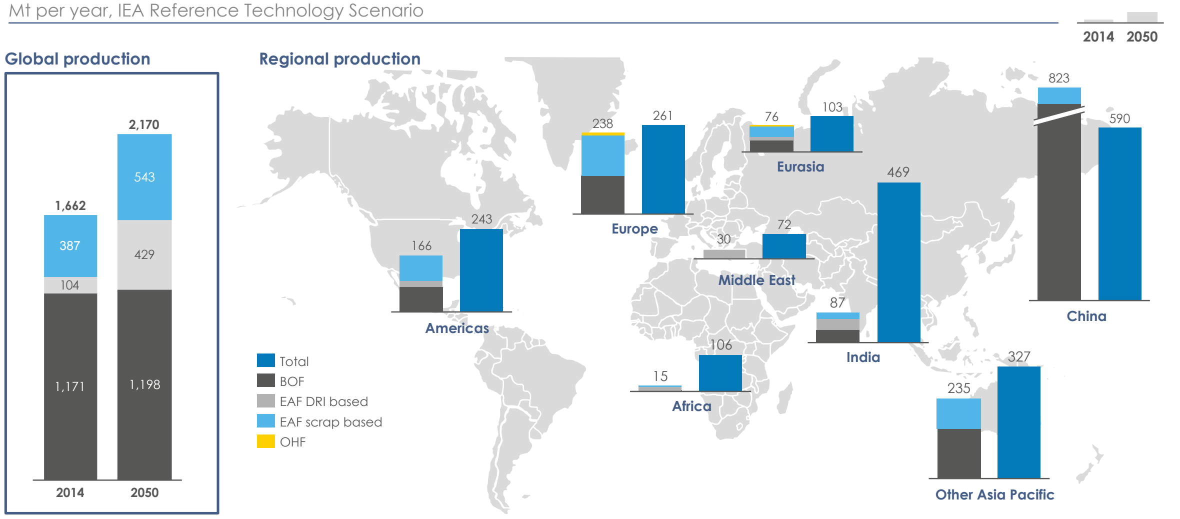


Note: Global and China bar graphs are not on the same scale as other regions/countries.
Source: IEA (2017), *Energy Technology Perspectives;* IEA-CSI (2018), *Technology Roadmap – Low-carbon transition in the cement industry*

Exhibit 2.1

Global annual steel production is expected to increase by 30% by mid-century

Global steel production
Mt per year, IEA Reference Technology Scenario



Note: Global and China bar graphs are not on the same scale as other regions/countries.
Source: IEA (2017), *Energy Technology Perspectives*

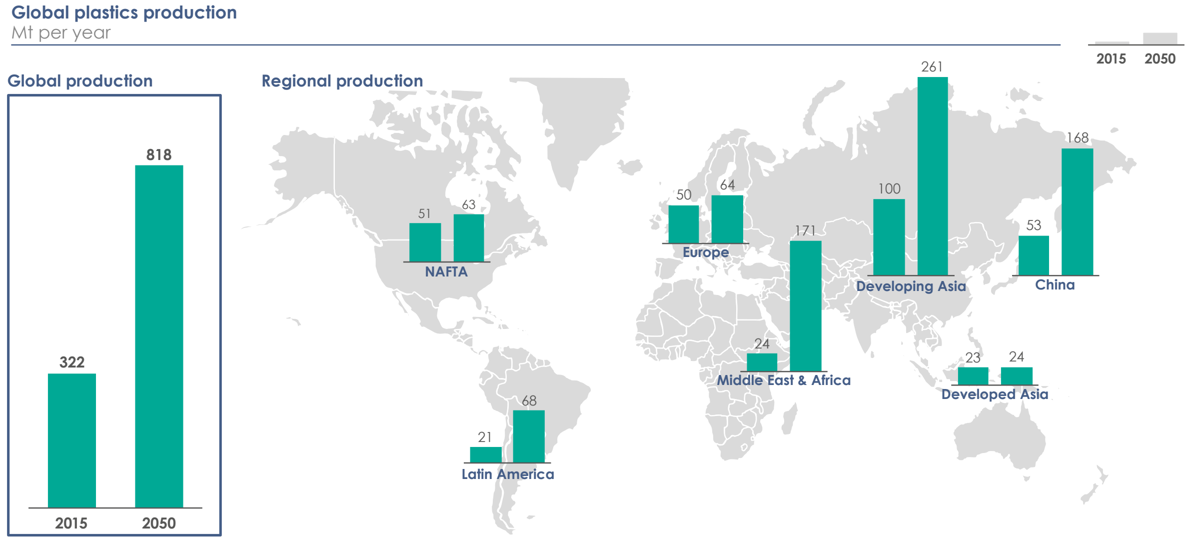
Exhibit 2.2

If demand growth of these magnitudes occurred, and if there were no major changes to production processes, **total emissions in these sectors could grow from 5.6Mt CO_2 today to 7.1Mt by 2050**[9]. This, in turn, would account for an increasing share of total emissions (from 16% to 18%), as power decarbonization and electrification drive emissions reductions in the easier-to-abate sectors of the economy.

However, in principle, there are huge opportunities to reduce demand for each of these materials, while continuing to deliver the manufactured products, vehicles, buildings and infrastructure that consumers around the world want to access. Analysis by the ETC's knowledge partner Material Economics[10] has concluded that **emissions from key industrial sectors could be cut by 56% below business-as-usual projections in Europe and 40% globally by 2050** if feasible improvements were achieved in the efficiency with which materials are used [Exhibit 2.4].

This entails two major developments: (i) making better use of existing stocks of materials through **greater and better recycling and reuse** and (ii) **reducing the materials requirements** in key value chains (e.g. transport, buildings, consumer goods, etc.) through improved product design, longer product lifetime, and new business models that deliver the same level of service to end consumers with a smaller quantity of product (e.g. car sharing).

Global annual plastics production could increase by up to 150% by mid-century



Source: Material Economics (2018), *The circular economy – a powerful force for climate action*

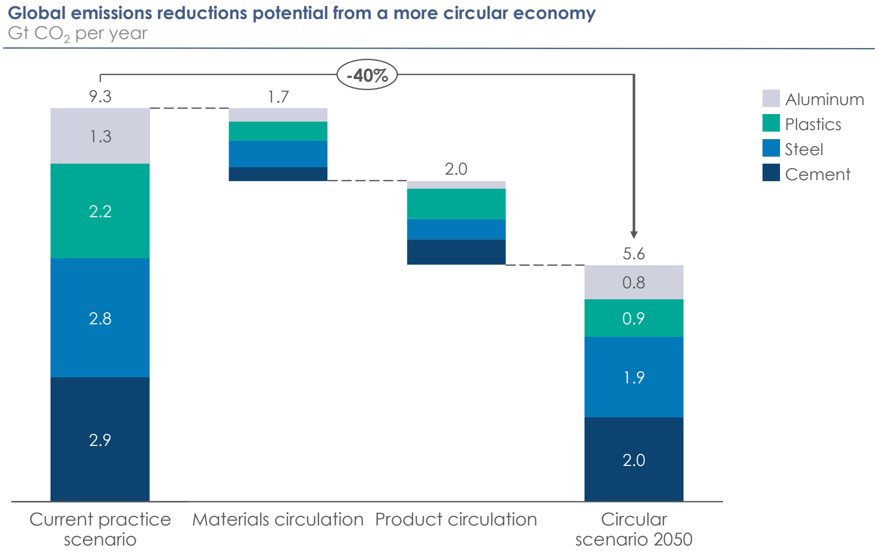
Exhibit 2.3

---

[9] IEA (2017), *Energy Technology Perspectives,* Reference Technology Scenario

[10] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*

A more circular economy can cut emissions from the harder-to-abate sectors in industry by 40% by 2050



Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 2.4

- Although about 83% of steel is already recycled when reaching end-of-life today (and up to 90% in some countries), this could be increased further if products were redesigned to facilitate end-of-life recycling into high-quality steel and limit downgrading in the recycling process. In addition, products, buildings and infrastructure could also be designed to use less steel. Applied across the whole world, this could **cut virgin steel demand globally by 38% by 2050**, and materially reduce total emissions given the far greater carbon intensity of virgin steel production (around $2tCO_2$ per tonne of steel) compared to scrap-based steel production (around $0.4tCO_2$ per tonne of steel and falling as electricity becomes less carbon-intensive)[11].

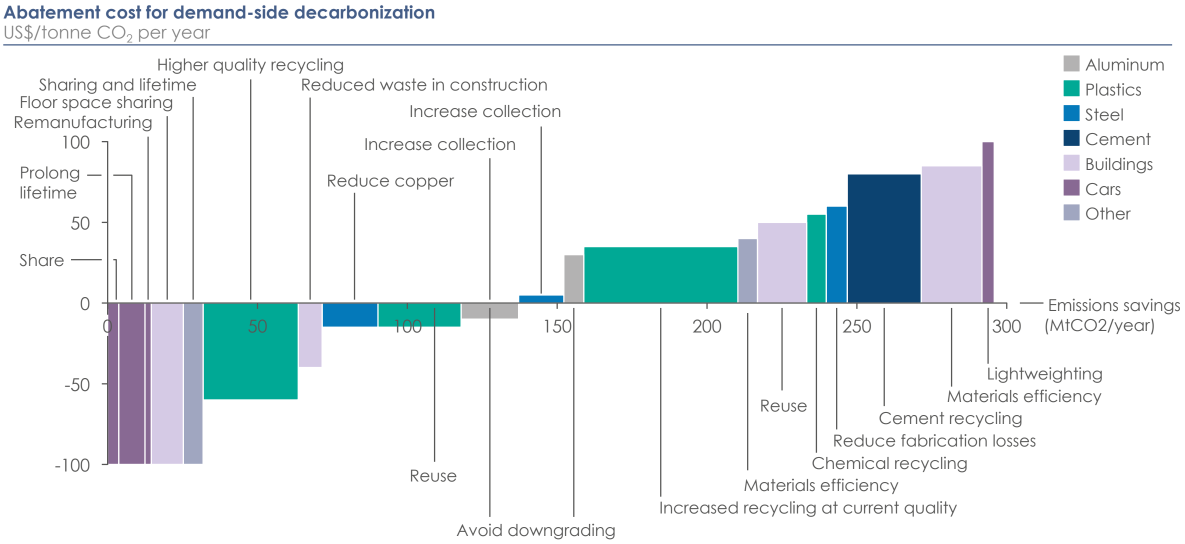
- There are also **significant opportunities to reduce cement demand by designing buildings more efficiently**, by recycling un-hydrated cement found in end-of-life concrete, and by reusing concrete itself. **Global emissions from cement production could be reduced by some 34% by 2050** in a circular scenario. In addition, there could be a very large long-term opportunity to use timber rather than concrete in construction, which would not only deliver significant reduction in emissions from cement production, but also constitute a permanent carbon sink. The key constraint here is the available supply of timber. To replace 25% of the 6.4 billion m^3 of concrete used each year with timber would require an increase of global forest cover of about 14% – a land area representing 1.5 times the size of India[12]. **A long-term reforestation program to support timber substitution is desirable** and could potentially be carried out on already degraded land, but it would have to be carefully conceived to avoid any adverse impact on biodiversity and it could, in any case, not make a major difference to concrete and cement demand for several decades. **A range of alternative low-carbon building materials are also currently being developed**, which could potentially substitute for concrete in the latter part of the century.
- **The greatest opportunities for circularity lie in plastics**, where it is vital for decarbonization

---

[11] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*

[12] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Demand-side decarbonization is feasible at a lower cost than supply-side decarbonization



Source: Material Economics (2018), *The circular economy: a powerful force for climate change*

Exhibit 2.5

strategies to address end-of-life emissions from incineration or decomposition in addition to emissions from production. While claims are often made that, for instance, the EU achieves 30% plastics recycling, the true figure is only about 10%[13]. Moreover, it can be argued that most current recycling does not achieve "closed loop recycling" into equally high-quality and high-priced plastic products (for instance, PET bottles recycled into PET bottles), but "downcycling" into lower value plastics (for instance black pots)[14]. With radical changes to the way in which plastics are used and handled, 28% of all plastics demand could be eliminated or substituted, while 25% of all plastics could be recycled and 2% re-used, delivering **a 56% reduction in global lifecycle emissions from plastics**. It is important to note, however, that significant end-of-life emissions would still remain. Eliminating these remaining emissions will require either: (i) a shift to non-fossil-fuel feedstock (bio-feedstock or electrochemical feedstock, with significant implications for total biomass and electricity demand respectively); (ii) the use of end-of-life plastics in, for instance, road and other construction foundations and surfaces; (iii) a remaining role for storage of plastics in secure, permanent and sealed landfilling sites – constituting in practice a form of carbon storage.

Material Economics analysis suggests that **the average cost of abatement for circular economy levers could be very low**, with some relatively expensive options (e.g. un-hydrated cement recycling) balanced by options that, at least in theory, should deliver positive returns (e.g. high-quality mechanical recycling of plastics) [Exhibit 2.5]. This is in contrast to the supply-side decarbonization options considered in the next section, which are likely to impose significant (but still acceptable) costs to the economy and to end consumers. Achieving the major demand reductions described above will, however, require radical changes to industry practices and investment, supported by strong public policies. These are discussed in Chapter 5.

---

[13] Material Economics (2018), *The circular economy – a powerful force for climate action*

[14] Material Economics (2018), *The circular economy – a powerful force for climate action*

ILLUSTRATION 2.1 – Chemical recycling of plastics attracts investment

According to Material Economics, chemical recycling of plastics could save up to $30MtCO_2$ per year, if it could substitute for virgin plastics production and avoid end-of-life emissions from plastics incineration, and this despite the fact that chemicals recycling is an energy-intensive process. The lifecycle carbon emissions of plastics produced through chemical recycling could 1 tonne CO_2 per tonne plastics produced results (instead of up to 5.1 tonne for virgin plastics)[15]. Chemical recycling is, in particular, an option for mixed and impure plastics waste flow that cannot be mechanically recycled.

Many companies are currently investing to develop chemical recycling:

- The Finnish energy company Neste is currently collaborating with the British company ReNewELP to convert plastic waste into fuels, chemical feedstocks and new plastics. A plant is planned in Wilton, England, that could convert 20,000 Mt of plastic waste into fuels[16].
- LyondellBasell, one of the world's largest plastics, chemical and refining company started has started a cooperation with Karlsruhe Institute of Technology (KIT) to develop a new catalyst and process technology to decompose post-consumer plastic waste (e.g. mixed packaging) into monomers which can be used in a polymerization processes to produce new plastics[17].
- Unilever announced, in 2017, a technology – CreaSolv – jointly developed with the Fraunhofer Institute for Process Engineering and Packaging IVV, with enables the chemical recycling of sachet waste to turn them into plastic. Hundreds of billions of plastic sachets are thrown away globally each year, ending up in landfills, streets or our oceans. Unilever is in the process of opening a pilot plant in Indonesia to trial CreaSolv on a commercial scale[18]. This initiative is part of Unilever's broader pledge to increase the use of recycled plastic content in its packaging by 25% and make 100% of packaging recyclable, reusable and compostable by 2025[19].

---

15 Material Economics (2018), *The circular economy: a powerful force for climate change*

16 Chemicals and Engineering News (2018, August 26), Volume 96, Issue 34, *Firm plans chemical recycling of plastics*

17 British Plastics & Rubber (2018, July 26), *LyondellBasell signs agreement with the Karlsruhe Institute of Technology to advance chemical recycling*

18 NIKKEY Asian Review (2017, May 18), *Unilever to test new packaging-recycling tech in Indonesia*

19 Unilever (2010), *Unilever develops new technology to tackle the global issue of plastic sachet waste*

(II) ENERGY EFFICIENCY IMPROVEMENT

Across all sectors of the global economy there are large opportunities to drive improved energy efficiency, and it is vital that climate mitigation strategies focus on these opportunities as well as on decarbonization technologies. **Opportunities for energy efficiency within the harder-to-abate industrial sectors are less than in some other parts of the economy** (such as, for instance, the residential sector where there are often huge opportunities to improve the efficiency of heating/ cooling through insulation and equipment). This reflects the fact that industrial operations are tightly managed, and the energy-intensive nature of the harder-to-abate sectors has created strong incentives to reduce energy costs.

But even within these sectors, there are many plants operating well below best available technology, in particular in developing economies, and a continual flow of new production technologies creates opportunities to improve the best available frontier. **Resulting energy efficiency improvement potentials are estimated to be about 10 to 20%**[20].

- **In cement production,** the IFC-World Bank estimates that **efficiency improvements of 10% might be possible**[21]. Similarly, the IEA and the Cement Sustainability Initiative (CSI) estimate that the global average energy intensity of clinker production could be reduced by 11% by 2050[22], reducing resulting emissions when fossil fuels are used to generate the energy. Dry kilns are significantly more energy efficient than wet kilns, and using pre-calciners, multistage cyclone heaters, and multichannel burners could deliver significant energy efficiency improvements as well. **The decrease of clinker-to-cement ratio is also a key element** of a sustainable cement industry, it has the potential of reducing almost 8% of total CO_2 emissions from the sector by 2050. Finally, process control and management in the different stages of cement production can

---

20 McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

21 IFC (2018), *Improving thermal and electric energy efficiency at cement plants: international best practice*

22 IEA & CSI (2018), *Technology Roadmap – low carbon transition in the cement industry*

> THERE ARE FOUR MAIN ROUTES TO THE SUPPLY-SIDE DECARBONIZATION OF INDUSTRY.

deliver some additional benefits[23].

- **In steel production**, applying best available technologies to all plants might **reduce energy consumption by 15 to 20%**[24]. In particular, there are underexploited opportunities to capture high-pressure gas leaving the furnace and use it to power other equipment, or to apply "coke dry quenching" (cooling using an inert gas instead of sprayed water). Other emerging technologies that might be commercially available by 2020 include top gas recycling in the blast furnace, Jet Basic Oxygen Furnace (Jet BOF) technology and scrap purification technology, each potentially delivering significant reductions in energy requirement. For example, Jet BOF with top gas recycling could reduce electricity consumption by 60%, coke gas consumption by 37% and coal consumption by 16%[25].
- **In plastics production, energy efficiency improvements in monomer production could reach 15 to 20%**[26]. Recent IEA analysis highlights that using naphtha catalytic cracking could itself deliver a 15% improvement[27].

Many of these energy efficiency improvements could in principle deliver attractive rates of return, thus **creating opportunities to abate CO_2 emissions at negative marginal cost** and significantly reducing the average abatement cost in the harder-to-abate industrial sectors. However, they often entail high upfront capital costs that individual industry players cannot always bear, especially in developing economies. It is therefore vital to create strong incentives to grasp these opportunities, and the policies required to drive more radical decarbonization – such as carbon pricing – will also help achieve this lower-cost abatement potential. But energy efficiency improvements alone will be inadequate to achieve full decarbonization.

(III) SUPPLY-SIDE DECARBONIZATION OPTIONS

Across the three industrial sectors we have analyzed, **there are opportunities to significantly reduce and eventually eliminate carbon emissions** at costs which, while significant for these industries themselves, would have little impact on total economic growth or on the living standards of individual consumers. Improvements in energy efficiency, even with broadly unchanged production processes, have an important role to play, but more fundamental changes will be needed to deliver complete decarbonization.

Technology options for decarbonization

It is technically possible to produce cement, steel and plastics while releasing close to net-zero CO_2 emissions in the atmosphere. In all cases (with the exception of new cement chemistries), this is achieved via one of four routes (or a combination thereof):

- **Direct electrification** of heat production, which will be zero-carbon once electricity generation has itself been fully decarbonized;
- **The use of biomass,** whether as an energy carrier or as a chemical feedstock, and whether in raw solid form or processed into biofuels or biogas – whose impact on carbon emissions varies depending on whether biomass production triggers any change in land use and whether all energy (and fertilizer) inputs to the biomass production and transformation process are themselves zero-carbon;
- **The application of carbon capture,** combined with either use or storage – since carbon capture itself involves significant electricity inputs, this also requires zero-carbon electricity to achieve full decarbonization;
- **The use of hydrogen as an energy carrier or reduction agent,** which could in turn be produced from zero-carbon electricity via electrolysis, from steam methane reforming combined with carbon capture, or from biomethane reforming (although the latter is unlikely to develop at scale, given constraints on biomass availability).

These four sets of technologies can be applied across all the harder-to-abate industrial sectors:

- **Within cement production,** the energy input for heat generation could be electrified, or switched from coal to biomass, biogas or hydrogen. However, process emissions arising

---

[23] Environmental Protection Agency, U.S. EPA. Worrell E., K. Kermeli, C. Galitsky. (2013). *Energy efficiency improvement and cost saving opportunities for cement making. United States*

[24] McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

[25] Silveira, Xylia et al. (2018), *Worldwide resource efficient steel production*

[26] McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

[27] IEA (2018), *The future of petrochemicals*

from the transformation of limestone (calcium carbonate, C_ACO_3) into calcium oxide (C_AO) would still remain. The only alternative to carbon capture on process emissions to achieve radical decarbonization of cement production is therefore the use of alternative cement chemistries that do not use limestone feedstock or reduce Portland clinker input. Several alternative options exist with different carbon reduction potential. Magnesia-based cement and alkali/geopolymer binders, such as pozzolan, appear to be the most promising alternatives, but could be constrained by availability of raw materials.

- **In steel,** blast furnace virgin production could be decarbonized by capturing CO_2 emissions, or using sustainable charcoal as a heat source and reduction agent. Hydrogen can be used to produce virgin steel via direct reduction of iron (DRI). Scrap-based steel production (i.e. recycling) is already typically done in electric arc furnaces (EAF) and, in the long run, the direct use of electricity to reduce iron ore via electrolysis may become viable.
- **In plastics,** the heat input to monomer production could be electrified, or switched to biogas or hydrogen. Carbon capture could also be applied to the exhaust gases of pyrolysis furnaces. But even full decarbonization of monomer production would not be sufficient to remove all the emissions from plastics, given both emissions in other steps of the production process and at end-of-life. It will, therefore, be essential for a significant proportion of plastics to be made from bio-feedstocks rather than from ethane or naphtha, and for end-of-life management to be greatly improved through recycling or secure landfilling. In the long term, new electrochemical processes may become possible.

The technical feasibility of producing cement, steel and plastics with close to zero CO_2 emissions is not therefore in doubt and Illustrations 1.1, 1.2 and 1.3 highlight examples of companies which are developing zero-carbon technologies and planning to deploy them at scale over the next three decades. It will, however, require significant inputs of low and eventually zero-carbon electricity, as well, as some level of carbon capture and sequestration. Cross-sectoral implications are developed in Chapters 6 and 7.

ILLUSTRATION 2.2 – HYBRIT: a public-private partnership for fossil-free steel

The 'Hydrogen Breakthrough Ironmaking Technology' project (HYBRIT) was launched in 2016 in Sweden, as a joint venture between the steel producer SSAB, iron ore extractor LAB and state-owned electricity company Vattenfall, with the support of the Swedish government. The three owning companies will invest SEK 830 million in the first pilot plants, while the Swedish Energy Agency will contribute an additional SEK 528 million. The goal of HYBRIT is to develop a zero-carbon steelmaking process based on hydrogen reduction of iron, instead of coal and coke and be in a position to scale a fossil-free, ore-based industrial steel production process by 2040.

After an initial research phase and pre-feasibility study, the construction of a world-unique pilot plant in Sweden has now started. They are expected to be delivered by 2020. Pilot plant trials will run until 2024, with subsequent demonstration plant trials from 2025 to 2035. These trials are essential to test new production techniques at scale and refine engineering requirements.

Keys to the success of HYBRIT are the local availability of low-carbon electricity from hydro sources (which makes zero-carbon hydrogen production at larger scale possible), the leading position of the Swedish steel industry (with some of the world's highest quality magnetite-iron ore) and the commitment of the government to a low-carbon future. Finally, involved companies are able and willing to cooperate with each other as they are involved at different stages of the steelmaking process and not directly competing with each other.

Promoters of HYBRIT are confident that, while today fossil-fuel-free steel would be more expensive than traditional steel, expected declining prices in zero-carbon electricity and increasing CO_2 prices the future fossil-free steel will eventually make hydrogen-base steel cost-competitive. HYBRIT is expected to reduce Sweden's total CO_2 emissions by 10% and Finland's by 7%[28].

[28] HYBRIT (2018), *Towards Fossil-Free Steel*

Decarbonization costs

The least costly route to decarbonization will vary according to local conditions and the changing price of key inputs, in particular the price at which electricity is available for industrial applications. In cement and plastics, significant decarbonization costs are likely unavoidable due, respectively, to the difficulty of removing process emissions and to the need for low-carbon feedstock to remove end-of-life emissions. Steel decarbonization is likely to be less costly. Implications for the global economy and for end-consumer prices are discussed in Chapter 4.

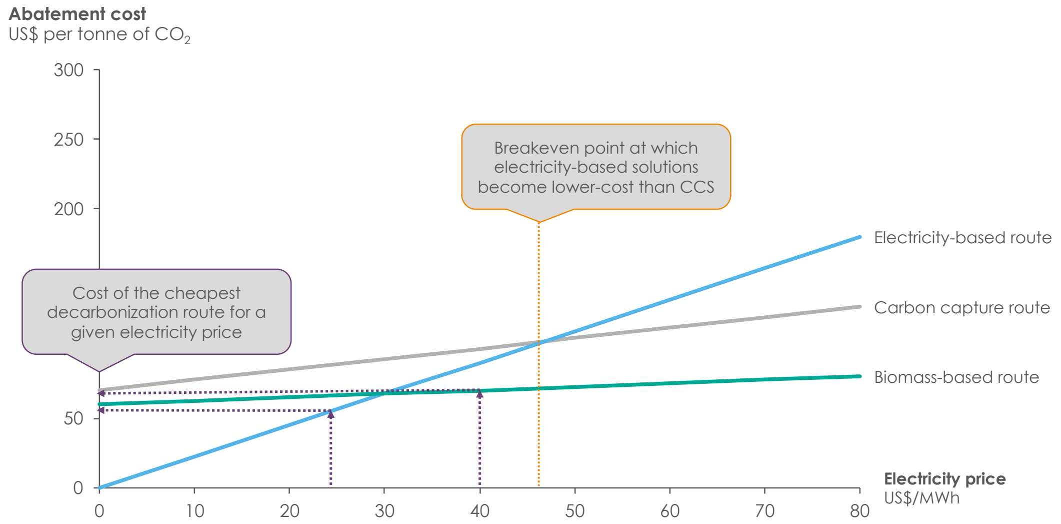
Exhibit 2.6 sets out the conceptual framework for understanding how the abatement cost per tonne of CO_2 saved (on the vertical axis) varies with the cost of zero-carbon electricity (shown on the horizontal axis)[29]:

- If electricity is used as the decarbonization route, the **cost per tonne of CO_2 saved will vary strongly with the electricity price** and could become negative if electricity prices were extremely low. The same is true if decarbonization is achieved via the use of hydrogen itself produced from electricity.
- Installing **CO_2 capture equipment and paying for CO_2 transport and storage will always add to the cost of existing fossil-fuel-based processes** and will therefore always impose a positive cost of carbon abatement, with the cost per tonne rising slightly as electricity prices rise, due to the electricity inputs to the capture process. The same is true if decarbonization is achieved via the use of hydrogen itself produced from SMR combined with carbon capture.
- **Bioenergy is likely always to be significantly higher than fossil fuel alternatives,** generating a positive cost of abatement per tonne, which will tend to be less affected by electricity prices. These costs, however, will differ significantly by type of biomass and by region, implying a differentiated role for bioenergy across geographies.
- The interaction between the lines indicates how low electricity prices have to be for the electrification route to achieve lower costs than the carbon capture or bioenergy routes.

The analysis by the ETC's knowledge partner McKinsey suggests that[30]:

- **In cement production,** using biomass for heat plus CCS on process emissions might always be the lowest-cost route to decarbonization, even if renewable electricity prices were zero, given the significant additional cost likely to be involved in the construction of electric kilns. But, if zero-carbon electricity were available below **US$42/MWh** for a greenfield project (US$22/MWh for brownfield), electrification of heat production combined with

In each industry sector, there is a trade-off between three major decarbonization routes: electrification (direct or indirect), carbon capture or use of biomass



Source: McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 2.6

---

[29] McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

[30] McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

CCS to capture the process emissions might be cheaper than simply applying CCS to both heat and process emissions.

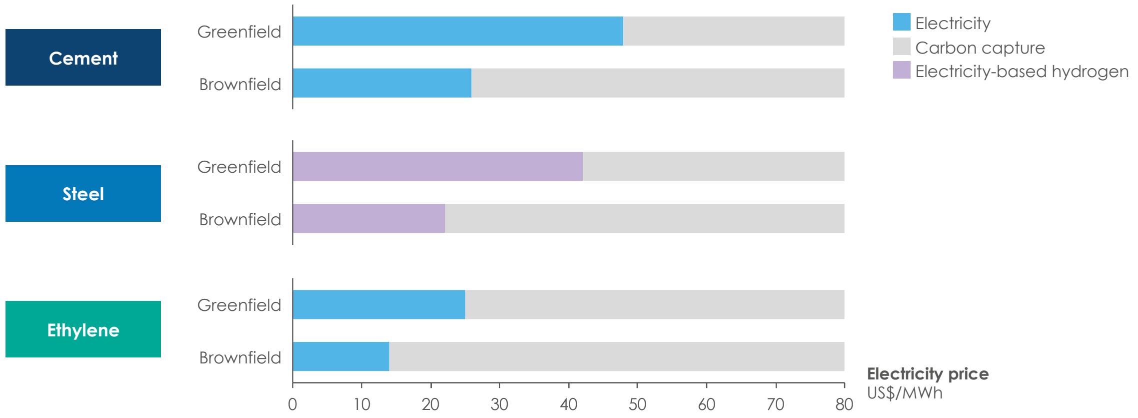
- **For steel**, the use of hydrogen in DRI-EAF might be lower cost than carbon capture on BOF if wholesale prices for zero-carbon electricity were below about **US$45/MWh** for a greenfield plant and US$25/MWh in a brownfield project. However, unless electricity cost fall below US$20/MWh, using charcoal in blast furnaces could deliver carbon emission reductions at a lower cost per tonne saved in locations, like Brazil, where it might be available on a significant scale.
- **For plastics,** electrification of the heat input to monomer production could be a cheaper route to decarbonization than CCS if electricity costs less than **US$25/MWh** for a greenfield plant (US$15/MWh for brownfield). Using biodiesel as a feedstock would represent a very high cost per tonne of CO_2 saved if calculated based on production emissions only (US$1,000 per tonne), but would represent a much lower abatement cost of US$200 per tonne if end-of-life emissions were (as they should be) taken into account. Several of the recycling options considered earlier would, however, eliminate end-of-life emissions at a lower cost.

Exhibit 2.7 illustrates at which price of zero-carbon electricity the electricity-based route would become cheaper than carbon capture for each of the three industrial sectors. Exhibit 2.8 illustrates which technology option would be the cheapest route to decarbonization at different electricity costs and what would be the implied abatement cost per tonne of CO_2. The use of biomass is not represented on these exhibits: although we acknowledge that biomass use may well be the lowest-cost decarbonization option in many cases today, this will vary significantly by region and the **limited availability of sustainable biomass** (discussed in Chapter 6) **will limit its use in industrial applications.**

For reasons we set out in Chapter 5, we believe that **there will be some locations in which renewable electricity is available at prices below the breakeven points** illustrated on Exhibits 2.7 and 2.8. Taking into account the probable balance between greenfield and brownfield sites, the opportunity to choose a cheaper biomass route in some locations, as well as, regional variations in electricity and carbon capture prices across different geographies, McKinsey & Company suggests that[31]:

Whether electricity-based decarbonization is cheaper than a carbon capture route will be strongly driven by the electricity price

Cheapest supply-side decarbonization route of primary production depending on electricity price
US$/MWh



Note: Biomass may be lower cost in some geographies but is not considered as a priority option due to limited availability
Source: McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 2.7

---

[31] McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

- **Cement** decarbonization would cost on average US$130 per tonne.
- **Steel** can be decarbonized on average at US$60 per tonne (and maybe considerably less in a scenario where cheap renewable electricity would be widely available).
- **Plastics** decarbonization should be possible at an average cost of US$295 per tonne, once taking into account the use of bio-feedstock[32].

The implications of such costs for the economy and for end consumers are considered in Chapter 4 (alongside those for the transport sectors).

Implications for different locations

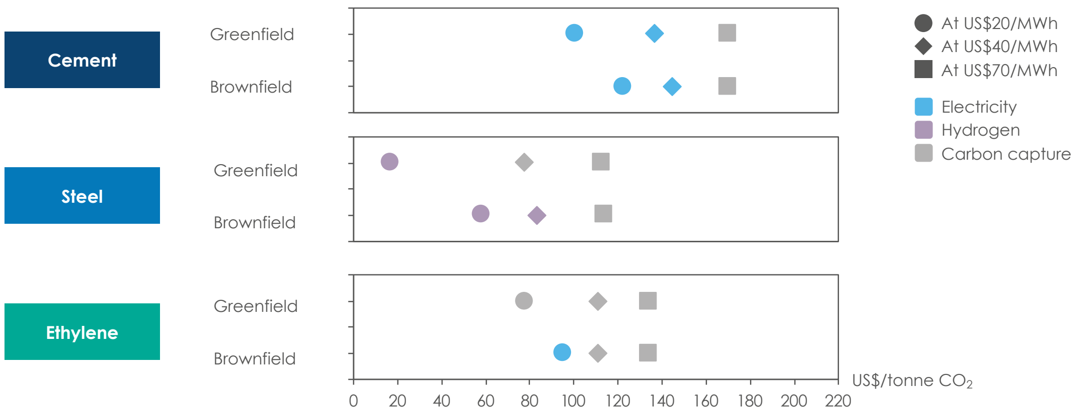
Given the analysis above, national governments and industry can and should set targets to achieve zero CO_2 emissions from harder-to-abate sectors in industry by mid-century. But, while the end objective is clear, the precise route to decarbonization cannot and does not need to be defined in advance. **The industry decarbonization pathway will be determined by unpredictable future cost developments and will vary by location** (as described in more details in Chapter 6):

- The price of renewable electricity will vary greatly by location given huge variations in wind and solar resources. In some locations, renewable electricity will be available at a wholesale price of below US$20/MWh. In others, prices might be US$70/MWh.
- Carbon capture costs will vary by sector, but are likely, in the long run, to be somewhat similar in different regions. However, transportation and storage costs will vary significantly by location.
- The natural resource endowments of biomass vary hugely by continent. For instance, Latin America has 17 times the forestry endowment per capita of China[33]. As a result, options available in some locations (for instance the use of charcoal instead of coal in steel blast furnaces in Brazil) may be irrelevant in many others. In addition, the use of biomass should be managed carefully given limited supply of truly sustainable biomass.

Public policy therefore cannot be based on a precise prediction of the optimal way forward. Instead, it should **impose sufficiently strong carbon prices and regulations to ensure that decarbonization is achieved via one route or another**, leaving it to the market to decide the optimal mix of different routes, while also supporting those technologies which are certain to play a significant role. Chapter 9 describes the detailed implications for policy.

The decarbonization cost per tonne of CO_2 will vary depending on industry and on local electricity prices

Cheapest supply-side decarbonization route and abatement cost at different electricity prices
US$/tonne CO_2



Note: Bioenergy may be lower in cost in some geographies but is not considered as a priority option due to limited availability
Source: McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 2.8

---

[32] SYSTEMIQ analysis for the Energy Transitions Commission (2018)
[33] SYSTEMIQ analysis for the Energy Transitions Commission (2018), based on nationmaster.com

ILLUSTRATION 2.3 – Dalmia Cement targets net-zero CO_2 emissions by 2040

The Indian cement producer Dalmia Cement (Bharat) Limited has already achieved the lowest cement carbon footprint in the world according to CDP. Between 2015 to 2016, Dalmia Cement adopted the latest technologies to implement international energy management standards for the industry – in particular by increasing the use of 'blended' cement, hence optimizing the clinker-to-cement ratio, and by reducing energy intensity. It was able to reduce CO_2 emissions to 526kg/t cement produced as a group average and 342kg/t in its most efficient operations (in comparison to a global average of 900kg/t). This created co-benefits as using industrial waste products (as blast furnace slag from the steel industry and fly ash from thermal power plants) extends the lifespan of cement. In parallel, the company decided to become "water positive", given high risks on its water ecosystem. The company's earnings went up by 70% and costs were cut by 27% as a result of this strategic move.

At the Global Climate Action Summit in September 2018, Dalmia Cement announced its long-term vision of becoming carbon-negative by 2040. The company has commissioned 8MW of new solar power and became the first cement company worldwide to join the RE100 initiative, committing to 100 percent renewable energy use. Recognizing that production emissions and energy intensity are directly linked to operating costs, Managing Director and CEO Mahindra Singhi set as a priority to convert climate risks into business opportunities and new revenue streams[34].

[34] Economic Times – India Times (2018, September 17), *Dalmia Cement aims to be carbon negative by 2040*

(IV) THE TRANSITION TO NET-ZERO CARBON

Although it will eventually be possible to fully decarbonize cement, steel and plastics, it is vital to recognize the **constraints C - that may slow progress** to full decarbonization and to assess whether transitional option should be pursued, even if these deliver only partial decarbonization. This section therefore considers implementation constraints and transition options.

Implementation challenges and constraints

One crucial feature of the heavy industry sectors is that **production plants often have very long lives**. Steel blast furnaces are sometimes used without fundamental retrofit for 30 to 40 years; so too are some cement kilns. As a result, **where existing plants can still be used for many years, the switching cost to fundamentally new technologies may be much higher than where new industrial capacity will be built** in the next decades to meet increasing demand.

- This is particularly true for the electrification and hydrogen routes: the electricity and hydrogen prices required to make it cost-effective to replace an existing brownfield plant are considerably lower than when a greenfield facility is in any case being constructed.
- In comparison, carbon capture can, in most cases, be retrofitted onto already existing plants, although, by definition, will add significant cost to existing operations. Similarly, while bioenergy sources can in many cases be used within existing plants, bioenergy is likely to be significantly more expensive than fossil fuels for many years and perhaps permanently.

Moreover, **many of the technologies that would enable full decarbonization are not yet commercially ready**. Hydrogen-based industrial processes and cement kiln electrification, for instance, may not be commercially ready till 2040. Progress towards decarbonization is therefore likely to take considerable time and will vary depending on sector, region and indeed individual plants.
In particular:

- **In cement,** further significant development will be required before kiln electrification is feasible, and significant kiln rebuilding will then be needed. This may favor use of biomass or carbon capture to achieve decarbonization.
- **In steel,** switching from blast furnace reduction to hydrogen-based DRI is likely to require the scrapping of existing plants, though

some intermediate transition paths are now being developed, which would allow partial replacement of coking coal with hydrogen even within blast furnaces. Where methane/syngas-based DRI is already in place, a transition to hydrogen could be managed more easily, in the phased fashion envisaged, for instance, by the German steel company Salzgitter.

- **In plastics,** major development work is still required to bring electric furnaces to commercial readiness, and even greater research efforts needed to develop entirely new electrochemical processes. As a result, initial progress towards production decarbonization may be slow. Forceful action to increase recycling as soon as possible will therefore be particularly vital in the plastics sector, both to reduce primary production volumes and to limit end-of-life emissions.

Given the long lead times and major new investments required, it is vital for public policy to provide clear incentives for change – whether via carbon pricing or regulations –, established well in advance and becoming stronger over time, and for businesses facing these incentives to develop long-term strategic plans to achieve net-zero CO_2 emissions over a 30 to 40-year period.

Transition options: the role of gas in industry

Progress to full decarbonization will inevitably be gradual. In particular, where the route taken is electrification or the use of hydrogen, change will take several decades. It is, therefore, vital to consider intermediate options which would at least reduce emissions in the short-term, while ensuring that partial solutions do not preclude or delay more radical change.

On average, gas combustion typically produces around 50% less emissions than coal (depending on coal quality)[35]: switching from coal to gas could therefore significantly reduce emissions, **provided that methane leakage across the whole production, distribution and application chain is less than 1-3%** (depending on applications)[36]. Full decarbonization would require subsequent application of carbon capture, the substitution of biogas for natural gas, or a switch to the electrification/hydrogen route. Provided strategies for eventual full decarbonization are in place, an immediate transition to gas could play a significant role in some sectors and regions.

LONG ASSET LIVES MAY SLOW DOWN PROGRESS

- **In cement**, where carbon capture will in any case be required to capture the process emissions, **switching from coal to gas kiln heating** would be easier and more rapidly implementable than kiln electrification, with the subsequent application of capture or use of biogas allowing a route to full decarbonization.
- **In steel**, there is limited potential to switch existing blast furnaces to gas. But **switching from blast furnace production to methane-based DRI** would result in significant immediate emission reductions (e.g. up to 50%) and could enable subsequent transition to hydrogen-based DRI.
- **Plastics production** in developed economies already primarily uses either gas-based (ethane) or oil-based (naphtha) feedstocks, but there is still significant use of coal in China. **Switching the Chinese chemical industry from coal to gas feedstocks** could therefore deliver significant CO_2 emissions reductions.
- Similarly, **China makes a significant amount of hydrogen, and thus ammonia, starting with coal rather than gas**. Switching to gas could deliver significant immediate emissions reductions, and carbon capture on SMR could then provide a route to full decarbonization.

Even **a fairly moderate carbon price could be a powerful incentive** to drive change: in the UK, a carbon price of about US$25 per tonne has driven a rapid shift from coal to gas power generation. Carbon prices should be used to encourage a similar switch in industrial sectors.

Gas could therefore, in principle, play a significant role as a transition fuel enabling short-term emissions reduction in industry. However, limited local availability of gas, in particular in China and India, may, in practice, constrain that potential, unless LNG provides a route to rapid deployment in these locations.

To ensure that the use of gas as a transition fuel is truly beneficial for the climate, methane leakages need to be tightly controlled and strategies to eventually progress to full decarbonization in place. These conditions are developed in Chapter 7.

---

[35] Salovaara, Jackson (2011), *Coal to Natural Gas Fuel Switching and CO_2 Emissions Reduction, Harvard College*

[36] Yue Qin et al (2017), *Environmental Science & Technology*

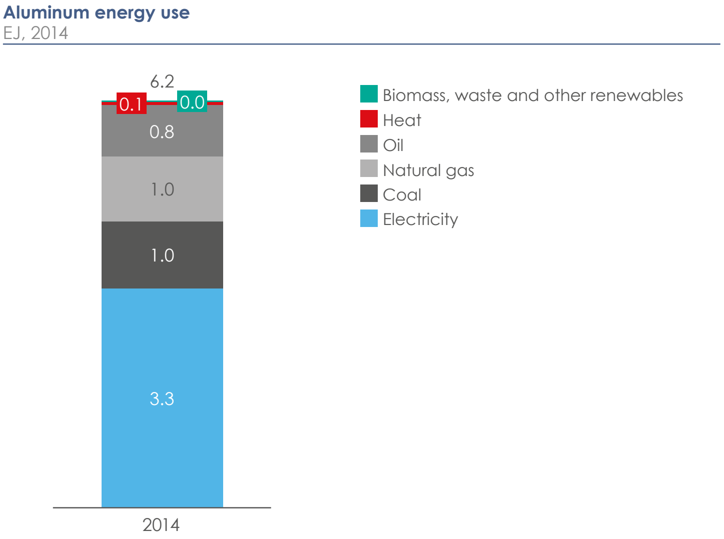
DECARBONIZING ALUMINUM

Aluminum production accounts today for 6.2EJ of energy use and 0.3Mt of CO_2 emissions[37] [Exhibit 2.9]. From 1990 to 2008, the aluminum industry achieved a reduction in the greenhouse gas intensity of its production of circa 22% globally. Despite this reduction, global emissions from the sector remained around the same level due to increase in demand[38]. Unlike in the case of iron and steel, a significant proportion of aluminum is already produced via the direct electrochemical process of electrolysis and, as a result, **aluminum production can in principle be largely decarbonized as and when electricity generation is decarbonized.**

Additional efficiency is achievable through automation and processes optimization to decrease the energy consumption of the different production stages. For example, the theoretical minimum energy consumption from smelters is half of the present energy consumption of the average smelter in the US[39].

The total economic cost of decarbonization could be significantly reduced by increasing the percentage of aluminum which is recycled. Recent estimates show that there is enormous potential to reduce virgin aluminum production in developed countries and regions. Europe has the potential to reduce its primary aluminum consumption to 30% of present levels, Japan 60%, the United States 65% and China 85%[40].

Electricity is the major energy source used in aluminum production



Source: IEA(2017), *Energy Technology Perspectives*

Exhibit 2.9

---

[37] IEA (2017), *Energy Technology Perspectives*

[38] Columbia Climate Center (2012), *The GNCS Factsheets: Mitigating Emissions from Aluminum*

[39] Columbia Climate Center (2012), *The GNCS Factsheets: Mitigating Emissions from Aluminum*

[40] Hiroki Hatayama et al (2009), *Assessment of the Recycling Potential of Aluminum in Japan, the United States, Europe and China*

DECARBONIZING AMMONIA

Apart from plastics, **ammonia is the most important chemical in terms of energy use and CO_2 emissions**. Global emissions from ammonia production are 15% higher than those from ethylene and more than double compared to other chemicals such as propylene, methanol and BTX[41].

As Chapters 3 and 5 will discuss, moreover, **the use of ammonia is likely to grow significantly**, with major potential application as a shipping fuel and as an energy carrier on an international scale. It is therefore essential to cut the emissions resulting from ammonia production and use.

On the production side, there are two main routes to decarbonization:

- The first option is to **apply carbon capture** on the CO_2 stream resulting from the currently dominant steam methane reforming (SMR) process for hydrogen production. The CO_2 stream produced in the SMR process is twofold. The process CO_2 stream is relatively pure, therefore capture costs are minimal. In most ammonia plants, these concentrated flows are already captured and used for urea or methane production. The remaining emissions relate to natural gas combustion and are more diluted and costlier to capture. The cost-competitiveness of SMR plus carbon capture will therefore depend on how much of the CO_2 streams is actually captured and on whether the heat input can be electrified (rather than produced by combustion of gas). In the best case scenario, in any case, the SMR route would only be a close-to-zero-carbon solution, given 10-20% of leakage in the capture process.
- The second option is to **shift to the production of hydrogen from electrolysis.** This could become the dominant production route. The cost will depend on the cost of zero-carbon electricity and on the capital cost of electrolysis. As Chapter 5 will describe, both these costs are likely to fall significantly over time, particularly in regions with favorable wind and solar resources.

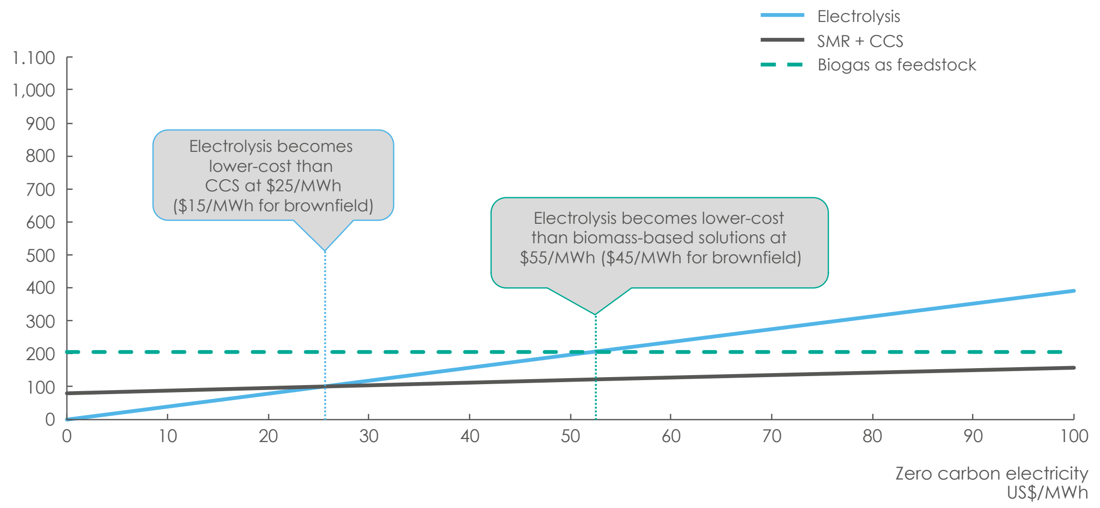
The optimal route forward to reach net-zero CO_2 emissions from ammonia production will therefore vary by region in the light of natural resource availability and electricity prices [Exhibit 2.10]. But, by one route or another, it will be **possible to decarbonize ammonia production at a relatively low cost** of US$80/t$CO_2$ saved or lower.

---

[41] IEA (2013), *Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*

Electricity-based ammonia production becomes lower-cost than fossil fuel-based production with CCS if electricity is cheaper than US$25/MWh

Abatement cost in ammonia production – greenfield
US$/tonne CO_2



Electrolysis becomes lower-cost than CCS at $25/MWh ($15/MWh for brownfield)

Electrolysis becomes lower-cost than biomass-based solutions at $55/MWh ($45/MWh for brownfield)

Source: McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 2.10

While decarbonizing ammonia production will allow zero-carbon use of ammonia in transport and energy-related applications, **the majority of ammonia is currently being used in urea-based fertilizers**, with CO_2 (often captured from the SMR process) combined with ammonia to produce the fertilizer. **This CO_2 is in turn released when the urea-based fertilizers are used**. Elimination of these CO_2 emissions will therefore require either:

- A move away from urea-based to other (e.g. nitrate-based) fertilizers;
- Use of biogas as the input to a SMR process, from which CO_2 is then captured and used in the production of urea-based fertilizers;
- The use of CO_2 directly captured from the air (DAC) combined with zero-carbon ammonia.

Targeted policies will therefore be required to deliver the long-term elimination of in-use emissions from urea-based fertilizers alongside the easier and less costly decarbonization of ammonia production.

3

The road to net-zero carbon: Heavy-duty transport

Total emissions from all the transport sectors amount to 4.5Gt[1] and, under all business-as-usual scenarios, are predicted to grow significantly over the next 40 years [Exhibit 3.1]. Today, passenger cars account for over half of all transport emissions. But the predominant long-term route to decarbonization of light-duty road transport, through battery electric vehicles (BEVs) using decarbonized electricity is now fairly clear, even if the precise pace of transition is still uncertain. By contrast, in the heavy-duty transport sectors, heavy-duty road transport, shipping and aviation, **the constraints imposed by battery weight make the transition more complex**. As a result, these three sectors will almost certainly account for a rising proportion of transport emissions and of all energy sector emissions over the next 20 to 30 years if an additional set of decarbonization technologies are not developed.

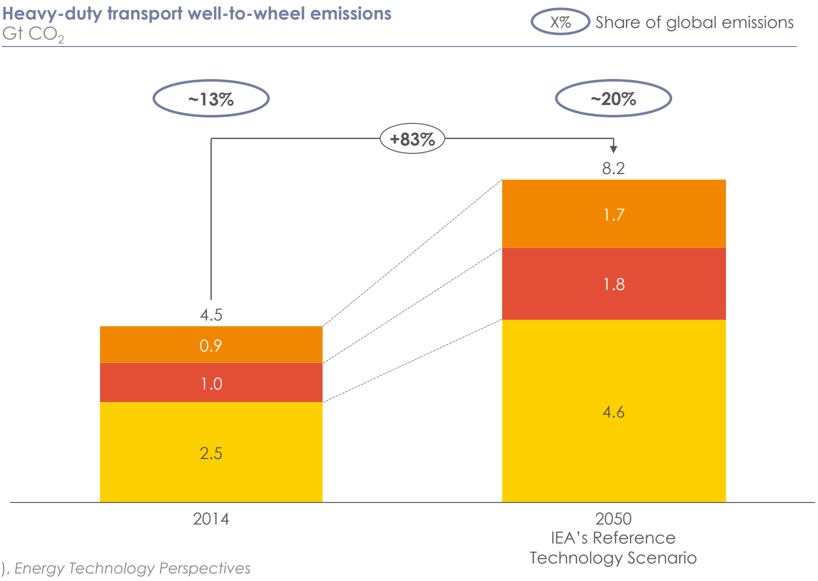
As with the industrial sectors discussed in Chapter 2, our overall conclusion is that each of the **three heavy-duty transport sectors could be completely decarbonized** by mid-century at costs which, while significant for individual industry players in the case of shipping and aviation, will make little difference to economic growth or consumer living standards.

However, the story for the transport sectors differs from the industrial sectors in three respects:

- While there are **opportunities to constrain transport demand** below business-as-usual levels, they are smaller than in the industrial sectors.
- The opportunities to **improve energy efficiency** appear to be even greater in the transport sectors than in the energy-intensive industrial sectors.
- Although, for industry, the optimal balance between different decarbonization paths within each sector is highly uncertain, in the transport sectors, inherent factors make **some paths far more probable than others.**
- **Transitional complexities appear to be less important** in transport than in industry, and the appropriate role of natural gas as a transition fuel is even smaller.

Detailed analyses of the heavy-road transport, shipping and aviation sectors is set out in Appendices 5-7.

Carbon emissions from heavy-duty transport could increase by 83% by 2050 in a business-as-usual scenario



Source: IEA (2017), *Energy Technology Perspectives*

Exhibit 3.1

---

[1] IEA (2017), *Energy Technology Perspectives*

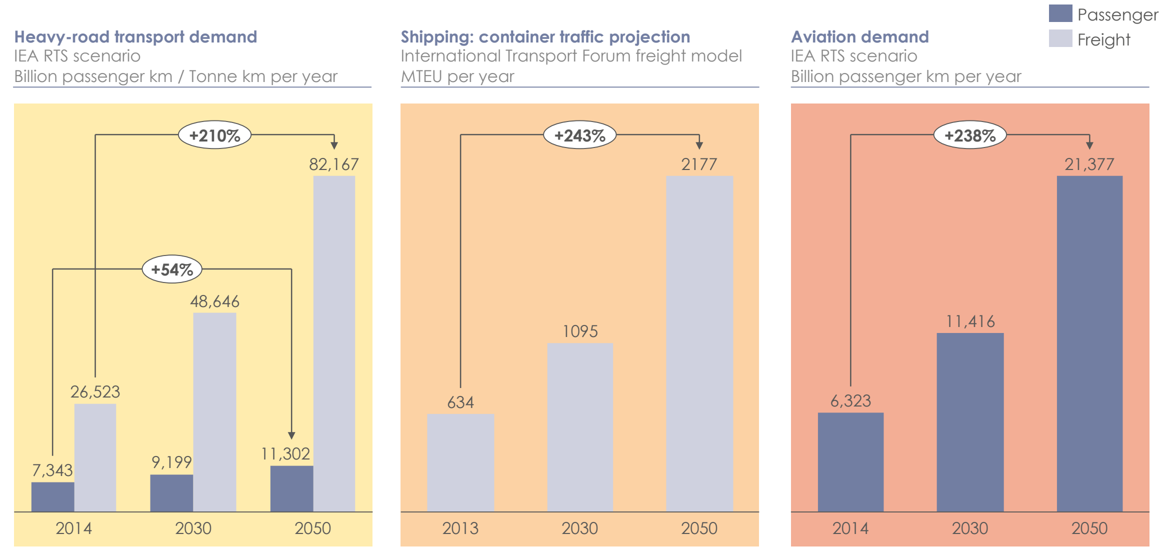
(I) DEMAND OUTLOOKS AND OPPORTUNITIES TO MODERATE DEMAND GROWTH

The expected growth in traffic volumes across all heavy-duty transport modes reflects the fact that **transport demand is highly income-elastic**. This is the case for both passenger travel (e.g. car journeys or flights) and freight travel, which contributes to increasingly intensive trade flows within countries and across the world. Accordingly, the growth in emissions over the next decade is expected to be driven by China, India and South-East Asia [Exhibits 3.2 and 3.3].

Chapter 2 describes the very large opportunity to reduce the use of cement, steel and plastics, while continuing to deliver the same benefit to consumers, through greater materials efficiency and recycling/reuse. Although, in the transport sectors, the consumer benefit does not derive from the existence of a stock of materials, but rather from the continual new provision of transport services, there are significant opportunities to reduce the volume of the demand for these services. The most important lever is logistics and operational efficiency, followed by modal shift. Our estimates suggest that **the potential to reduce carbon emissions through demand-side measures could reach 20%,** which is considerably less than in the industrial sectors, but still constitutes a meaningful contribution to emissions reduction [Exhibit 3.4].

- **Heavy-road transport** emissions could be reduced by **shifting road freight to more carbon-efficient rail, coastal or waterway shipping** – as well as shifting passenger bus transport to rail. However, the scope for such modal shift varies greatly by specific locations, depending on the availability and quality of the rail and waterway infrastructure. **Logistics and operational efficiency** improvements could in principle deliver major increases in load factors reducing the movement of underutilized trucks: eliminating backhauls and consolidating loads could eliminate up to 15% of truck ton-miles. Other helpful measures could include efficiency-based driver training and maximum speed reductions, which could deliver a total of 5% fuel use reduction[2]. The opportunity to reduce traffic growth below business-as-usual levels may theoretically reach 30%, but achieving this potential will be difficult, given the fragmented nature of the sector.

Heavy-duty transport demand is expected to increase significantly in the next 30 years



Source: IEA (2017), *Energy Technology Perspectives;* OECD (2017), *IFT Transport Outlook 2017*

Exhibit 3.2

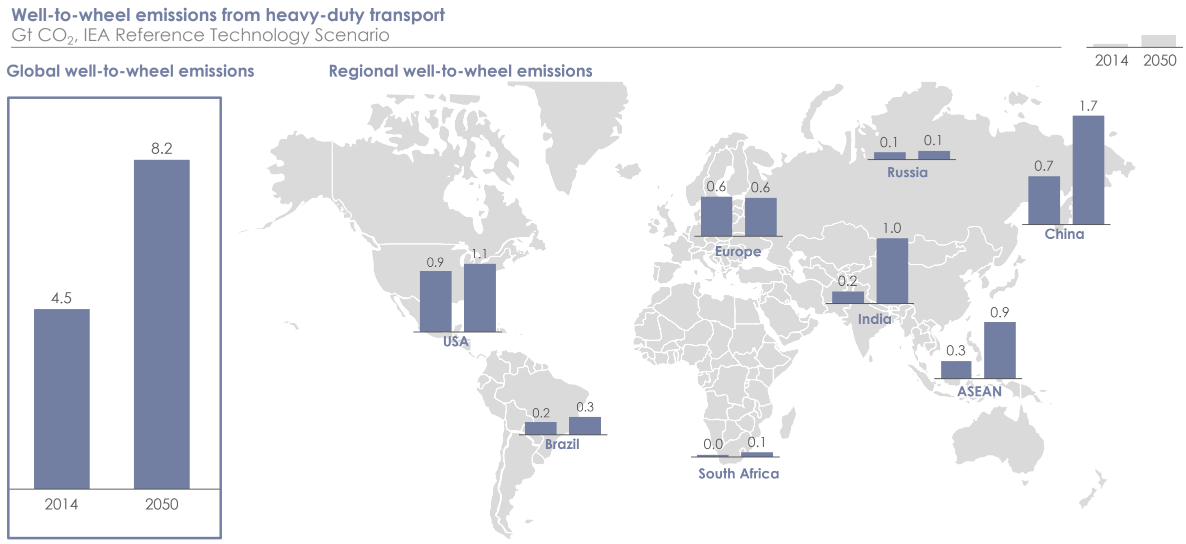
---

[2] Rocky Mountain Institute (2014), *Reinventing fire: transportation sector methodology*

- Since **shipping** is already the least carbon-intensive way to move freight, the potential for beneficial modal shift is slight. Some of the China-to-Europe trade may shift to rail, which, if powered by electricity or hydrogen, might be lower-carbon. But, for most shipping routes, modal shift is effectively impossible. Overall, **the potential to moderate shipping freight volumes through deliberate policy are likely to be slight**. Irrespectively, shipping demand may turn out to be less than forecast if, for instance, demand for coal, oil and LNG transport decline (in line with climate imperatives) or if manufacturing returns (in a highly automated form) to developed countries. Conversely, new international trades may emerge in hydrogen and ammonia.
- Emissions from **aviation could be reduced by shifting short and medium-distance passenger traffic to less carbon-intensive high-speed rail.** Such a shift has been witnessed between London and Paris, or between Beijing and Shanghai, but it requires significant investments in the rail infrastructure. With international flights accounting for over 55% of global emissions, the total potential impact of such a shift will, in any case, be limited. **Significantly higher prices for air travel** – which as discussed below may be needed to pay for zero-carbon fuels – **could moderate the growth of both leisure and business travel**. But, with a high income-elasticity of demand offsetting the price-elasticity effect, strong growth in total passenger flights is still likely. In addition, there are significant opportunities to reduce energy use and emissions via **better Air Traffic Management (ATM)**. Estimates suggest that operational and load factor improvements combined with trip passenger reduction could **achieve up to 15% reduction of fuel usage between 2010 and 2050**[3]**.**

It is still vitally important for those sectors to pursue logistics and operational efficiency, and for public policy to encourage moderation of transport demand growth. Many of the policies which will help drive supply-side decarbonization – in particular carbon pricing – will tend to also moderate demand. But, to a greater extent than in the industrial sectors, emissions reductions in transport will have to rely primarily on supply-side decarbonization.

The growth in heavy-duty transport emissions is concentrated in Asia



Source: IEA (2017), *Energy Technology Perspectives*

Exhibit 3.3

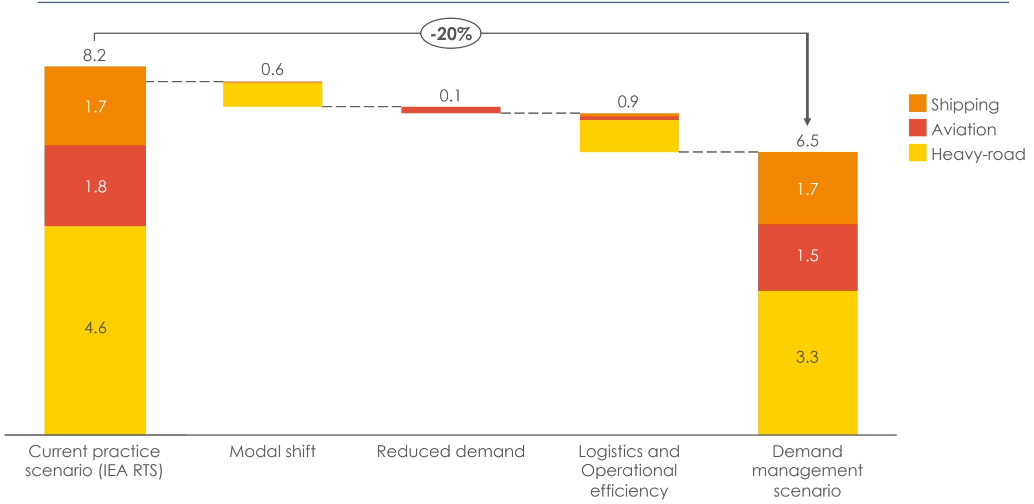
---

[3] Rocky Mountain Institute (2014), *Reinventing fire: transportation sector methodology*

Demand management can cut emissions from the harder-to-abate sectors in transport by 20% by 2050

Global emissions reductions potential from demand management

Gt CO_2 per year, 2050



Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 3.4

(II) ENERGY EFFICIENCY IMPROVEMENT

The opportunities to improve energy efficiency appear to be even greater in the transport sectors than in the energy-intensive industrial sectors:

- **In heavy-road transport**, there is significant potential to improve the **efficiency of internal combustion engines** (which will help reduce carbon emissions in the short term, prior to a probable switch to electric engines), and to **improve aerodynamic and tyre design** (which will improve the efficiency and reduce the operational costs of electric or hydrogen trucks as much as ICEs). There is, however, less potential for light-weighting in trucking than in cars, given the far lower ratio of vehicle weight to cargo/passenger weight. Overall, the Rocky Mountain Institute identified **a 45% aggregate efficiency gain potential** from design levers only[4]. Given the limited public policy focus on heavy-road transport until now, these opportunities have not been grasped as aggressively in trucking as in automobiles. But, in May 2018, the European Commission presented a legislative proposal which would require CO_2 emissions per tonne km for lorries, buses and coaches to fall by 15% by 2025 and 30% by 2030 vs. 2019 levels[5]. Before 2030, much of this improvement will likely be achieved through improvements in ICE trucks. **In the 2030s, the switch from ICE to electric or hydrogen trucks will likely be the most important energy efficiency lever**, given that electric engines are typically 45% more efficient than internal combustion engines.
- In theory, **shipping may present the greatest energy efficiency opportunity**. Estimates suggest that improved hull shape and materials, larger ships, drag reductions, hotel-load savings, and better engines and propulsors – together with minor logistics and routing improvements – could in principle deliver **overall efficiency improvements of 30-55%**[6]. Wind-sail assistance technologies could also very significantly reduce fuel use. Better optimization of voyage plans plus optimal approaches to ship speed (via slow steaming) could also in principle deliver significant reductions. However, the fragmented nature of the shipping industry, with its complex contracting structure, reduces the incentives to drive efficiency to its theoretical maximum level.
- **In aviation**, the **thermodynamic efficiency of new engines** is currently around 50% versus a maximum potential of 65-70%[7]. But, **new aircraft designs** could also achieve major improvements via the use of composite structure components, laminar flow control and open rotors, with improvements of 30% believed possible by 2030[8]. Beyond 2030, **more radical aircraft redesign**

---

4 Rocky Mountain Institute (2014), *Reinventing Fire: transportation sector methodology*

5 European Commission (May 2018), *Proposal for a Regulation of the European Parliament and of the Council setting CO_2 emission performance standards for new heavy-duty vehicles*

6 Rocky Mountain Institute (2005), *Winning the Oil Endgame*

7 National Academies of Sciences, Engineering, and Medicine (2016), *Commercial Aircraft Propulsion and Energy Systems Research Reducing Global Carbon Emissions*

8 IATA (2013), *Technology Roadmap*

(e.g. the introduction of blended wing bodies or radical changes in the positioning of fuel tanks to enable hydrogen-fueled planes) promises further improvement[9]. In addition, there are significant opportunities to reduce energy use and emissions via **better Air Traffic Management (ATM)** and via **improved ground operations**, for instance, by using electricity while standing and reducing the use of jet engines to power ground movement. Even if all these opportunities could be implemented, however, total global aviation emissions would still likely grow. The IATA roadmap (which aims for a 50% reduction in total industry emissions by 2050) assumes that **energy efficiency improvements could reduce emissions by about 30-45%** below business-as-usual, but that further reductions would require new fuels[10].

Across heavy-duty transport, it will probably be extremely challenging to achieve the maximum efficiency improvement which in theory exists. But **the scale of the energy efficiency improvement potential (35-40% in aggregate terms for all three sectors) is significant.** It is therefore essential that public policy and industry initiatives drive as much improvement as possible. In the heavy-road transport sector, regulation is likely to play a major role. In shipping and aviation, on which national regulations have only a limited reach, the most powerful lever is likely to be the expectation of higher fuel prices which will almost certainly be required to drive decarbonization. **Significant improvements in energy efficiency would in turn materially reduce the cost of achieving decarbonization.**

(III) SUPPLY-SIDE DECARBONIZATION OPTIONS

Across the three heavy-duty transport sectors, there are significant opportunities to improve energy efficiency while continuing to use fossil fuels, but **to achieve full decarbonization will require either new sources of energy (combined with electric engines) or new liquid fuels** (to be used in existing internal combustion engines). In each of the sectors, complete decarbonization is technically feasible and the probable route forward is clearer than in the industrial sectors. In aviation and shipping, the costs of decarbonization will likely be significant for companies operating in this sector, but will make little difference to overall economic growth or consumers living standards.

Probable paths to decarbonization

Across heavy-road transport, shipping and aviation, there are several ways through which complete decarbonization could in theory be achieved. But, unlike in the industrial sectors, **it is possible to identify the most likely decarbonization route for each sector**, and it is probable that dominant solutions will emerge across the world with less variation by region than in the industrial sectors.

This reflects four key differences between the transport sectors and the industrial sectors [Exhibit 3.5]:

- **Carbon capture on transport is not economically feasible**, due to the far smaller scale of each individual emitting unit. As a result, the zero-carbon solutions for transport fall into one of three categories: electrification, use of hydrogen-based fuels (hydrogen, ammonia, synfuels), or use of biofuels or biogas. Hydrogen and hydrogen-based fuels could be produced via electrolysis, which is likely to be the predominant route in the long term, or by SMR plus carbon capture (as described in Chapter 6).
- **Electric engines are inherently more efficient than thermal engines**, converting up to 95% of stored energy into kinetic energy, against a maximum of 40% achievable with ICE, and 70% with jet engines. Electricity-based solutions therefore have an inherent advantage in transport sectors, which does not apply in industrial processes, where electrical and chemical routes to produce heat are similarly efficient. As a result, electric drivetrains will tend to eventually dominate in any situation (in particular surface transport) where the combination of energy storage requirements, plus ease and speed of recharging/refueling, make either battery or hydrogen fuel-cell solutions feasible. In addition, since electric engines produce zero emissions, close to zero waste heat and minimal noise, they deliver **significant local environmental benefits in dense urban settings**. Policies driven by local environmental concerns (rather than by climate change per se) are therefore likely to give a major boost to the development of electric solutions.
- Conversely, **battery gravimetric density and hydrogen volumetric density are significant impediments** to the use of electric engines in long-distance shipping and aviation. Large investments are now being devoted to improving battery density (see Chapter 8) and it is likely that significant progress will be made within the next 10 years, increasing the range over which battery electric trucks

---

[9] Rocky Mountain Institute (2014), *Reinventing Fire: transportation sector methodology*

[10] IATA (2013), *Technology Roadmap*

Electric drivetrains will dominate in heavy-road transport and short-haul shipping and aviation

	Most probable option for short haul	Most probable option for long haul
Heavy-road transport	Battery electric vehicles	Battery electric vehicles (with or without catenary wiring) or Fuel-cell electric vehicles
Shipping	Battery electric vehicles or Fuel-cell electric vehicles	Ammonia or Hydrogen (primarily) Biofuels or Synfuels
Aviation	Battery electric vehicles or Fuel-cell electric vehicles	Biofuels or Synfuels

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 3.5

ILLUSTRATION 3.1 – Automotive companies are racing to put electric and hydrogen trucks on the road

The trucking industry is witnessing a surge in competition from truck manufacturing companies to lead the adoption of new electric and hydrogen fleets. Tesla and Nikola have already announced new models, while Daimler's Mercedes-Benz truck division is developing commercial trials. Chinese manufacturers are targeting potential export markets to hold their electric truck sales volume dominance.

- Nikola recently unveiled a new version of its hydrogen-powered electric semitrailer truck that will be aimed at European customers. This could be the first European zero-emission commercial truck and may also serve other international markets including Asia and Australia. Nikola is currently working with Norwegian firm Nel Hydrogen to deploy more than 700 hydrogen stations across the U.S. and Canada by 2028, and European stations are planned to come online around 2022 aiming to cover most of the European market by 2030.
- Meanwhile, Tesla continues to develop its all-electric long-haul truck Tesla Semi. The company has not yet released the actual specifications of its battery for the Semi, but its roadmap includes the commercialization of two versions of the vehicle, a 800-km long range and a 480-km short range versions. Elon Musk, CEO, has stated that the vehicle would likely have a range close to 970km per charge.
- Daimler's Mercedes-Benz Electric Truck division is currently conducting trials of an all-electric truck for on-road testing, expecting to continue over the next year. The test will be conducted over a 100km daily tour with a 25-tonne truck that includes a refrigeration unit for food. The company has been working with this technology since 2010, and has been producing a first series of fully electric trucks since 2017.

will be feasible. But, we estimate that battery gravimetric density would have to increase at least six times to make battery electric flight feasible for intercontinental travel[11].

- Manufacturing economies of scale (in particular heavy-road transport and aviation) and reluctance to deploy competing recharging/refueling infrastructure (in heavy-road transport) may tend to **favor the emergence of dominant technological solutions for each transport mode** to a greater extent than in industry. Industrial plant design is to a degree bespoke, with different solutions possible in different locations reflecting varying natural resource endowments. But, in truck and airplane production, large economies of scale advantages in design and manufacturing can be achieved by producing large numbers of the same designs. Some technological approaches (e.g. airplanes using a liquid hydrocarbon fuel) may therefore tend to dominate, even if, in theory, major product redesign (e.g. to store hydrogen in larger airframes) could be envisaged.

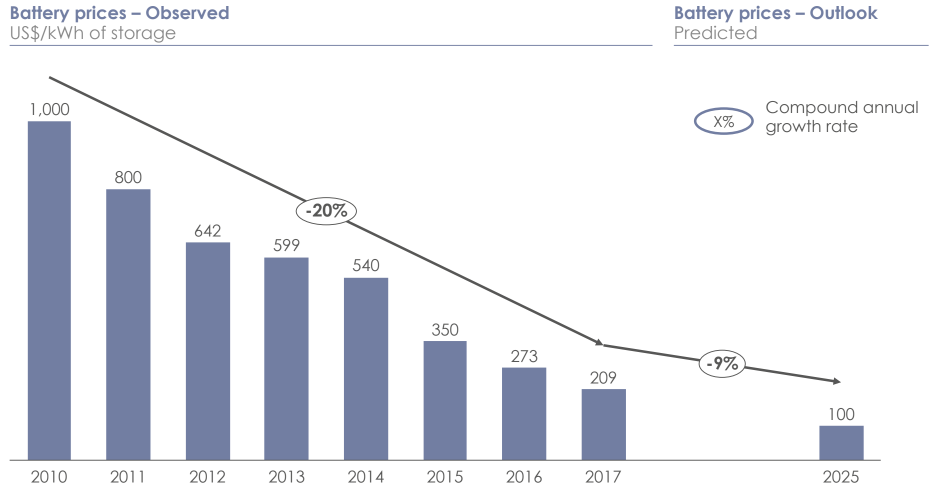
Given these factors, it is possible to define the most probable/dominant path to decarbonization for each of the three sectors.

Heavy-road transport

In the heavy-road transport sector, **electric drivetrains are likely to dominate** in the long-term, certainly for short and medium distance, and potentially for long distance as well. The rapid growth of the electric auto industry is driving **rapid battery cost reductions** [Exhibit 3.6], which are likely to take ownership costs for new electric trucks below those of ICE trucks during the course of the 2020s, and eventually make electric trucks cost-competitive even on an upfront cost basis. China's plans to have 1 million electric buses in place by 2025 will give a further boost to large electric engine and large battery development[12]. McKinsey & Company estimate that BEV trucks will become cost-competitive for urban short-haul vehicles in the early 2020s, and that long-haul BEV trucks will become cost-competitive in Europe between 2023-2031, and even in the US (where excise duties are lower) by 2029-31[13].

For long-distance freight, however, hydrogen fuel-cells may always have an advantage over battery electric trucks, in particular given battery size and speed of refueling (vs. recharging). There may also be, certainly in transition and perhaps permanently, a significant role for hybrid solutions with, for instance, batteries plus range extending fuel-powered generators.

Battery prices have decreased annually by 20% in the last decade and are expected to reach US$100/kWh by 2025



Source: Bloomberg New Energy Finance (2017)

Exhibit 3.6

---

[11] SYSTEMIQ analysis for the Energy Transitions Commission (2018). See details in the Appendix.
[12] BNED (2018), *Electric buses in cities*
[13] McKinsey Center for Future Mobility (2017), *What's sparking electric-vehicle adoption in the truck industry?*

ILLUSTRATION 3.2 – The deployment of urban electric buses in China

Within eight years, the 12-million-inhabitant city of Shenzhen became the first city in the world to electrify 100% of its public buses[1]. In Shenzhen, the total of 16,359 buses – equivalent to London's bus fleet size – consume nearly 75% less energy than diesel buses with an average operating mileage in 2016 of 174.4 km per day and energy consumption of 106 kWh per 100km, resulting in savings of 366,000 tons of coal annually.

This city-level program is part of a larger government-initiative, led by the Ministry of Transport, Ministry of Finance, and Ministry of Industry and Information Technology, who have put forward a project in 2015 to replace existing traditional-fuel buses by a new-energy bus fleet. This program is driven by the aspiration to make cities pollution-free. The targeted proportion of electric buses is 80% in nine cities, 65% in six cities and 30% in other provinces. As a result, across China, the number of new-energy buses has increased from less than 0.33% of the total in 2013 up to 39.5% in 2017, resulting in a reduction of 8.5Mt CO_2 between 2013-2017. If this trend continues, CO_2 emissions will be reduced by 33Mt by 2021[2].

To drive implementation, the Chinese central government provides upfront investment support and grants, making the costs of electric buses on par with diesel buses, while local governments have introduced a series of subsidies and tax reductions to encourage the development and uptake of new-energy vehicles. The scale at which electric buses are now being deployed also drives cost reductions which benefit not only buyers of electric buses in China, but also buyers of electric vehicles worldwide.

Increasingly, other cities around the world are putting in place strategies to go all-electric, such as London by 2030 or New York by 2040.

[1] World Resource Institute (2018), *How Did Shenzhen, China Build World's Largest Electric Bus Fleet?*

[2] Institute for Transportation & Development Policy (2018), *China Tackles Climate Change with Electric Buses*

Catenary overhead wiring on major freight routes could dramatically reduce the battery size required to support long-distance range, making battery electric vehicles appropriate for longer distances, but would require significant infrastructure investment. Other breakthrough innovation may also drive further direct electrification in the future, for instance electrified roads that recharge the batteries of cars and trucks driving on it, which are currently at demonstration phase.

The pace of progress towards electric drivetrains – and the precise mix of BEVs vs. FCEVs – will reflect future technological developments, in particular in battery density and cost, feasible recharging speed, and hydrogen fuel-cell efficiency and cost. But the long-term direction of change towards electric drivetrains is clear. Two implications follow:

- First, while biofuels may play a transitional role in truck decarbonization, their eventual role will probably be limited – this is explored further in Chapter 7;
- Second, the role of intermediate gas-based solutions (CNG and LPG) is likely to be limited too (see Section (iii) below).

Shipping

In the shipping sector, economics and technical feasibility argue strongly in favor of **"drop-in" fuels which can be used in existing engines**, in particular for long-distance container, bulk and tanker transport. In particular, the long life of ship engines creates a strong incentive to find a "drop-in" alternative to heavy fuel oil/marine diesel oil (HFO/MDO). Fortunately, **ship engines (unlike aero-engines) can use a wide range of alternative fuels with only moderate adaptation required**. Analysis conducted by UMAS/Lloyds Register, therefore, identifies two of the most likely routes to shipping decarbonization [Exhibit 3.7]:

- The use of biodiesel, although likely to be limited by scarce sustainable supply of biomass;
- The use of ammonia, based on zero-carbon hydrogen, which is likely to be preferred to direct hydrogen use for long distances due to lower volume and greater ease of storage[14].

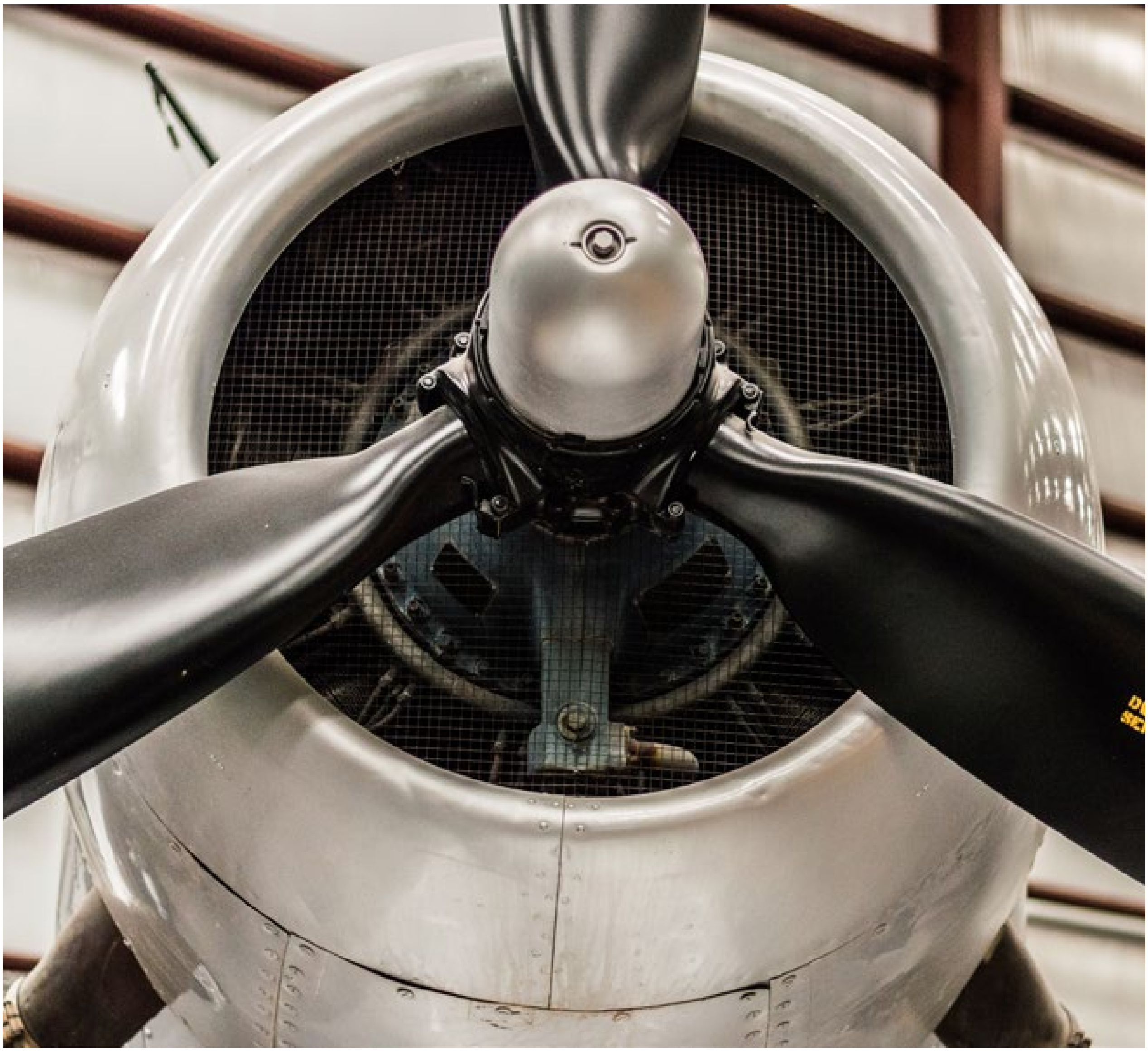
In parallel, **BEV and FCEV solutions will almost certainly play a significant role in riverine, coastal, Ropax and short-distance cruising markets**, and the range over which they are economic will tend to expand over time. But analysis of the weight

[14] Lloyd's Register & UMAS (2017), *Zero-emission Vessels 2030*

ILLUSTRATION 3.3: Testing ammonia in shipping

In 2018, the International Maritime Organization (IMO) has issued its initial greenhouse gas strategy, which commits the global shipping industry to emission reductions which cannot be reached with fossil-fuel. The strategy emphasizes the significant need for carbon-free liquid fuels, like ammonia. The current target is a 50% reduction by 2050. Following on from the IMO publication, the International Chamber of Shipping (ICS) published a short response report, which supported and further reiterated the fact that reaching the goal of zero emissions can only be derived from zero-CO_2 fuels.

A major step towards reaching this target comes from the announcement of a new project made in January 2018 by a Dutch consortium including Yara, the world's biggest producer of ammonia, C-Job Naval Architects, Proton Ventures and Future Proof Shipping (FPS), a spinoff from Enviu. The initial phase of this two-year project will involve theoretical and laboratory work and will result in a pilot-scale demonstration of "the technical feasibility and cost effectiveness of an ammonia marine tanker fuelled by its own cargo." In order to make this project more focused for the shipping industry, there will be an in-depth focus and assessment of the safety of ammonia in bunkering, storage, consumption and leakage/failure. The outcome of this research project will be crucial for the adoption of full-scale ammonia fuels in the shipping industry.



and volume requirements for battery or hydrogen energy storage, and of the implications for available cargo space, suggest that they will not be feasible or economic for longer journeys in the foreseeable future.

Aviation

In the aviation sector, **battery electric and hydrogen-based planes may well play a role in short to medium-distance flights**, and for an increasing range of plane sizes. Multiple plane designs are now being developed, with some experts believing that battery- or hydrogen-powered flights might become feasible for planes up to 100-seater flying 300-500 km. Radical airframe redesign could in principle make even longer-distance hydrogen-powered flight possible.

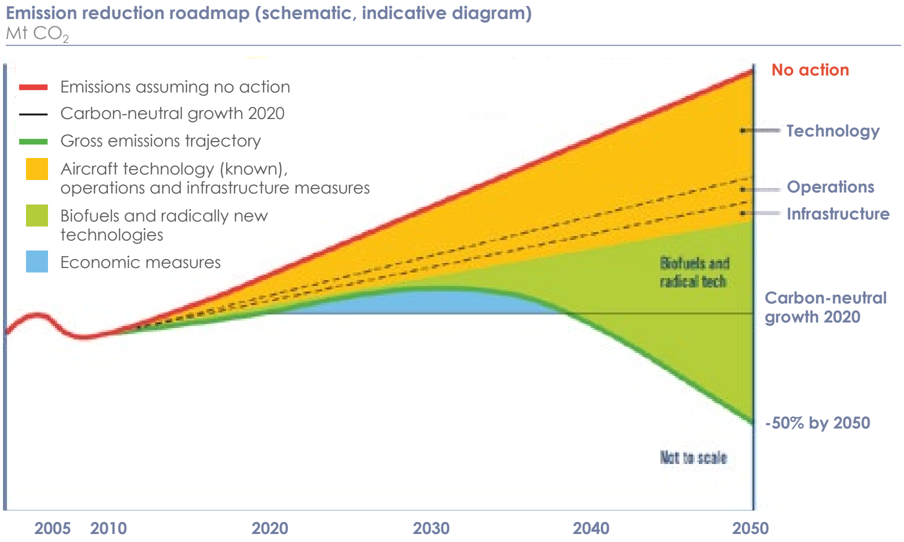
But, the best current assumption is that, in the foreseeable future, **international flight will continue to rely on** energy sources with a combination of gravimetric and volumetric density which can only be delivered by **liquid hydrocarbon fuels.** The economics of airframe and aero-engine development (with extremely long lead times) will strongly favor decarbonization solutions which allow a "drop-in" zero-carbon fuel to be used in existing engines, i.e. **biofuels or synthetic fuels** which are the precise chemical equivalent of conventional jet fuels but derived from zero-carbon sources.

Illustration: Industry associations and governments take first steps towards decarbonization of the aviation industry[15]

2018 marks the 10th year anniversary of the adoption of short and long-term goals of climate change mitigation measures by the aviation industry. In its first decarbonization roadmap, the International Air Transport Association (IATA) – representing 280 airlines – has set three main targets: 1.5% per year improvement in fuel efficiency from 2009 to 2020, carbon-neutral growth starting 2020, and 50% reduction in CO_2 emissions by 2050 relative to 2005 levels[16]. These objectives, although insufficient to enable a net-zero-carbon economy by mid-century, remain an essential first step and great example of industry commitment. To achieve them, the aviation industry has committed to improvements in the following areas [Exhibit 3.7]:

- **Operations**: More than a third of the planned emissions reductions could come from efficiency improvements, in planes themselves and in operations (including via better air traffic management).
- **Sustainable Aviation Fuels:** The Sustainable Alternative Aviation Fuels Strategy is the framework by which the IATA hopes to meet its emission reduction target. Most of the emissions reduction will have to come from a switch to low-carbon fuels, or Sustainable Aviation Fuels (SAF), sourced from a variety of renewable and recycled feedstocks. In order for aviation fuels to be considered sustainable and not need to be offset, the fuels will need to meet ICAO's sustainability criteria, or Standards and Recommended Practices (SARPs), first-ever CO_2 emission standards for aircraft, adopted in June 2018. These low-carbon alternatives are significantly more expensive than traditional jet fuels, including a significant pricing factor for distribution, blending and fuel quality testing, putting industry adoption and SAF production capacity development at risk. However, many airlines have concluded long-term offtake agreements with SAF suppliers and different airports have agreed to supply SAFs through hydrant systems. For instance, British Airways announced in 2017 a new partnership with renewable fuels company Velocys, investing massively in a large-scale waste-to-fuel plant.
- **Market-based measures:** Unlike other solutions, these measures do not aim to reduce emissions, but to offset them. Under CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), aircraft operators of ICAO[17] member states will be required to offset CO_2 emission units based on their annual fuel consumption. This scheme is detailed in Chapter 9.

The International Air Transport Association (IATA) has set global goals for the reduction of aviation's emissions



Source: IATA (2013), *IATA Technology Roadmap, 4th edition*

Exhibit 3.7

---

[15] Sources: IATA (2018), *Countdown to CORSIA*; IATA (2013), *IATA Annual Review*; ICAO (2017), *Sustainable Aviation Fuels Guide*

[16] Hassan M., Pfaender H., Mavris D. (2018), *Probabilistic assessment of aviation CO_2 emissions targets*

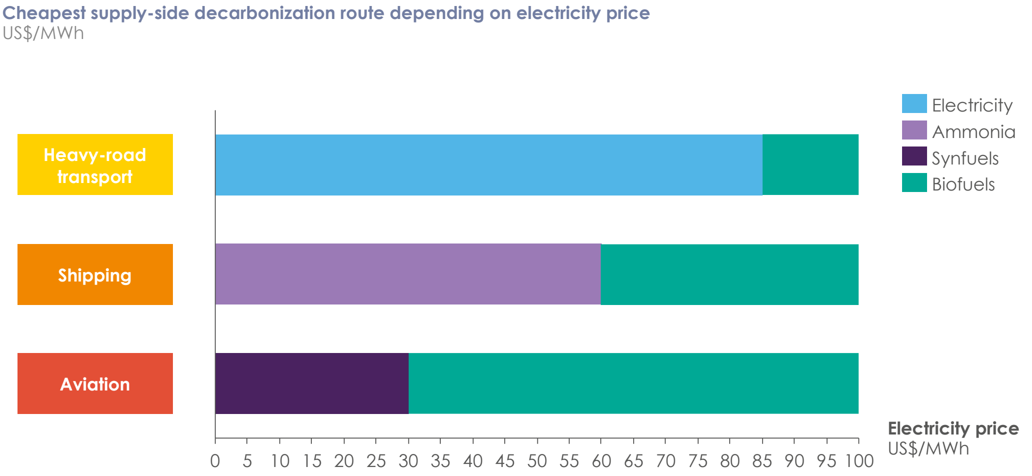
[17] ICAO: International Civil Aviation Organization, specialized agency of the United Nations

Decarbonization costs

Complete decarbonization of the three heavy-duty transport sectors is therefore technically feasible. Decarbonization costs, however, will vary significantly across sectors. While **in aviation and shipping costs will be significant**, they will be very limited in heavy-road transport.

- **For heavy-road transport**, our analysis suggests that a long-term switch to battery electric vehicles (over the range where it is feasible) will impose **no additional ownership costs**, since the full cost of BEV purchase and lifetime operation will, by 2030, be less than the cost of diesel (or biofuel) ICEs, even in situations where no excise duties or carbon price are imposed. This reflects the inherent efficiency advantage of electric versus thermal engines. The economics of hydrogen fuel-cell vehicles versus ICEs will depend on the price of hydrogen, but it is possible that hydrogen vehicles will undercut diesel/biofuel vehicles by 2030, even without excise duties or carbon price. Averaged across all distances, **the impact of heavy-road transport decarbonization on freight costs and thus end-product prices are likely to be minimal**. However, there will be infrastructure costs related to the deployment of recharging/refueling infrastructure which are covered in Chapter 4.
- **For shipping**, however, the impact of switching to biofuels or ammonia would be significant, possibly increasing voyage costs by **as much as 120%**, with an implied abatement cost of around US$350 per tonne of CO_2 saved. If the ammonia was made using hydrogen produced from electricity, the cost would fall with the price of renewable electricity. But even with electricity available at US$20/MWh and hydrogen costing US$5c/kWh, using ammonia in a ship engine instead of HFO/MTO would increase voyage costs by around 50%, with an implied abatement cost of around US$150 per tonne of CO_2 saved. Even such significant increases in freight costs, however, would only **1% or less to final product prices of internationally traded goods**[18].
- **For aviation**, the key question is the cost of biofuels or synthetic fuels relative to conventional jet fuel. Estimates of today's production costs suggest that bio-based jet fuel might cost 2-3

The electricity-based decarbonization route (direct or indirect) can be cheaper than the biofuels route depending on transport mode and on electricity prices



Note: Shipping trade-off based on annual total cost for a bulk container. Aviation trade-off based on bio jet with 100% cost premium vs. kerosene jet fuel, and synthetic fuels production with 50% energy efficiency.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018). Shipping: UMAS analysis for the Energy Transitions Commission (2018)

Exhibit 3.8

---

[18] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

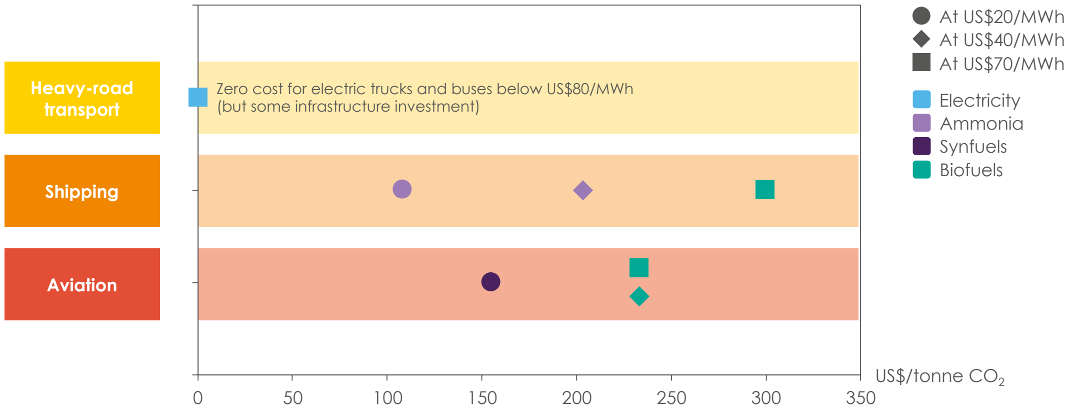
times fossil-based jet fuel[19], but this cost premium will likely decline very significantly over time as large-scale production drives economy of scale and learning curve effects. **A cost penalty of less than 100% (and perhaps much less) can almost certainly be attained**. For synthetic jet fuel, estimates suggest that, if renewable electricity were available at US$20/MWh, synthetic jet fuel could be delivered for about US$1.10/litre[20]. The best-case assumption is therefore that switching to zero-carbon fuels will impose a significant burden, with **a material impact on overall airline costs and ticket prices.** If the cost premium were 100% (or around US$0.5/litre), the abatement costs per tonne of CO_2 saved would be about US$200, and this might add about 10-20% (e.g. US$80) to an economy class ticket on a long distance (6,500km) international flight. This would not, however, have a material impact on overall standard of living or economic growth, and may simply need to be accepted as the unavoidable cost of decarbonizing the aviation sector.

Exhibit 3.8 illustrates at which price of zero-carbon electricity the electricity-based route would become cheaper than biofuels for each of the three heavy-duty transport modes. Exhibit 3.9 then illustrates what would be the decarbonization cost (expressed in US$ per tonne of CO_2) based on the cheapest decarbonization option for different electricity prices.

Decarbonizing aviation and shipping is likely to entail significant abatement costs. Along with cement and plastics in industry, they will likely be the most expensive sectors to decarbonize. But, **the costs discussed here would be very significantly reduced if the important energy efficiency potential discussed earlier were achieved**, and higher fuel costs would provide a very powerful incentive to pursue these improvements. The total impact on end consumers is therefore highly likely to be significantly less than the estimates presented above.

The decarbonization cost per tonne of CO_2 will vary across heavy-duty transport sectors and will also depend on local electricity prices

Cheapest supply-side decarbonization route and abatement cost at different electricity prices
US$/tonne CO_2



Note: Shipping trade-off based on annual total cost for a bulk container. Aviation trade-off based on bio jet with 100% cost premium vs. kerosene jet fuel, and synthetic fuels production with 50% energy efficiency.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018). Shipping: UMAS analysis for the Energy Transitions Commission (2018)

Exhibit 3.9

---

[19] SYSTEMIQ analysis for the Energy Transitions Commission (2018)
[20] SYSTEMIQ analysis for the Energy Transitions Commission (2018), based on expert interviews.

(IV) THE TRANSITION TO NET-ZERO CARBON

In the transport sectors as in the industrial sectors, it would be quite possible to achieve complete decarbonization by 2050-2060, and both public policy and business investment should be driven by that objective. In the transport sectors, moreover, implementation challenges, though still important, are somewhat less complex than in industry, and the appropriate role of gas as a transition fuel therefore more limited.

Implementation challenges and constraints

Two factors make achieving the transition to zero-carbon more straightforward in transport than in industry: (i) in the heavy-road transport sector, faster asset turnover, and (ii) in shipping and aviation, the fact that decarbonization will probably happen through the use of new fuels within existing engine designs.

- **Trucks and buses** typically have shorter lifetimes (e.g. 10 to 15 years) than steel furnaces or cement kilns. As a result, if battery electric or hydrogen fuel-cell trucks began to dominate new truck purchases from the mid-2020s onwards, **fairly complete decarbonization of developed world trucking fleets could be achieved by 2040**, particularly if regulations or incentives were used to accelerate the scrapping of older diesel or petrol trucks. In developing countries, specific regulations will likely be needed to offset the danger that import of cheap second-hand diesel or petrol trucks no longer used in advanced economies slow down decarbonization progress. One possible transitional option could be to use sustainable biofuels during the transition period in developing countries. The crucial implementation challenge is to **ensure rapid enough development of either or both high-speed electric charging infrastructure and hydrogen refueling stations.**
- **In shipping, asset lifetimes can be as long as in the industrial sectors** (i.e. 30 years or more), and the introduction of battery electric or hydrogen solutions in the riverine, coastal, Ropax and short-distance cruising markets may therefore take significant time, unless driven by strong regulatory requirements of the sort which Norway is currently introducing. In the long-distance bulk carrier, tanker and containerships segments, however, the most likely route forward is to **use new low-carbon fuels in existing engines**. While, in the case of ammonia, this may require significant new investment in storage tanks and other ancillary equipment, it will not require the scrapping of existing boats, nor of existing engines. The pace of **transition will therefore be driven primarily by the cost of ammonia and biofuels production,** carbon prices and regulation, rather than by the asset turnover cycle. With forceful policy, and at some cost, full decarbonization is entirely feasible by mid-century.
- **In aviation,** airframes and engines often have long lifetimes too, but the probable dominant route to decarbonization – **use of zero-carbon jet fuel in existing engines** – greatly simplifies the transition challenge. Asset lives and investment cycles will impose no constraint on the pace of decarbonization, which will instead be **determined by the cost of new fuels**, carbon prices and regulation. Transition challenges would be higher if entirely new technologies – like battery electric or hydrogen-based aviation – were to be deployed. These solutions would require the build-up of recharging/refueling infrastructure in airports. Moreover, while they may initially create incremental traffic in short-distance/small-plane applications (rather than replace existing aircrafts), the subsequent extension of these technologies into the mid-range/mid-size sector will depend on the turnover of existing fleets. Overall, **full aviation decarbonization by mid-century** appears to be technically feasible if societies are willing to bear the higher cost of zero-carbon fuels.

Transition options: the role of gas in heavy-duty transport

The likely and appropriate role of natural gas as a transition fuel in the transport sectors is less than in the industrial sectors for three reasons:

- As explained above, transition challenges are much lower in the heavy-duty transport sectors than in the industrial sectors, therefore making it **possible to switch directly from current fossil-fuel-based options to zero-carbon options** (electricity, hydrogen or biofuels-based) possibly as early as in the 2020s and certainly in the 2030s. The need for a lower-carbon transitional fuel is therefore likely to be limited in scope and in time. Any transitional solution would indeed need to be deployed now and would likely be phased out as early as the 2030s.
- While switching from coal to gas in industry can theoretically reduce carbon emissions by about 50%[21], switching from oil-based gasoline or diesel to gas would only reduce CO_2 emissions by as

---

[21] If methane emissions across the gas value chain are under control.

low as 5% and up to 20% in other applications, if and only if methane leakages across the value chain were lower than 1-2%[22]. Methane leakages today are often significantly higher, cancelling the potential benefits of a switch to gas. **Any expansion of gas use in the transport sectors would therefore have to be strictly conditioned to a prior reduction of methane leakages** across the upstream, midstream and downstream gas value chain to less than 1%. Moreover, there is a greater danger in transport than industry that the benefits of a switch to gas could be more than offset if it delayed progress to complete decarbonization.

- Finally, **options to phase out of natural gas by the early 2040s** while reusing the natural gas equipment and infrastructure are more limited in transport than in industry. The development of biogas could provide an alternative route to full decarbonization, but, given limits on the sustainable supply of biomass and the lower efficiency of combustion engines compared to electric engines, is unlikely to play a major role in the long term. Moreover, unlike in the industrial sectors, there is no option of first switching to natural gas and then later applying carbon capture on the same gas-based processes to achieve full decarbonization.

The case for a significant transitional use of gas is therefore weaker in the transport sectors than in industry:

- **In heavy-road transport**, it would be possible to modify existing gasoline engines to use methane over the next decade, and such conversions do not endanger a major lock-in effect, given the relatively short asset life of trucks. However, environmental gain is limited: taking into account methane leakage, Transport & Environment concludes that CNG/LNG trucks emit -2% to +5% GHGs compared with best practice diesel engines[23]. In addition, with battery electric and hydrogen fuel-cell vehicles likely to provide an increasingly cost-effective route to total decarbonization in the 2020s and early 2030s, **a major role for gas in trucking is unnecessary and unlikely to emerge.**
- **In shipping**, existing ship engines could use LNG with limited engine adaptation, and **some scenarios therefore suggest a significant role for LNG as a transition fuel.** But replacing HFO/MDO with LNG will only deliver emissions reductions of 12% to 9%[24] once accounting for methane leakages. The development of LNG infrastructure for ship operation could also **endanger lock-in to a partial emissions reduction solution** and it is therefore important to ensure that LNG developments are thought through so as to **enable a shift to truly zero-carbon emissions options as soon as they are available** (most probably in the mid-to-late 2030s), possibly by ensuring that gas infrastructure is built with the intent of repurposing it for hydrogen later on. If it were clear that large quantities of truly sustainable biogas could be produced at a price likely to undercut ammonia or biodiesel, this would strengthen the case for a significant transitional LNG role within shipping.
- **In aviation**, while it is theoretically possible to power planes with methane, our base case assumption is that long-distance international flight is likely to require the **energy density of a liquid hydrocarbon fuel** equivalent to jet fuel, with biofuels or synthetic fuels enabling zero-carbon flights while utilizing existing engines and distribution infrastructure.

Finally, it should be noted that, in some locations, the cost-effective way to produce hydrogen and ammonia for use in heavy-duty transport might be to use gas as an input to steam methane reforming (SMR) combined with carbon capture. There might therefore be **a greater indirect role than direct role for natural gas in transport**. Developing hydrogen-based transport solutions, instead of gas-based transport solutions, might reduce the overall cost of the transition by removing the need for investment in gas engines and infrastructure that could later get stranded. The transition would then happen upstream, with a progressive switch from SMR plus CCS to electrolysis not impacting the downstream transport infrastructure required.

Overall, any role for natural gas as a transition fuel must be constrained by:

- Strong policies and investments to ensure that **methane leakage** is sufficiently low to make the transition to gas truly beneficial for the climate;
- Pre-announced policies to impose sufficiently high-carbon prices or tough regulation that transport will eventually **move beyond natural gas to electricity, hydrogen or bioenergy-based routes** to complete decarbonization.

Chapter 7 discusses the overall implications for gas as a transition fuel, considering not only the industrial and transport sectors, but also heating.

---

[22] Analysis based on light-duty CNG car example. Environmental Defense Fund (2012), *The climate impacts of methane emissions*

[23] Transport & Environment (2018), *CNG and LNG for vehicles and ships - the facts*

[24] Transport & Environment (2018), *CNG and LNG for vehicles and ships - the facts*

4 Costs of full decarbonization in harder-to-abate sectors

As Chapter 2 and 3 argued, it is technically possible to eventually achieve full decarbonization of the harder-to-abate sectors "within themselves" (i.e. without purchasing offsets from other energy-using sectors or from the land use sector). Aggregating the likely cost of emissions reduction, moreover, suggests that **the cost to the global economy of such a decarbonization strategy would be no more than 0.5% of the global GDP** and almost certainly significantly less.

But, since **costs per tonne of CO_2 saved will vary significantly by sector**, this raises important issues about optimal approaches to carbon pricing and the use of offsets. This chapter therefore considers in turn:

i. Abatement costs per tonne of CO_2 saved;
ii. The cost to the global economy of fully decarbonizing the harder-to-abate sectors;
iii. Implications for the cost of intermediate products purchased by businesses and of end products purchased by consumers;
iv. Investment requirements and financing challenges;
v. Implications for optimal carbon pricing and the use of offsets.

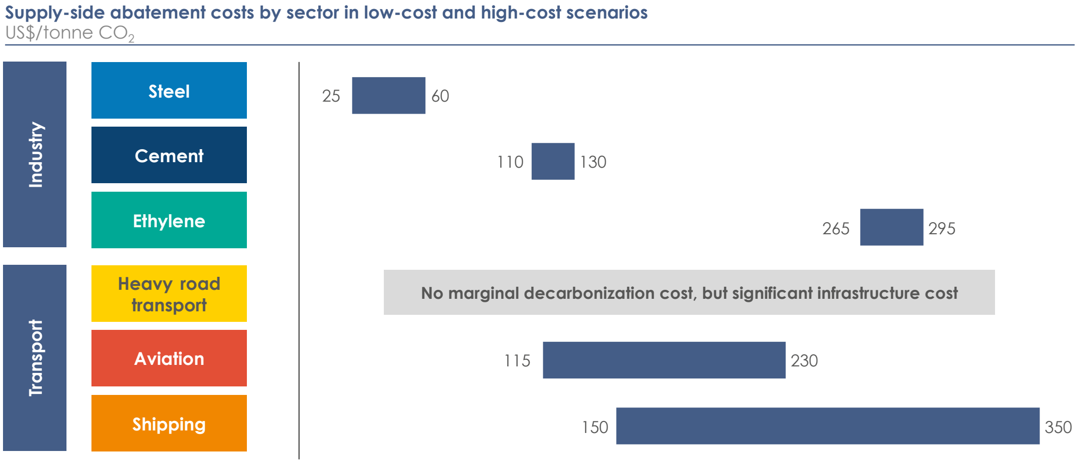
(I) ABATEMENT COSTS PER TONNE OF CO_2 SAVED

The estimated costs of supply-side decarbonization shown in Chapters 2 and 3 vary significantly by sector and technology. It will likely cost less than US$45/t$CO_2$ to decarbonize ammonia production by applying carbon capture to SMR, but could cost as much as US$350/t$CO_2$ to decarbonize long-distance shipping through the use of ammonia. Actual costs – and the least-cost routes to decarbonization – will depend on future technological developments and cost trends, and will vary by region in the light of natural resource endowments.

The figures shown on Exhibit 4.1 represent a reasonable indication of **where the higher costs and the cheapest opportunities are likely to lie.**

- **In industry**, reaching zero lifecycle carbon emissions from plastics could cost close to US$300 per tonne of CO_2, while steel would be much cheaper to decarbonize. The availability of low-cost, zero-carbon electricity would make a major difference to the cost of industry decarbonization, especially in steel: if zero-carbon electricity was available at US$20/MWh across the world, decarbonizing steel could cost only US$25/t$CO_2$ (instead of US$60/t$CO_2$ if zero-carbon electricity is available at US$40/MWh).

Costs of supply-side decarbonization vary greatly by sectors



Source: Industry: McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* / Shipping: UMAS analysis for the Energy Transitions Commission (2018) / Other transport sectors: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 4.1

- **In transport,** zero-carbon buses and trucks are likely to be cost-competitive with current ICE vehicles, regardless of the electricity prices. By contrast, the cost of decarbonizing aviation and shipping could vary tremendously depending on the cost of zero-carbon fuels.

Given the relatively high cost of many supply-side decarbonization options, it is essential to simultaneously pursue **lower-cost carbon abatement options from energy efficiency improvement and demand management** to lower the overall cost of the transition in each sector.

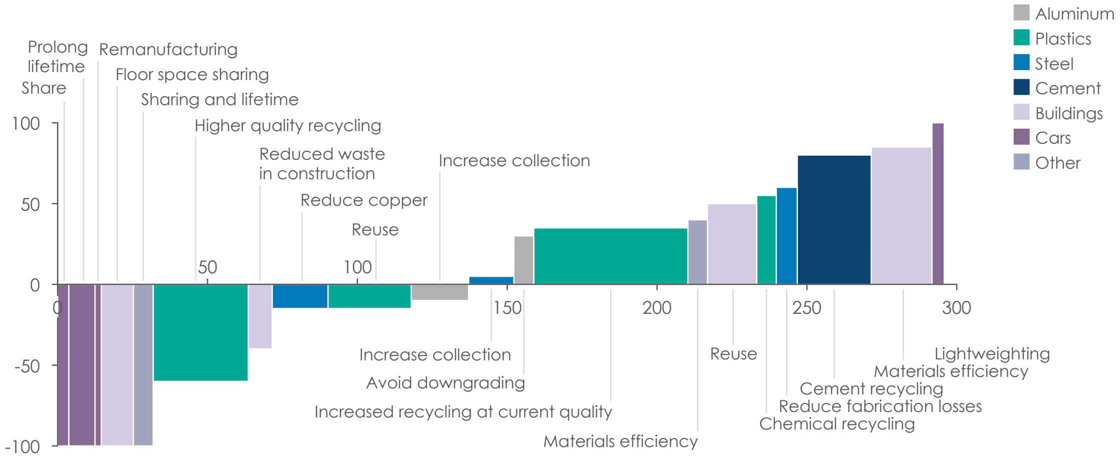
- Across all sectors, **energy efficiency improvements** offer opportunities for initial CO_2 emissions reduction at low-to-negative cost.
- In the industrial sectors, as described in Chapter 2, there are also major opportunities to **reduce demand via materials efficiency and recycling**. Most of these measures could deliver emissions reductions at a lower cost per tonne of CO_2 than supply-side decarbonization technologies and, in some cases, even at negative costs [Exhibit 4.2]. In particular, there are significant opportunities to reduce demand for plastics through mechanical recycling, which in principle could result in a net economic gain.
- In the transport sector, as described in Chapter 3, the opportunities for demand reduction are less significant, but could reach 20% if all opportunities for modal shift and logistics efficiency improvement were achieved. Although modal shift might require significant investments, we expect logistics efficiency improvements to deliver CO_2 emissions reduction at a lower cost than a switch to zero-carbon fuels.

Average abatement costs per tonne of CO_2 in each sector, may therefore, be below even the lower-cost estimates shown on Exhibit 4.1.

IT IS ESSENTIAL TO DECREASE THE COST OF DECARBONIZATION THROUGH ENERGY EFFICIENCY IMPROVEMENT AND DEMAND MANAGEMENT

Demand-side decarbonization is feasible at a lower cost than supply-side decarbonization

Abatement cost for demand-side decarbonization
US$/tonne CO_2 per year



Source: Material Economics (2018), *The circular economy: a powerful force for climate change*

Exhibit 4.2

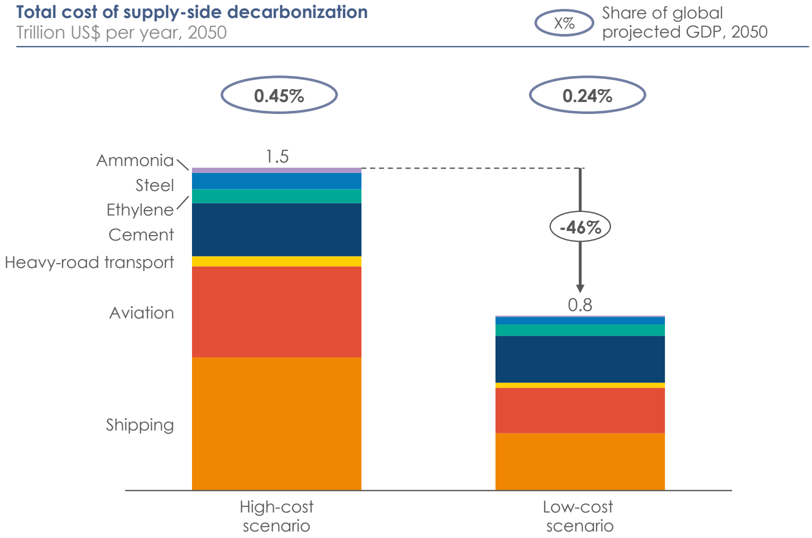
(II) COST TO THE GLOBAL ECONOMY

An initial estimate of the maximum annual cost to the global economy of achieving net-zero CO_2 emissions within heavy industry and heavy-duty transport (with no use of offsets) can be generated by multiplying the supply-side decarbonization costs per tonne per sector shown on Exhibit 4.1 by the future volumes of CO_2 expected to be produced by each sector in a business-as-usual scenario.

This suggests that total costs of **running decarbonized harder-to-abate sectors could amount to less than 0.5% of global GDP in 2050** – or US$1.5 trillion per annum [Exhibit 4.3]. These decarbonization costs could be significantly reduced by three factors:

- **Lower renewable energy costs:** If zero-carbon electricity was available at US$20/MWh across the world (instead of US$40/MWh), decarbonizing heavy industry would cost 25% less. The noticeable exception is the cement sector, where process emissions cannot be eliminated via electrification (regardless of how low the cost of electricity can be) and will require the application of carbon capture. Similarly, the cost of decarbonizing shipping and aviation would fall by 55% if the additional cost of biofuels or synfuels could be brought down to US$0.3 per litre (instead of US$0.6 per litre). Overall, **lower renewable energy prices could reduce the total cost to the global economy from 0.45% to 0.24% of global GDP** [Exhibit 4.3].
- **Demand management:** Greater recycling and reuse of materials within a more circular economy, combined with logistics efficiency and modal shifts in transport sectors, could **reduce the decarbonization costs for harder-to-abate sectors by 40% to 45%,** bringing them down to 0.15-0.25% of global GDP [Exhibit 4.4].
- **Future technological development**: History tells us that learning curve effects and economies of scale often reduce technology costs by more than anticipated, and new and unanticipated technologies emerge. If this occurs in the future, the cost of decarbonization could be dramatically reduced or even eliminated. For instance, the cost of decarbonizing cement could be far lower if the learning curve effect and economies of scale bring down the cost of carbon capture. Similarly, the cost of decarbonizing aviation and shipping would be far lower if dramatic battery density improvements allowed a greater role for electrification.

Decarbonizing the harder-to-abate sectors using supply-side decarbonization technologies only would cost less than 1% of global GDP by 2050



Source: SYSTEMIQ analysis for the Energy Transitions Commission, (2018); McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*

Exhibit 4.3

Any estimate of total cost to the global economy is inherently uncertain. In particular, it is very difficult to assess how much of the potential for low (or negative) cost abatement through demand management will in fact be achieved. But it is clear that:

- Even if decarbonizing the harder-to-abate sectors of the economy incurred the maximum cost to the global economy illustrated on Exhibit 4.3, this would make **minimal difference to the growth of global prosperity** over the next half-century.
- Appropriate policies to drive innovation, energy efficiency, materials efficiency, materials circularity and demand management in transport **could very significantly reduce even these minor costs.**
- The aggregated costs are **dominated by shipping, aviation and cement,** but the total costs to decarbonize the other harder-to-abate sectors of the economy are trivial, relative to global GDP.
- Even when taking into account potential costs of decarbonizing the easier-to-abate sectors of the economy, **the cost of running a fully zero-carbon economy would very likely be well less than 1% of GDP.**

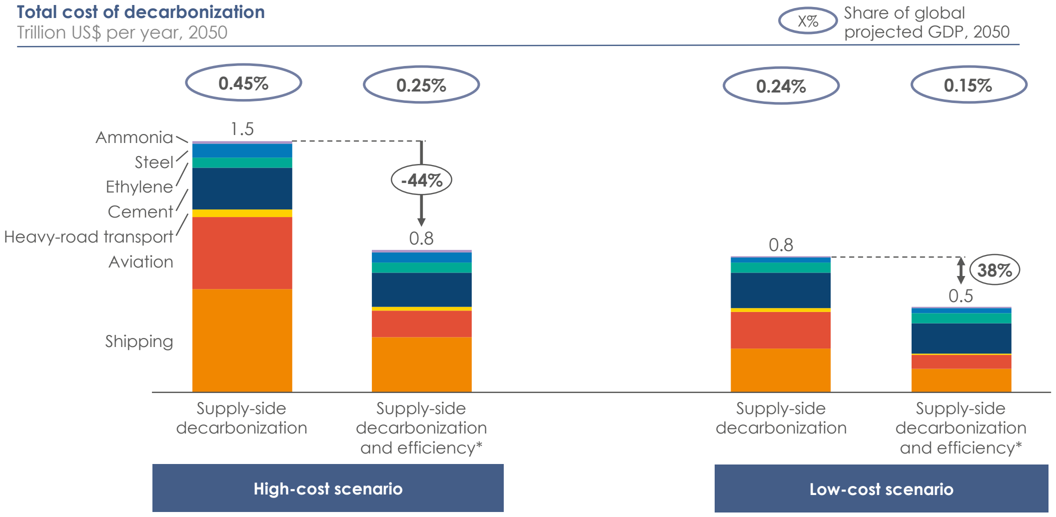
(III) IMPACT ON PRODUCT PRICES FOR BUSINESSES AND END CONSUMERS

It is useful to consider what the impact of decarbonization might be on the price of intermediate products purchased by businesses, and end products purchased by consumers. Here again, the three biggest impacts relate to cement, shipping and aviation. The analysis reveals that:

- **None of the increases in end-consumer prices are sufficiently large to be an argument against forceful policies to drive decarbonization.**
- However, decarbonization is likely to have a **significant impact on the price of intermediate products** purchased by businesses, with important consequences for optimal approaches to carbon pricing.

Exhibits 4.5 and 4.6 respectively set out estimates of the potential impact of supply-side decarbonization on industrial product prices and on end consumer prices, using the higher costs per tonne shown on Exhibit 4.1.

Decarbonizing the harder-to-abate sectors would cost significantly less if pursuing energy efficiency improvement and demand management opportunities



Note: The term "efficiency" covers energy efficiency, materials efficiency, materials circularity, and demand management in transport.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) based on McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* and Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 4.4

In key heavy industries, decarbonization would incur significant additional costs on intermediate products, which would create stronger incentives for materials efficiency, materials recycling and product substitution, but would not impose major costs on end consumers:

- In the case of cement, **the price of a tonne of cement could double** if cement were to be zero-carbon. High transport costs (relative to the value of the product) make markets largely domestic and limit potential issues related to international competitiveness. But, with concrete costs increasing by 30%, careful policies would be required to ensure that zero-carbon cement/concrete is not disadvantaged versus other construction materials. The likely **impact on total building construction costs, however, is quite minor** (+3%).
- In the case of steel, the **impact on the end price of a typical automobile is around 1%**, making it highly likely that consumers would be willing to support policies – whether carbon prices or "green steel" mandates – which would drive decarbonization. But, since the **impact on the price of a tonne of steel could be as much as +20%**, steel companies could be severely disadvantaged if policy requirements did not apply equally to all relevant domestic and international competitors.
- In the area of plastics, the impact on end consumer prices of decarbonizing ethylene production will be trivial, with **the price of a bottle of soda increasing no more than 1%**. However, it would **add 50% to the price of ethylene**, creating similar international competitiveness issues as for steel.

In the heavy-duty transport sectors, costs will be concentrated in shipping and aviation, where high intermediate costs would create incentives for demand reduction and modal shift. The most significant costs to end consumers will lie in aviation.

- **In trucking,** the cost of decarbonization per tonne of CO_2 saved is likely to become very low over time as both battery and electricity prices decline, with **trivial resulting impacts on freight costs and end product prices**. BEVs and FCEVs will, however, demand infrastructure investment, as addressed later in this report.
- **In shipping,** decarbonization could significantly add to total international freight costs, but the **impact on total imported good prices would be less than 5%.** This cost increase would be significantly reduced if higher fuel prices focused on the significant opportunities for improved efficiency (via ship design, sail assistance, or slower speeds).
- **In aviation,** using bio jet fuel or synthetic jet fuel, which cost 50-100% more than conventional jet fuel, would add US$40-80 dollars or **10-20% to the price of a long-distance economy ticket.** This would be a significant price increase for this specific item of consumer expenditure, but the impact on overall living standards would be slight, since expenditure on international aviation accounts for less than 3% of global household consumption. Moreover, this price impact might be significantly reduced if higher fuel prices created an incentive for engine and airframe efficiency improvements. Increased travel costs might also trigger some beneficial **shifts to videoconferencing** (reducing business travel) and **slow down the expected growth in leisure travel.**

In summary, the potential impacts on end product prices do not establish any reason against targeting the full decarbonization of the harder-to-abate sectors by mid-century.

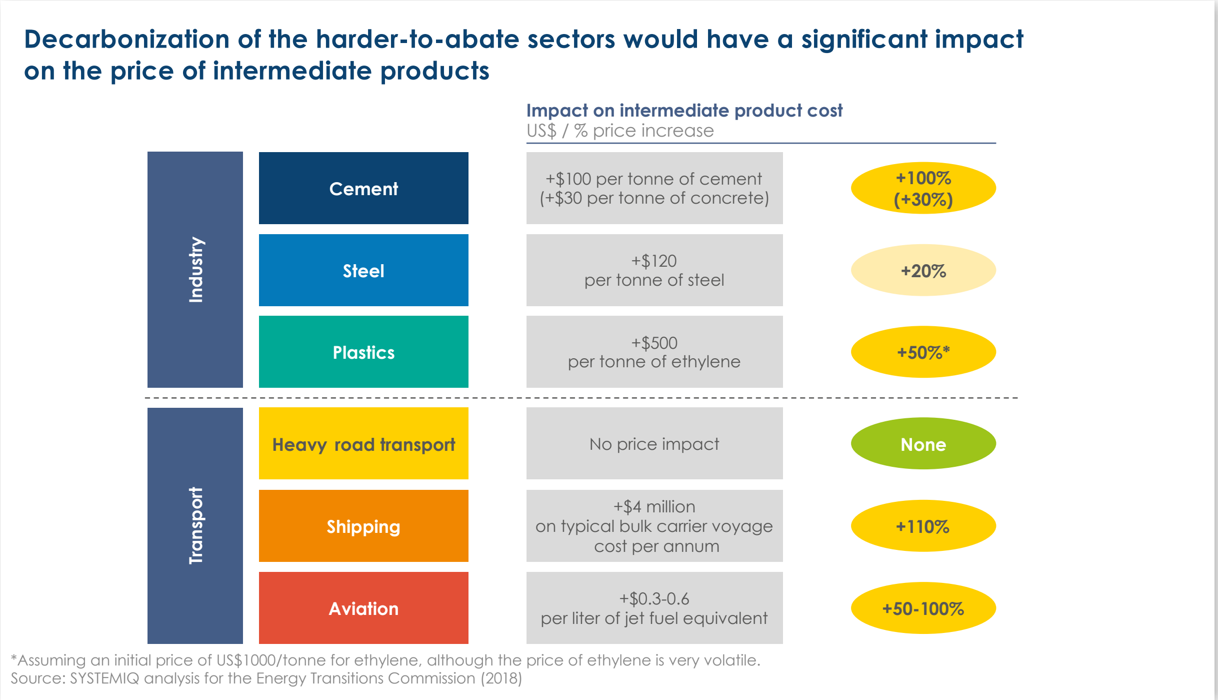
(IV) INVESTMENT REQUIREMENTS AND FINANCING CHALLENGES

Although the additional cost to the global economy of having decarbonized heavy industry and heavy-duty transport will be limited, **achieving net-zero CO_2 emissions from these sectors will require large investments.** These investments will be made mostly by the private sector, but some direct public sector investment as well as public support to private investment will also be required. Yet, given the scale of global savings and investment, he level of investment required to decarbonize harder-to-abate sectors appears to be small, and there is **no reason to believe that financial shortage will constrain the path to net-zero CO_2 emissions.**

In *Better Energy, Greater Prosperity*[1], we presented estimates, drawn from the New Climate Economy report (2014)[2], of the **total investment needed to drive the first stage of the transition towards a low-carbon economy** (across all sectors) between now and 2030. Key insights from this analysis were as follows:

- Total investment from 2015 to 2030 in the energy production and distribution system could be slightly lower if the world was on a path to well below 2°C than under a business-as-usual scenario (US$21.3 trillion versus US$22.6 trillion), with **significant additional investment in low-carbon power being more than offset by declines in investment in fossil fuel production and distribution.**
- **The biggest increases in incremental investment** (+US$8.8 trillion over 2015 to 2030) **were likely to be in energy efficiency equipment** (e.g. improved building insulation, better HVAC systems, and new autos, buses and trucks) rather than in the energy production system itself.
- Total incremental capital investment per annum, at around US$300-US$600 billion, when compared with total global savings and investments of over US$20 trillion, was **not large enough to create any macroeconomic challenge**, particularly in a world where the balance between desired savings rates and investment opportunities is continuing to produce historically low real interest rates.

Our analysis of the harder-to-abate sectors is consistent with these conclusions. This is also consistent with latest modelled estimates of the total incremental investment needs across all



Decarbonization of the harder-to-abate sectors would have a significant impact on the price of intermediate products

		Impact on intermediate product cost US$ / % price increase	
Industry	Cement	+$100 per tonne of cement (+$30 per tonne of concrete)	+100% (+30%)
	Steel	+$120 per tonne of steel	+20%
	Plastics	+$500 per tonne of ethylene	+50%*
Transport	Heavy road transport	No price impact	None
	Shipping	+$4 million on typical bulk carrier voyage cost per annum	+110%
	Aviation	+$0.3-0.6 per liter of jet fuel equivalent	+50-100%

*Assuming an initial price of US$1000/tonne for ethylene, although the price of ethylene is very volatile.
Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 4.5

---

[1] Energy Transitions Commission (2017), *Better Energy, Greater Prosperity*

[2] New Climate Economy (2014), *Better Growth, Better Climate*

sectors of the economy. The latest IPCC report on the impact of 1.5°C warming notes that these estimates vary dramatically – from US$0.2 trillion to US$1.8 trillion per annum –, but with a median estimate of around US$0.9 trillion per annum[3]. Assuming a global GDP growth of 3% from now to 2050, this median figure would imply incremental investment of less than 0.6% of cumulative GDP, and with only the more extreme estimates exceeding 1%[4].

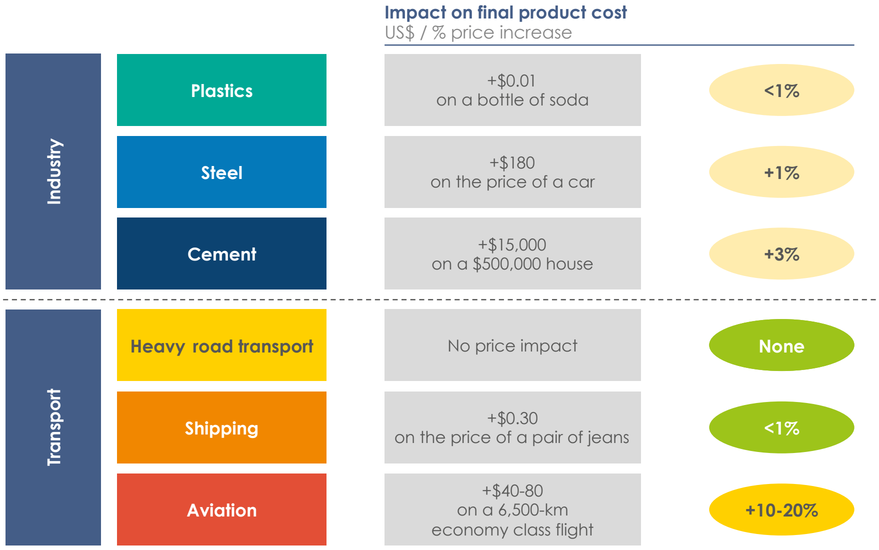
Investment within the harder-to-abate sectors

In the industrial sectors, it is inherently difficult to estimate incremental net investment, since new investments in low- or zero-carbon plants will replace investments which would have occurred in any case to renew industry assets and meet increased demand. But McKinsey estimates that over the 35 years (from 2015 to 2050), **additional capital expenditure could amount to US$5.5 to US$8.4 trillion**[5], depending on the electricity price assumed. Notably, almost all incremental increases come from capital expenditure in the cement sector, with very small incremental investment needs in other sectors and close to zero if electricity prices are very low. The incremental investment would only be **around 0.1% of possible cumulative GDP over 35 years and less than 0.5% of probable global savings and investments**[6].

In the transport sectors, additional upfront capital cost faced within the sectors themselves will not be material.

- In trucking, it is likely that, by 2030, **the upfront cost of new battery electric trucks will be below the upfront cost of ICE trucks** and, while FCEV trucks may be more expensive, the total impact across the whole sector will not be material at the macroeconomic level.
- Within shipping and aviation, if decarbonization is primarily achieved via the use of zero-carbon fuels in existing engines and vehicles, **no major new capital investment by the shipping and aviation industry** will be required to drive decarbonization, though with some incremental investment required in ship engines to allow the use of ammonia and maybe some greater investments required to drive energy efficiency improvements in ships and aircrafts. But we do not expect these to be material at the aggregate macroeconomic level.

Decarbonization of the harder-to-abate sectors would have a very small impact on prices for end consumers



		Impact on final product cost US$ / % price increase	
Industry	Plastics	+$0.01 on a bottle of soda	<1%
	Steel	+$180 on the price of a car	+1%
	Cement	+$15,000 on a $500,000 house	+3%
Transport	Heavy road transport	No price impact	None
	Shipping	+$0.30 on the price of a pair of jeans	<1%
	Aviation	+$40-80 on a 6,500-km economy class flight	+10-20%

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 4.6

---

[3] IPCC (2018), *Global warming of 1.5˚C*

[4] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

[5] McKinsey and Company (2018), *Decarbonization of the industrial sectors: the next frontier*

[6] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

At a macroeconomic level, total investment requirements within the harder-to-abate sectors themselves will not, therefore, be an impediment to achieving net-zero CO_2 emissions, provided appropriate policies create sufficiently strong incentives for investment. However, **high upfront investment costs may act as a barrier** to progress even where carbon prices make a shift to theoretically cost-competitive zero-carbon technologies, in particular in sectors or companies facing low margins. Direct public investment support (for instance through loan guarantees or repayable advances) may therefore be required to accelerate the transition.

Shared infrastructure investments

Even if total investment requirements are clearly manageable, it is important to note that some **shared infrastructure investments** may only occur with appropriate public coordination, regulation, or in some cases, public investment. In particular, infrastructure investments may be required to support widespread electrification, use of hydrogen in surface transport, and the development of CCS to support industrial decarbonization.

Widescale electrification of surface transport – both light-duty and heavy-duty transport – could require three categories of shared investment:

- **Reinforcement of local distribution networks:** These costs will vary **greatly with location and the current state of urbanization.** Where cities are being built for the first time, the investment costs of providing for greater future electricity use are extremely small; but where retrofit is required within existing urban environments, costs may be much more significant. The European Commission estimates suggest that the total investment required to support slow speed recharging for EVs (if they account for 30% of the total fleet in 2030) could amount to US$36 billion (US$13.5 billion for public infrastructure and US$22.5 billion for private charging)[7]. This would add US$1.2/MWh to the cost of electricity. Required investment will, however, be strongly **influenced by whether charging behavior is unconstrained** (with many owners seeking to charge at the same peak demand time) or optimal (with time-of-day pricing or other smart demand management techniques shifting a significant proportion of EV charging to off-peak times). Analysis of the incremental investment to support charging by 135,000 electric taxis and private hire by UK Power Networks vehicles shows that the costs could vary from US$130 per vehicle if charging behavior is unconstrained, to less than US$40 per vehicle if charging behavior is optimal[8].
- **High-speed charging networks:** Electrification of trucking will require high-speed charging at rates of several 100kW per hour. Some of this charging will occur at private depots and the incremental investment will likely be small if it occurs within the context of new depot construction or redesign. In addition, some shared high-speed charging networks will be required along major road routes. A network of 20,000 charge points across the EU would cost approximately US$2.1 billion[9].
- **Catenary overhead wiring:** Finally, if catenary overhead wiring did play a significant role in the path to zero-carbon trucking, investment costs of about US$7 billion would be required to cover 7,000 km of road (10% of the EU motorway network)[10].
- Similarly, **the widespread use of hydrogen trucks would require extensive refueling networks**. A European-wide network of 20,000 refueling stations might entail investment costs of US$57 billion[11].

Finally, as described in greater details in Chapter 6, 5-8Gt of carbon capture per annum are likely to be required to reach net-zero emissions from the energy and industrial system by mid-century. Within that, **3-7Gt might need to be stored underground,** while 1-2Gt could be used in CO_2-based products ensuring long-term sequestration. If the average pipeline distance from capture site to storage were 100-300 kilometers in the EU, this might require total capital investment of US$7-9 billion[12].

Many of these infrastructure investments (i.e. in high-speed charging networks) will likely be made by private sector companies. Some (i.e. catenary overhead wires) may need to be driven by public investment. And in others (i.e. CO_2 transportation pipelines), there will be a need for public coordination and planning even if the investments are made by the private sector. But **none of the investment needs are of the scale to make the transition to zero carbon difficult to finance or unacceptably costly**.

[7] Transport & Environment (2018), *Charging infrastructure report*
[8] UK Power Networks (2018, *Black Cab Green, London's Electric Cab and Private Hire Future*
[9] Based on Schroeder a., Traber T. (2011), *The economics of fast charging infrastructure for electric vehicles*
[10] SYSTEMIQ analysis for the Energy Transitions Commission
[11] Based on OECD/IEA (2017) *The Future of Trucks*
[12] Based on Kjarstad J., Johnsson F, (2009), *Ramp-up of large-scale CCS infrastructure in Europe*

(V) IMPLICATIONS FOR POLICY: CARBON PRICING AND USE OF OFFSETS

Neither the total economic cost as a percentage of GDP nor the potential impact on end product or service prices argue against seeking to achieve the total decarbonization of each of the harder-to-abate sectors by mid-century. But the fact that **very different costs will be incurred across sectors** raises important questions about the optimal approach to carbon pricing and the use of offsets in the transition period to a low-carbon economy or in the long-term.

Carbon pricing

In the long run and in principle, there would be no disadvantage to imposing carbon prices high enough to drive the decarbonization of even the highest-cost sectors. If, for instance, there was a carbon price of US$200 per tonne, which is sufficient to drive decarbonization of aviation, the eventual impact on steel prices would not be higher than forecast above, since steel would become totally decarbonized at a cost of US$60 per tonne.

But appropriate policies must also reflect:

- **The time that it will take for different sectors to achieve decarbonization,** given slow asset investment cycles and still incomplete progress towards the commercialization of some key technologies – which implies, for instance, that a US$200 per tonne carbon price imposed today would increase steel prices far more than shown in the previous section;
- **The effects of the very different exposure of different sectors of the economy to potential international competitiveness** – e.g. steel is internationally traded, while cement, for the most part, is not.

These complications may imply a role for **differentiated carbon prices by sector,** for unilateral domestic introduction of carbon prices in some sectors but not others, for taxes related to carbon-intensity of end products (rather than pricing of raw materials), or for the use of non-price regulatory levers. These issues are considered in Chapter 9.

Purchasing offsets

In the long run, however, it is essential that **the whole world achieves net-zero CO_2 emissions across the energy, industrial and land use systems combined**. Since there are limits to the total possible scale of natural carbon sequestration, land use offsets should ideally play only a transitional role and the energy and industrial sectors should eventually achieve net-zero CO_2 emissions “within themselves”.

But, since the marginal cost of decarbonization varies greatly among the harder-to-abate sectors and across the whole economy, the early stages of sectoral paths to net-zero CO_2 emissions in the harder-to-abate sectors could allow for the purchase of offsets from other sectors of the economy or from the land use sector. Two considerations particularly plead a favor of a transitional use of offsets:

- During the transition, though not in the long-term, it may be cost-effective for higher abatement cost sectors to purchase offsets from lower abatement cost sectors; and
- If there are lower-cost opportunities to reduce emissions via changes in land use (e.g. reforestation), it may be appropriate to use offsets purchased from the land use sector.

The price of these offsets would create an additional incentive for these industries to pursue long-term decarbonization options. These issues are considered in Chapter 7.

CARBON PRICES WILL BE REQUIRED BUT SHOULD BE DESIGNED TO AVOID INTERNATIONAL COMPETITIVENESS EFFECTS

5

A revolution in materials efficiency: Building a more circular economy

As Chapter 2 described, there are major opportunities to cut CO_2 emissions from the industrial sectors by reducing demand versus business-as-usual trends through more efficient use of materials. This entails two major developments:

- **Making better use of existing stocks** of materials through greater and better recycling and reuse;
- **Reducing the materials requirements in key value chains** (e.g. transport, buildings, consumer goods, etc.) through improved product design, longer product lifetime, and new sharing business models (e.g. car sharing).

Developing a more circular economy by using materials more efficiently, should be **a crucial element in any strategy** to reach net-zero carbon emissions from the energy and industrial systems, for multiple reasons:

- A more circular economy can reduce CO_2 emissions from four major industry sectors (plastics, steel, aluminum and cement) by 40% globally, and by 56% in developed economies like Europe by 2050[1]. It is potentially the **second biggest lever for CO_2 emissions reduction** after clean electrification.
- As Chapter 4 has already shown, demand-side measures can significantly **reduce the total cost** of achieving an eventual net-zero economy.
- In addition, it can **reduce the required scale of deployment** of supply-side decarbonization technologies **and the amount of renewable resources needed** to support that deployment (solar and wind resources, as well as biomass resources – which are particularly scarce).
- Since technology readiness and asset lives may delay progress to supply-side decarbonization in heavy industry, demand management can be a **route to early emissions reductions.**
- Circular economy models also bring **co-benefits**, such as decreasing risks of materials scarcity (for instance for batteries, as described in Chapter 6), reducing other social and environmental impacts of the mining and production of materials (for instance water pollution), and limiting waste leakages in the environment (in particular plastics waste).

Driving the circular economy agenda requires a combination of policy levers, including financial incentives and regulations. Some of these policies will also drive supply-side decarbonization. In particular, carbon prices, which increase the cost of carbon-intensive virgin materials production, will increase incentives for recycling. But tailored initiatives will also be needed to address the **complex and industry-specific barriers,** which stand in the way of more circular approaches. This chapter details these barriers and what would have to change to overcome them, specifically in the steel, plastics and cement sectors, as well as in the buildings/construction value chain.

(I) IMPROVING STEEL RECYCLING

In principle and in the long run, the world could get all the benefits derived from steel with no new primary production, with a stable stock of steel continuously recycled to provide products and services to the global population. Today, **in many emerging economies, per capita stocks are still growing rapidly** from low levels (about 1 tonne per capita in much of Africa) and populations continue to increase, making primary production essential, even if 100% recycling could be achieved. But, **in developed economies, stocks per capita are now reaching stability** at about 12 tonnes per person and, with population growth also stabilising, total stocks of steel are no longer growing. By the end of the century, this situation may become prevalent across the globe.

The importance of scrap-based steel recycling relative to virgin production will therefore increase gradually throughout the 21st century. The pace of this shift will make a big difference to virgin production needs and, as a result, to carbon emissions from the steel sector, since scrap-based steel production is far less carbon-intensive than virgin steel production, and could become effectively zero-carbon once electricity is decarbonized.

Most of the steel produced is already recycled: 83% across the world and, in some countries, as much as 90%. But further increases in recycling rates would still have a very large impact on CO_2 emissions. For instance, in any country which has already reached stable steel stocks, **increasing the recycling rate from 85% to 95% would cut the need for virgin steel production by two thirds** as well as CO_2 emissions by a similar amount.

---

[1] Material Economics analysis for the Energy Transitions Commission (2018)

There are, however, important **barriers to increasing recycling rates**, in particular:

- Some steel structures are simply **abandoned at end-of-life**, with no attempt to recycle or reuse material. While overall collection rates in the sector are relatively high, they can be as low as 50% for consumer products and 70% for new scrap resulting from production processes.
- **Nontrivial losses** of around 4-5% are incurred in the remelting processes.
- Moreover, steel recycling faces **a problem of "downcycling"** with high-quality steel ending up recycled into lower quality construction products such as rebar. This occurs because of the mixing of different alloys and other materials during the scrapping and collection processes, which makes it impossible to recycle back into high-quality products. One estimate suggests, for instance, that only 8% of steel originally used in car manufacture maintains sufficient quality at end of life to be used for the same purpose again[2]. A crucial driver of this problem is the fact that, in product scrapping and collection processes, copper (for instance from wiring systems, electric motors, or magnetic parts) gets mixed in with steel and, when the copper share in steel exceeds about 0.15%, steel becomes unsuitable for important product categories. This "downcycling" problem will become an increasingly important impediment to increased recycling rates over time, as copper contamination builds up in the global stock of steel. As long as total stocks of steel are increasing rapidly, there will be continued demand for downcycled construction steel, and qualities can be improved by mixing new virgin steel in with recycled materials. But, as an increasing number of countries reach steel stock stability, their ability to eliminate primary production will be limited by the downcycling phenomenon.

> CIRCULAR ECONOMY IS POTENTIALLY THE SECOND BIGGEST LEVER FOR CO_2 EMISSIONS REDUCTION AFTER CLEAN ELECTRIFICATION

The prize for overcoming these constraints would be very large. Estimates from Material Economics suggest that, in a technically feasible circular scenario, circa 565Mt of virgin steel production could be substituted annually by additional recycling in 2050, bringing the share of scrap-based production to 50% of the global steel production [Exhibit 5.1].

This would deliver a 21% cut in 2050 CO_2 emissions from global steel production. If, in addition, countries could **reduce the requirements for steel use** in key value chains, in particular through better building designs or the development of shared automobile business models, **the emissions reduction could be 37% by 2050** [Exhibit 5.2].

Achieving these significant emissions reductions will require **major changes in business practices**, building on greater coordination between companies across the value chain, currently for which there are no strong incentives. The key objectives, therefore, should be to aim for:

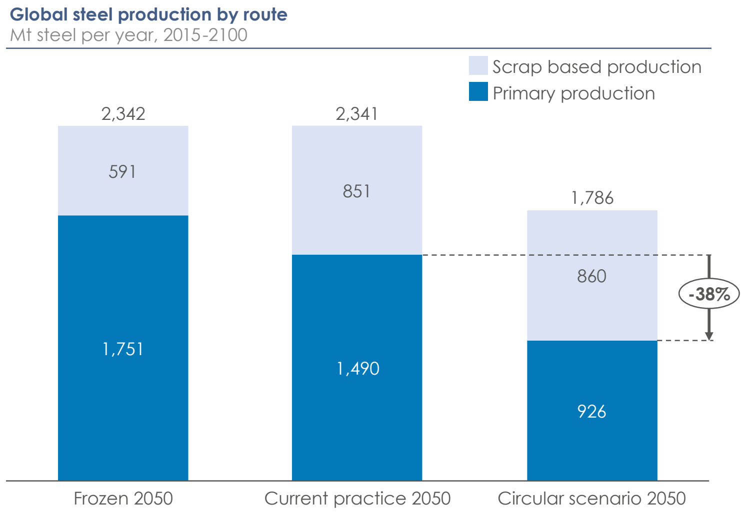
- **More complete recovery of end-of-life steel**, particularly in the construction sector and in the manufacturing sector – which will require better coordination between steel producers, product manufacturers and end consumers, possibly enforced by law through extended product responsibility;
- Greatly **improved separation of different steel products at end-of-life**, with different types of alloys sorted for recycling and with careful separation of copper from steel – thanks to improved dismantling techniques;
- **Improved product designs** that aim to reduce the steel requirements in products, prolong their lifetime, and make it easier to dismantle and separate different materials at end-of-life;
- **Better manufacturing processes** to reduce the scale of production scrap;
- The **development of metallurgy** to increase copper tolerance in high-quality steel products, or to allow the separation of copper from steel once mixing has already occurred.

Policies to drive these changes are examined in further details in Chapter 9.

---

[2] Material Economics (2018), *The circular economy: a powerful force for climate change*, based on MaterOhno, H., Matsubae, K., Nakajima, K., Nakamura, S. and Nagasaka, T. (2014), *Unintentional Flow of Alloying Elements in Steel during Recycling of End-of-Life Vehicles*

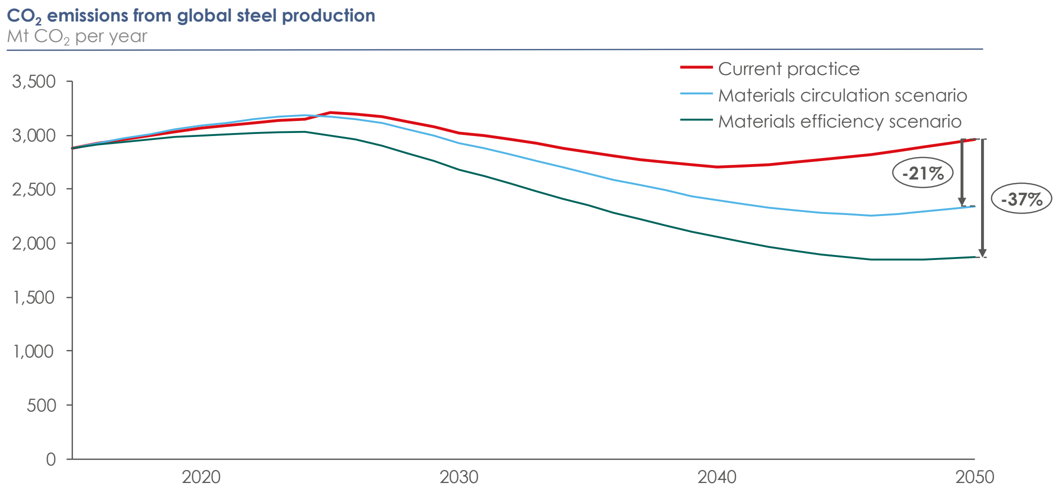
A circular scenario can significantly reduce primary steel production globally



Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 5.1

Materials efficiency can reduce emissions from steel production by 37% by mid-century



Note: Current practice scenario: Increase in steel stock per capita, adoption of best available technology by 2050, increase of scrap based production; Materials circulation scenario: Reduced steel losses and reduced downgrading of steel; Materials efficiency scenario: Besides materials circulation, the circular scenario also builds on demand reduction from value chains, resulting in reduced steel per capita by 25%

Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 5.2

(II) PLASTICS

Plastics are versatile, durable, low-cost materials, which deliver multiple economic and social benefits. As a result, **demand for plastics has grown rapidly and will likely continue to do so** as emerging economies grow in prosperity. Plastics usage is now 100kg per capita per annum in Europe, 140kg per capita in North America, and slowly increasing but still below 40kg per capita in many emerging economies[3]. Across the world, plastics use is expected to grow from 320Mt in 2015 to 800Mt by 2050 and over 1,300Mt by 2100. If this growth occurred without changes to the production methods or recycling, the combined emissions from plastics production and end-of-life incineration could exceed 280Gt between now and the end of the century[4], using up to one third of the entire available carbon budget, which is compatible with a 2°C scenario.

As Chapter 2 described, it is possible to decarbonize key elements of the plastics production process, for instance by electrifying monomer production furnaces, using biomass as an energy source, or applying carbon capture. But, some of the technologies required (in particular electric furnaces) are not yet ready for a large-scale commercial application and, **even if plastics production was decarbonized, end-of-life emissions would remain**. Today, primary plastics production produces emissions of about 2.5tCO_2 per tonne of plastics, but embedded carbon, which will eventually be released in the atmosphere, represents 2.3 to 2.7tCO_2 per tonne of plastics.

Eliminating end-of-life as well as production emissions could be achieved through a change in feedstock, substituting bio-feedstock of synthetic chemicals (produced from hydrogen and captured CO_2) for fossil fuels. However, limits to sustainable biomass supply will make it impossible to entirely substitute fossil fuels by bio-feedstock. Moreover, the use of synthetic chemicals is at its early stages of development and would likely be very costly (these issues are discussed in Chapter 6). It is therefore likely that **a large proportion of plastics will continue to be produced based on fossil fuel feedstock**.

In this context, it will be essential to manage the existing and future fossil-fuels-based plastics stock through better end-of-life management. Since plastic waste produces numerous environmental problems apart from CO_2 emissions, there has been considerable focus on recycling for many years. But **the true extent of recycling remains minor**. While it is often said that 30% of plastics waste are recycled in Europe, the percentage of new plastic demand which is met with recycled plastic products is still only 10% – and can be much lower in other geographies. This low effective recycling rate is the consequence of multiple barriers to effective recycling, including:

- Mixed and contaminated flows, with multiple plastic types mixed together, and co-mingled with other waste categories such as paper or metal;
- The use of additives, such as colorants, stabilizers and flame retardants, which are difficult to trace or to remove, hence making it impossible or expensive to recycle into high-quality plastic products;
- Contamination via the substances that plastics packaging hold, which in some cases can create insurmountable barriers to safe recycling – for instance, regulations require that some plastics used in medical applications are incinerated.

As a result, like steel, plastics recycling has a strong tendency to involve **"downcycling"**, with high-value plastics (i.e. PET plastic bottles) ending life as low-value flowerpots, traffic cones or garbage bags.

Greater circularity and efficiency in the plastics value chain could have a very significant impact on global CO_2 emissions: **emissions from both plastics production and end-of-life incineration could be reduced by 56%**[5], through a combination of the following levers [Exhibit 5.3]:

- Increasing **plastics reuse**;
- Increasing **mechanical recycling**, focusing on the five most common types of plastics (polyethylene, polypropylene, polystyrene, polyvinyl chloride, polyethylene terephthalate) – with the aim of nearing 30% recycling of global end-of-life plastics;
- Developing **chemical recycling** to recycle types of plastics that cannot be effectively recycled through mechanical recycling – potentially addressing nearly 20% of global end-of-life plastics;

---

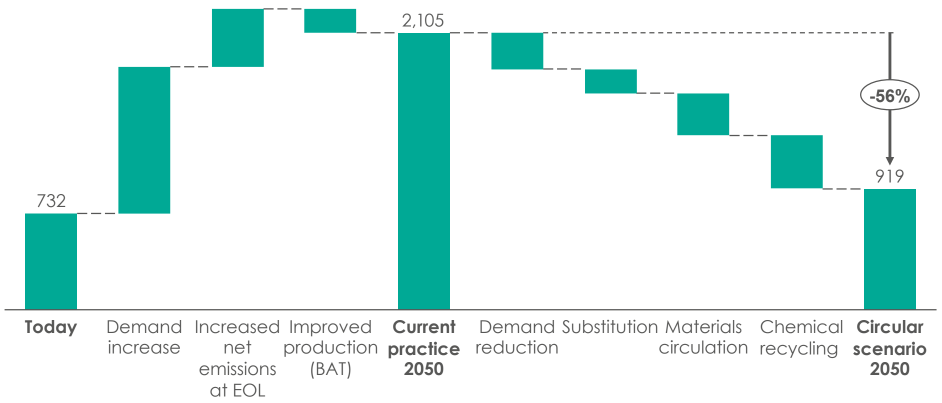
[3] Material Economics analysis for the Energy Transitions Commission (2018)

[4] Material Economics (2018), *The circular economy: a powerful force for climate change*

[5] Material Economics analysis for the Energy Transitions Commission (2018)

CO_2 emissions from plastics could be reduced by almost 60% in a circular 2050 scenario

Global CO_2 emissions from plastics (production and end of life)
Mt CO_2 per year

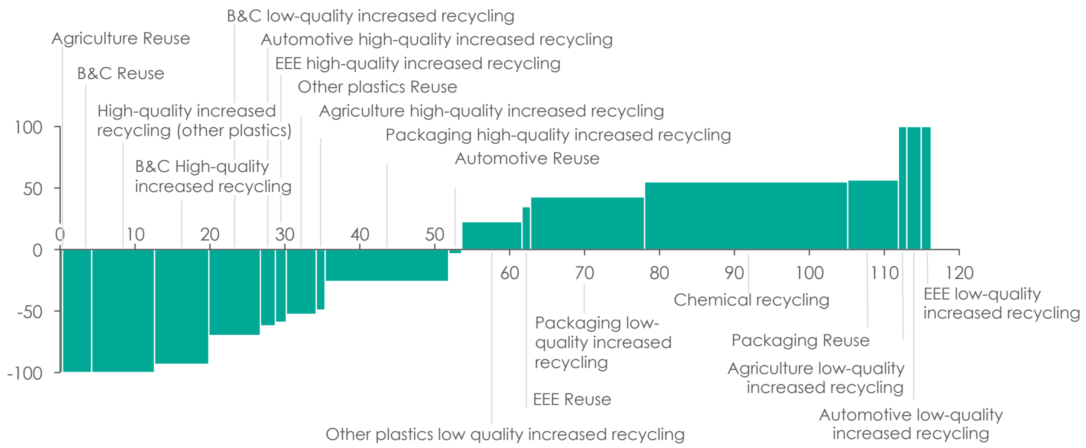


Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 5.3

Many forms of mechanical recycling of plastics should be economic without a carbon price and could even deliver CO_2 reductions at negative abatement costs

Abatement cost for plastics demand-size decarbonization
US$/tonne CO_2 per year



Source: Material Economics (2018), *The circular economy: a powerful force for climate change*

Exhibit 5.4

- Reducing demand for plastics, through **greater materials efficiency in end products** – plastics demand could be reduced by up to 35% in the cars and buildings value chains, 20% in packaging (by limiting overpackaging) and about 10% for remainder product groups;
- **Substituting fiber-based alternatives** for plastics – which could remove 15% of plastics used for packaging and 5% for remainder product groups.

This potential will not, however, be achieved without very major changes to product design and process at multiple points in the value chain. In particular:

- Products need to be **designed to make collection, sorting and high-quality recycling easier**, but upstream producers and users do not face natural incentives to act in ways which facilitate downstream recycling. Those incentives should therefore be created by policy.
- Collection process regulations need to focus as much on the **quality of collection processes** as on quantity.
- End-of-life processes need to be redesigned to **prevent the mixing of materials** which occurs, for instance, when cars are shredded rather than dismantled.
- A **large-scale mechanical and chemical recycling industry** needs to emerge, but will only do so if recycling regulations and collection processes are sufficiently common across localities to facilitate economies of scale in operations. Many forms of mechanical recycling should be economic without a carbon price and could indeed deliver CO_2 reductions at negative abatement costs, but chemical recycling is itself an energy-intensive process, which will only likely be economic (and decarbonized) if a significant carbon price of some US$50-US$70 per tonne is imposed [Exhibit 5.4].

EMISSIONS FROM BOTH PLASTICS PRODUCTION AND END-OF-LIFE INCINERATION COULD BE REDUCED BY 56% THROUGH GREATER CIRCULARITY

As a result, various public policy levers will need to be used. Imposing **a carbon price** would have a powerful effect: at US$60 per tonne of CO_2, and if imposed on both production and embedded emissions, it would increase the price of primary plastics production by around 20% on average and significantly increase incentives for recycling. But **regulations on product design, producer responsibility and end-of-life processes** will also be important.

Even an ambitious scenario for recycling and reuse, however, **would not achieve a 100% recycling rate**. Multiple thermoset and small-volume specialty plastics are either impossible or very costly to mechanically recycle; recycling processes will never achieve 100% yields; and collection and sorting processes will never be perfect. A path to net-zero CO_2 lifecycle emissions from plastics will therefore have to entail some combination of:

- **Circular practices** as described above;
- **The substitution** of other products for plastics;
- Some **replacement of fossil fuel feedstock** with bio or synthetic feedstocks, although this will be constrained by availability and cost of these feedstocks (as described in Chapter 6).
- A remaining role for **secured plastics landfilling**, but managed in such a tightly controlled fashion that it can avoid all local environmental harm and eliminate almost all CO_2 emissions, with plastic storage thus becoming a variant of carbon capture and storage.

(III) RECYCLING CEMENT AND CONCRETE

As Chapter 4 showed, decarbonizing cement production is likely to account for over **50% of the overall cost of decarbonizing heavy industry**, and a still higher percentage if the availability of very low-cost electricity reduces the cost of decarbonizing steel and chemicals. This is due to process emissions, which inevitably result when cement is made from limestone feedstock and which can only be eliminated, either by applying potentially expensive carbon capture or by shifting to new cement chemistries, which have not yet been deployed at scale and could be limited by availability of feedstock.

Opportunities for recycling, meanwhile, are much more limited in cement than in steel. Once hydrated, cement is virtually impossible to recycle. There is, however, a share of cement which remains un-hydrated within concrete and can potentially be recovered and reused if carefully designed processes are used to crush the concrete and separate the different constituent materials. Concrete can also be recycled and used again as aggregate in road construction. But inherent physical limits to recycling, combined with significant costs, mean that the potential for materials circularity in the cement-concrete value chain is unlikely to exceed 15-20%, versus the 95% in principle achievable in steel and the 65% potentially achievable in plastics.

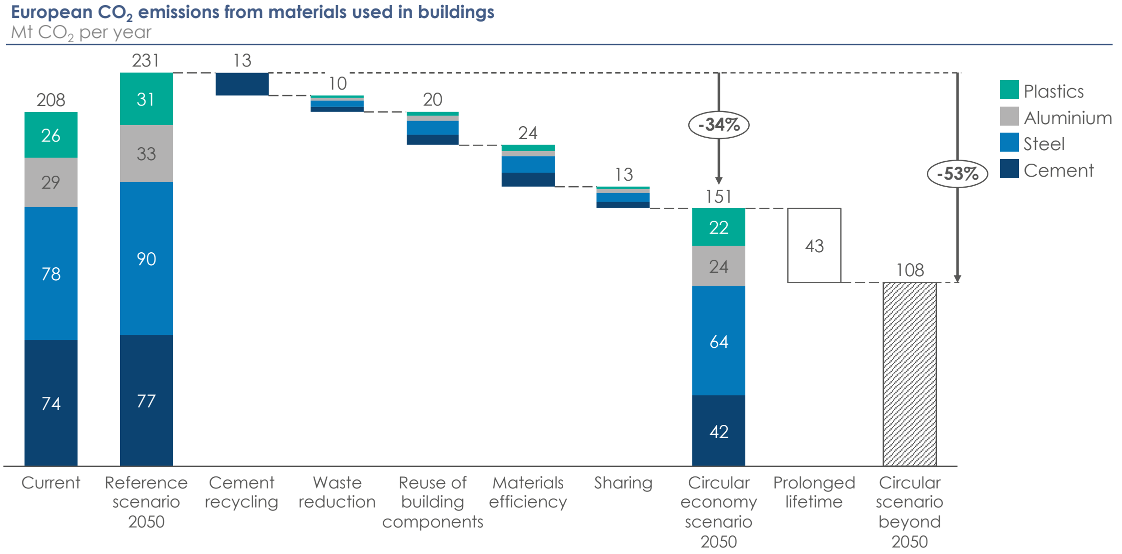
(IV) REDUCING MATERIALS REQUIREMENTS IN BUILDINGS

Although the potential to recycle cement is limited, there are much larger opportunities to reduce materials use in the construction industry, which are relevant for cement, as well as other materials like steel, aluminum and plastics. An ambitious scenario developed by Material Economics suggests that **demand for building materials could decrease by 26% by 2050** across the globe, and up to 34% in the European Union [Exhibit 5.5].

There are **four major opportunities** for greater materials efficiency in the construction sector:

- First, **waste reduction**, eliminating the 10 to 20% materials that industry experts believe are wasted on average during construction;
- Second, **reuse of building materials**, thanks to buildings designed so that structural elements – in particularly steel and concrete elements – can be reused when existing buildings undergo major rebuilds or even reused in new buildings;
- Third, **greater materials efficiency**, for instance avoiding the over-specification of structural elements;
- Fourth, and more speculatively, a **reduction in typical floorspace use per capita**, via a shift to a more shared approach, especially for office spaces, but also potentially for some residential spaces (e.g. sharing a laundry space or a children playroom).

In Europe, CO_2 emissions from materials used in buildings could be reduced by up to 53% due to greater materials efficiency



Source: Material Economics (2018), *The circular economy: a powerful force for climate change*

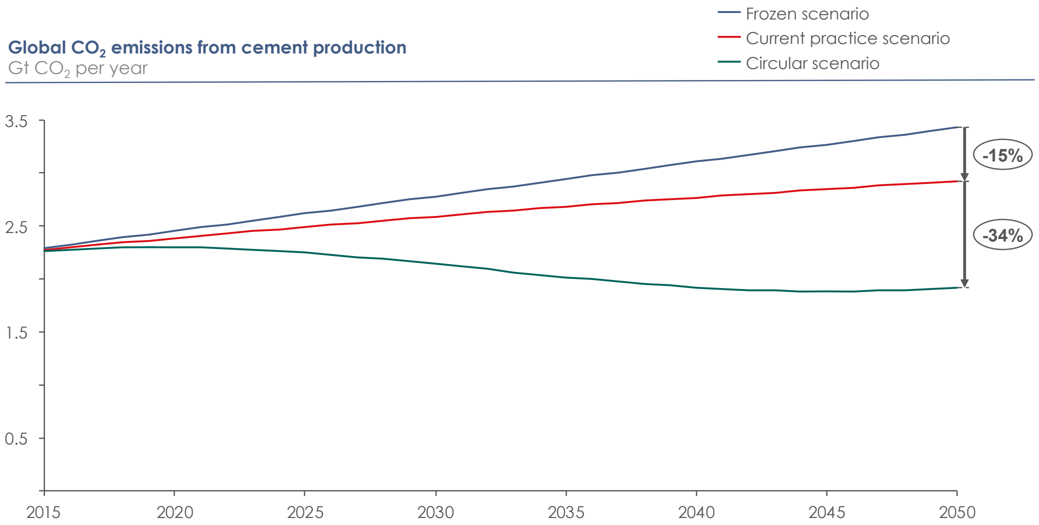
Exhibit 5.5

For cement, the combination of increased recycling and reduced materials requirements in buildings would translate into **1Gt of emissions reduction**, or 34% of global CO_2 emissions from the sector versus a business as usual reference scenario [Exhibit 5.6].

The opportunities will be **particularly important in the developing world**, which will account for almost all of growth in cement and other building materials consumption over the next half-century. Between now and 2050, the number of people living in cities is likely to grow from 4.2 billion (55%) today to 6.7 billion (68%), with almost all of this growth occurring in Africa, India, Latin America and Southeast Asia[6]. In these countries, the potential for cement recycling will be less than in developed countries, given the smaller number of buildings reaching end-of-life. But the opportunities to reduce materials use via optimal buildings design and construction technique is potentially huge and could considerably **decrease the cost of urbanization**.

These changes could be greatly **facilitated by the application of new technologies**, including building information modelling (BIM), the use of drones and 3D scanners for construction site inspections, greater use of automation and prefabrication, the use of robotics, and 3D printing. But they will also **require new regulatory approaches and industry collaborations** to foster industrywide savings which are difficult for any individual company in the value chain to achieve alone. The construction industry is, indeed, characterized by multiple contracting relationships, connecting numerous different companies, each often involved in only small parts of the total value chain. Moreover, buildings in use often pass through multiple asset owners, who may be different from the occupiers, reducing the potential for a coordinated approach to building design, building use and end-of-life dismantling. Achieving the potential savings indicated in this circular scenario will therefore be challenging and will require tight policy frameworks incentivizing cooperation across the value chain.

Global emissions from cement production could be reduced by circa 35% by 2050 in a circular scenario with some recycling and significant materials efficiency improvement in buildings



Note: Frozen scenario based on constant carbon intensity of cement production; Current practice scenario based on IEA 2DS reduction of cement production carbon intensity; Circular scenario based on 20% cement recycling by 2050, demand reduction in buildings and drop in cement use in infrastructures
Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 5.6

[6] UN Department of Economics and Social Affairs (2018)

6

Scaling cross-cutting decarbonization technologies: Orders of magnitude and system boundaries

For each of the harder-to-abate sectors, there are **three main routes to full supply-side decarbonization**:

- The use of electricity, either via direct electrification or in the form of electricity-based fuels (whether hydrogen, ammonia or synthetic hydrocarbons);
- The use of biomass as an energy source and/or as an alternative feedstock;
- The application of carbon capture (combined with either use or storage), which will enable the continued use of some fossil fuels – including as an alternative route to hydrogen production.

All three routes will be needed to some degree to achieve net-zero carbon emissions by mid-century, and it is unnecessary to predict the precise balance which will emerge. Several of the required policies described in Chapter 9 should focus on creating incentives – whether via carbon pricing or regulation – which will **prompt a market-driven search for the optimal balance**. But, it is valuable to identify:

- Whether there are any **system boundaries to the potential role of electricity, biomass and carbon capture and biomass**, and whether these limits are inherent or could be overcome by well-designed policy;
- Possible **orders of magnitude for the scale of deployment** of different solutions, to inform business investment decisions which will in turn drive self-reinforcing economy of scale, learning curve and cost reduction effects.

This chapter covers in turn:

i. **Electricity:** Decarbonization of the global economy will require massive increases in zero-carbon electricity supply for direct electrification as well as the production of electricity-based fuels. At the global level, available solar and wind resources appear to be sufficient to support most of that expansion, but with large variations in availability and cost between different regions of the world.

ii. **Biomass, bioenergy and bio-feedstock:** Biomass could potentially play a cost-effective role across multiple sectors. But tight sustainability standards are essential to avoid any reverse effect on climate and the environment. Moreover, with the sustainable supply of biomass unlikely to exceed 70EJ, it is essential to prioritize use in those sectors where there are least alternatives (e.g. aviation and plastics feedstock).

iii. **Carbon capture:** Carbon capture will probably be a necessary route to decarbonization in cement, and a cost-effective route to decarbonization of other industrial sectors in some regions. However, it is unlikely to be needed at the large scale that some scenarios envision (e.g. 20Gt per annum or more by end century). Our illustrative pathway indicates a potential need for 5-8Gt of carbon capture per annum by 2050, of which 3-7Gt would have to be stored underground.

The balance between the three routes will however **vary by region in the light of different natural resource endowment**.

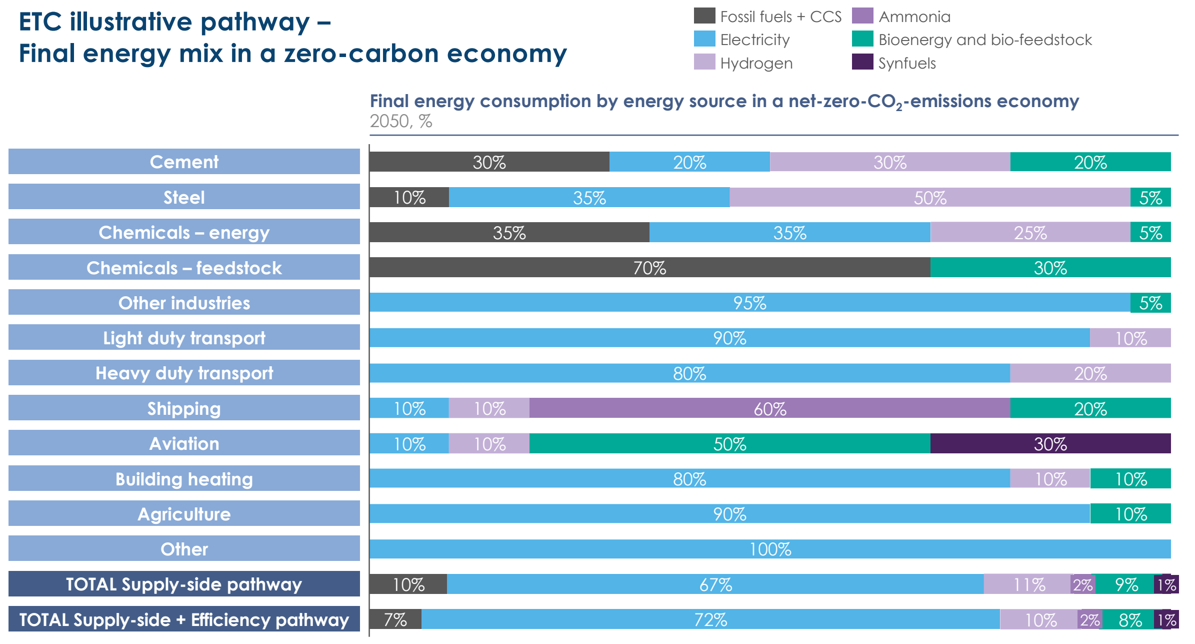
THE ETC'S ILLUSTRATIVE PATHWAYS TO NET-ZERO CARBON EMISSIONS

There are an infinite number of specific emission reduction pathways which could lead to net-zero CO_2 emissions in the harder-to-abate sectors, and by extension in the energy and industrial system, by mid-century, with varying levels of offsets from the land use system. These paths will reflect future technological developments. The global trajectory will also encompass differentiated trajectories per region, with developed economies reaching net-zero sooner than developing economies (2050-2060).

The ETC has not modelled a specific energy system scenario, but we have developed **illustrative pathways, which aim to provide a sense of the order of magnitude** of the probable scale of deployment of different solutions that would make it possible to reach close to net-zero carbon emissions from the energy and industrial system (without offsets from the land use sector) by mid-century.

- **The "supply-side decarbonization illustrative pathway**" is based on a possible mix of supply-side decarbonization technologies for each sector of the economy.
- **The "supply-side decarbonization and efficiency illustrative pathway"** shows how energy efficiency improvement combined with demand management in heavy industry and heavy-duty sectors could reduce the scale of the decarbonization challenge.

ETC illustrative pathway – Final energy mix in a zero-carbon economy



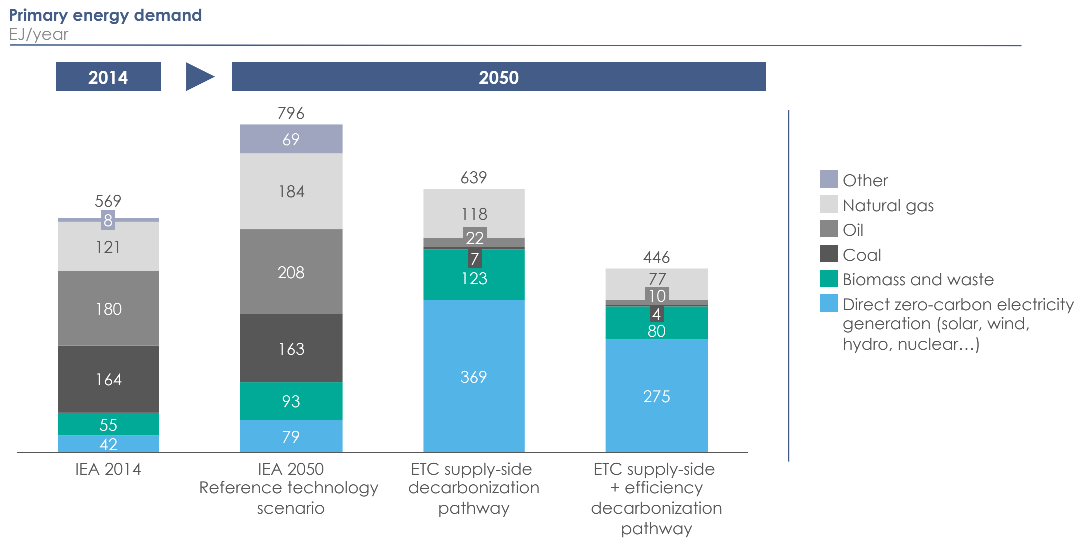
Source: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2018)

Exhibit 6.1

This analysis relies on **a mix of supply-side and demand-side routes** to zero-carbon in harder-to-abate sectors, which is informed by the sectoral analysis developed in Chapters 2 and 3, but is still, to some extent, arbitrary [Exhibit 6.1]. The model also accounts for an **illustrative decarbonized power mix** – meeting 89% of global power demand through direct zero-carbon electricity generation (solar, wind, hydro, geothermal, nuclear…), with some level of back-up from abated fossil fuels (7%) and biomass (4%)[1] – and for a **balanced hydrogen production mix** – 50% from electrolysis, 47.5% from SMR plus carbon capture, and 2.5% from biomethane reforming.

These illustrative pathways provide a useful indication of the scale at which different technologies should be developed, of the **possible final energy mix and primary energy mix** by mid-century [Exhibits 6.1 and 6.2] and of the amount of residual emissions that would likely need to be compensated by negative emissions from land use or BECCS. They constitute a useful tool to balance policy trade-offs, for instance to measure the implications of a lower supply of sustainable biomass for the required scale of renewables expansion, or the implications of a slower switch to electricity-based industrial processes for the necessary scale of underground carbon storage.

ETC illustrative pathway –
Primary energy mix in a zero-carbon economy



Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018); IEA (2017), *Energy Technology Perspectives*

Exhibit 6.2

---

[1] Based on the assessment of the potential scale of variable renewables deployment and pace of power decarbonization presented in Section (i) of this chapter and in Chapter 7.

(I) A MASSIVE EXPANSION OF ELECTRICITY AND ELECTRICITY-BASED FUELS

Building a zero-carbon economy will require massive expansion of total zero-carbon electricity generation. Today, electricity accounts for around 20% of global final energy demand. Within that, 65% is currently generated from fossil fuels, 17% from hydro, 10% from nuclear, and less than 5% from wind and solar. By contrast, in any feasible path to a zero-carbon economy, **the share of electricity in global final energy demand will rise to about 60-70%**, and this should be entirely produced from zero-carbon power sources.

Massive expansion of demand for electricity and electricity-based fuels

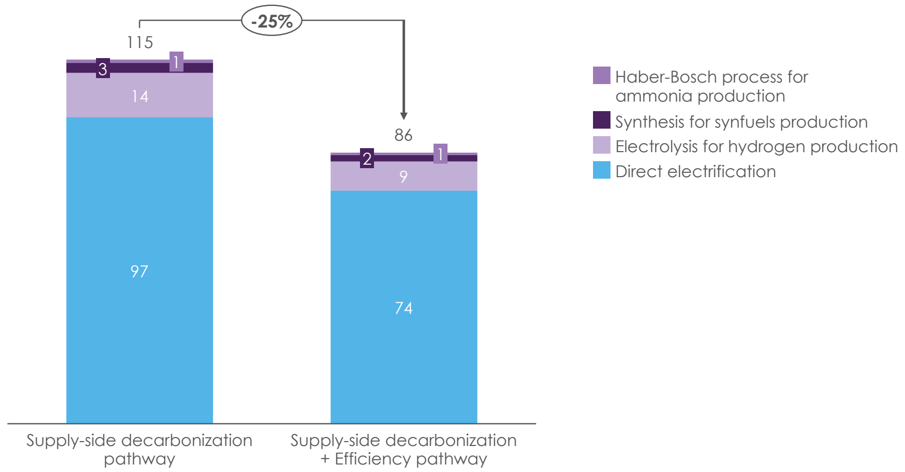
The ETC's indicative scenario suggests that total global electricity demand may increase from around 20,000TWh today to close to 115,000TWh by mid-century, if the Paris climate change objectives are to be achieved, demanding **a five-fold increase in power generation** [Exhibit 6.3]. This increase will likely be more important in developing countries, where population growth and economic growth would accentuate the trend, than in developed countries.

It will be driven mostly by direct electrification of the easier-to-abate and of large segments of the harder-to-abate sectors, and, to a lower extent by the electricity input needed for the production of hydrogen[2] and hydrogen-based fuels. Indeed, these direct and indirect forms of electrification are likely to play major roles in the decarbonization of all the harder-to-abate sectors [Exhibits 6.4 and 6.5].

- **In the transport sectors,** the energy efficiency advantage of electric engines will favor direct electrification or hydrogen fuel cell vehicles in any applications where the density disadvantages of batteries (in gravimetric terms) or hydrogen (in volume terms) can be overcome.
- **In the industrial sectors,** heat electrification and the use of hydrogen will eventually be cost-advantaged in locations where electricity costs are sufficiently low – although other solutions are likely to dominate in less favorable regions.
- **In heating,** electrification is also likely to increase, through induction and heat pumps. The latter have the fundamental advantage of delivering 300-400% efficiency in optimal locations. However, countries with significant winter heat peaks might still want to complement electrified heating with biogas or hydrogen heating networks (reusing the existing gas network) to flatten seasonal electricity peaks[3].

Gross electricity generation will need to reach 86,000 to 115,000 TWh/year by 2050 in a zero-carbon economy

Total electricity generated by 2050 in the ETC indicative pathways
000 TWh/year



Source: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2018)

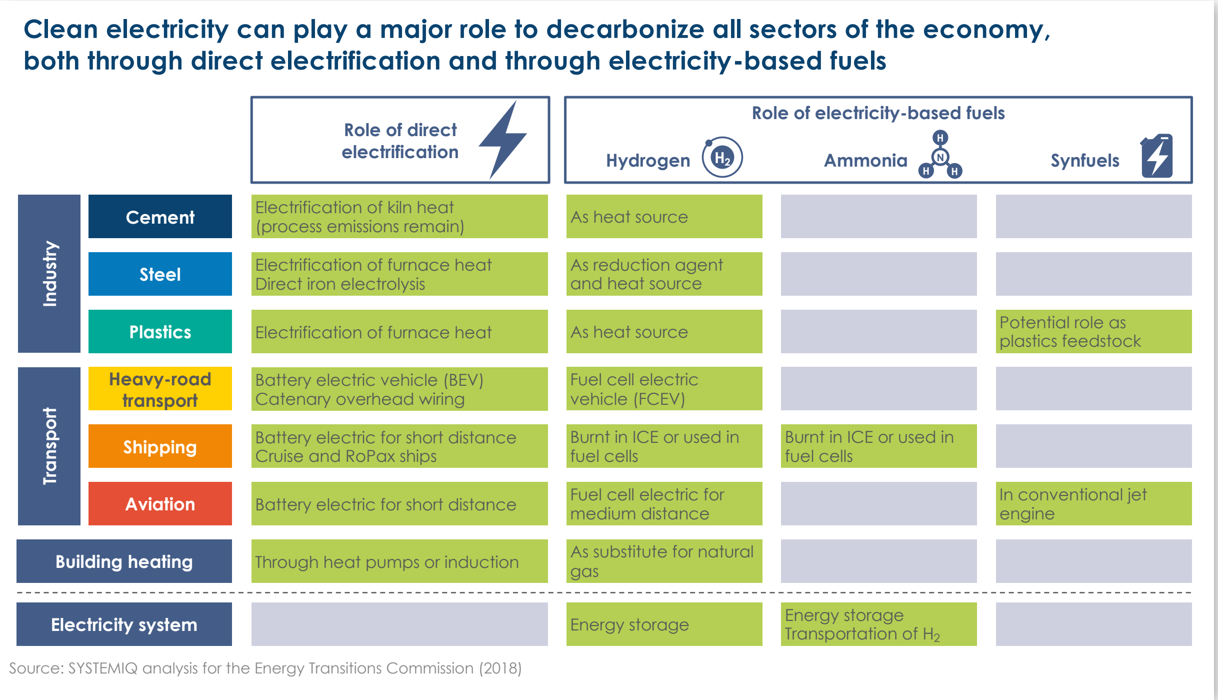
Exhibit 6.3

---

[2] Assuming that half of the hydrogen used in a zero-carbon economy would come from electrolysis.

[3] The ETC, however, has not analyzed in details pathways to decarbonize heat. Literature review presided to the illustrative heat generation mix used in our illustrative pathways.

Clean electricity can play a major role to decarbonize all sectors of the economy, both through direct electrification and through electricity-based fuels

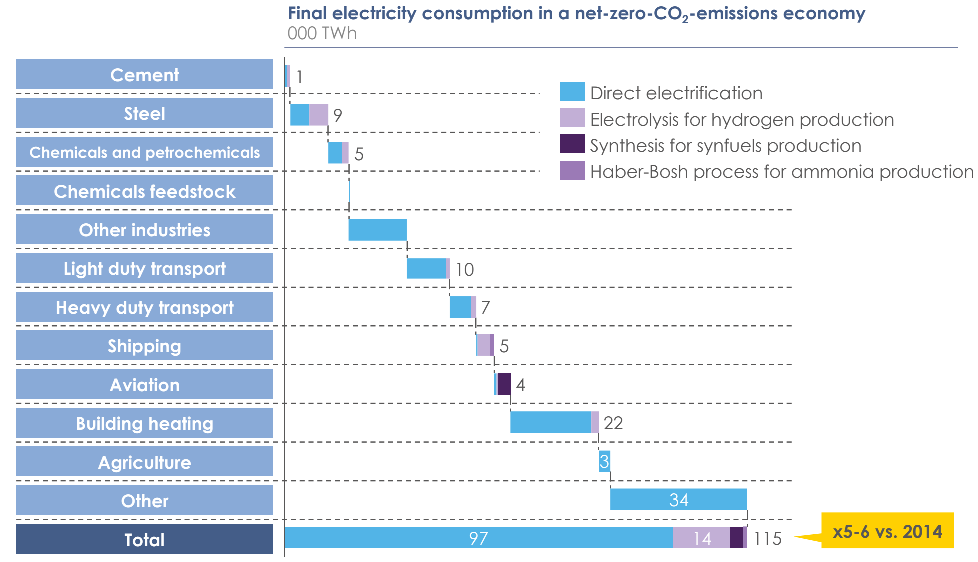


		Role of direct electrification	Role of electricity-based fuels: Hydrogen	Ammonia	Synfuels
Industry	Cement	Electrification of kiln heat (process emissions remain)	As heat source		
	Steel	Electrification of furnace heat Direct iron electrolysis	As reduction agent and heat source		
	Plastics	Electrification of furnace heat	As heat source		Potential role as plastics feedstock
Transport	Heavy-road transport	Battery electric vehicle (BEV) Catenary overhead wiring	Fuel cell electric vehicle (FCEV)		
	Shipping	Battery electric for short distance Cruise and RoPax ships	Burnt in ICE or used in fuel cells	Burnt in ICE or used in fuel cells	
	Aviation	Battery electric for short distance	Fuel cell electric for medium distance		In conventional jet engine
Building heating		Through heat pumps or induction	As substitute for natural gas		
Electricity system			Energy storage	Energy storage Transportation of H_2	

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 6.4

In a zero-carbon economy, final electricity consumption could reach up to 115,000 TWh



Source: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2018)

Exhibit 6.5

Our analysis shows that such a surge in zero-carbon electricity consumption is feasible, since:

- Renewable electricity costs will steadily fall, making **decarbonized power systems cost-competitive with current power systems** (even without a carbon price), and probably making direct and indirect electrification increasingly economic;
- There is **sufficient global wind and solar resources globally** to support this massive expansion, although availability costs will vary greatly by location, and some countries will face significant constraints;
- **Required mineral supplies for battery production (such as lithium and cobalt) are not a long-term constraint,** although continued technological progress and highly efficient materials recycling will be essential.

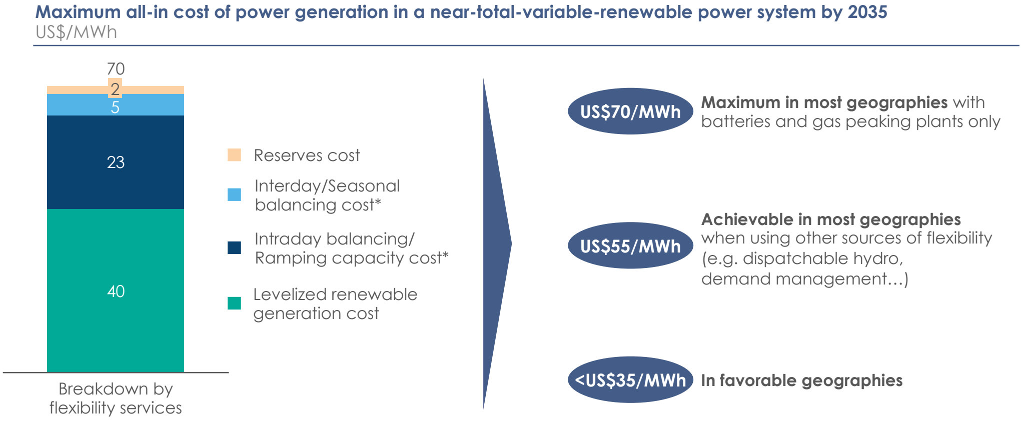
However, it will require a very significant ramp-up in renewable power as well as other forms of zero-carbon power generation. Strong policies to achieve energy efficiency improvement across all harder-to-abate sectors, greater materials efficiency and circularity, and limit demand growth in heavy-duty transport **could reduce the scale at which electricity is needed by a useful 25%** [Exhibit 6.3]. Given the scale of the investment challenge, it is vital to maximize these opportunities for demand constraint.

Falling costs of renewable electricity and green hydrogen

In *Better Energy, Greater Prosperity*, we argued that, by 2035 at the latest, it will be possible in almost all geographical locations to run electricity systems that are nearly completely (e.g. 85-90%) dependent on variable renewables while providing electricity at a maximum all-in cost of US$70/MWh, composed of US$40/MWh for renewable power generation and US$30/MWh for the provision of flexibility and backup[4]. However, **this total cost could fall to circa US$55/MWh** if a full range of flexibility options – including in particular the use of existing dispatchable power sources like hydro and smart demand management – were deployed. Even without a carbon price, these costs will make a renewable-based power system cost-competitive with a fossil-fuel-based power system.

In practice, this number may be even lower in especially favorable geographies. Indeed, since the publication of this analysis in April 2017, progress towards lower costs has been even faster than

Low-cost, low-carbon electricity is likely to be available in most geographies, with electricity below $35/MWh produced in most favorable locations



Note: Based on German resource and load profile / *Considers only two flexibility technologies: CCGT & Lithium-ion batteries / Levelized renewable energy generation cost includes all energy potentially produced, including amount curtailed or stored/shifted.
Source: Adapted from Climate Policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

Exhibit 6.6

---

[4] ETC-CPI (2017), *Low-cost, low-carbon power systems* – This does not include distribution costs.

anticipated, with some renewable power auction prices falling below US$20/MWh in the most favorable locations. We now estimate that **future all-in costs in favorable locations are likely to be US$35/MWh or even lower** [Exhibit 6.6].

Zero-carbon peak generation capacity will still be required to complement variable renewable power generation. Depending on local conditions, this could represent 10-15% of total power demand[5]. Peaking needs could be met by dispatchable hydro, biomass peaking plants and, although probably to a lower extent given the economics of peaking plants, by fossil fuel peaking plants combined with carbon capture or biomass peaking plants combined with carbon capture to create negative emissions.

Lower renewable electricity costs will make **cheaper production of zero-carbon hydrogen from electrolysis possible**. A recent IEA report described how hydrogen from electrolysis could become cost-competitive with hydrogen from SMR (even without adding CCS costs) if electricity prices were below US$30/MWh, and utilization rates high[6]. Lower costs for electrolysis equipment, which would almost certainly result from large-scale deployment, would make electrolysis cost-competitive even if electricity prices were somewhat higher [Exhibit 6.7].

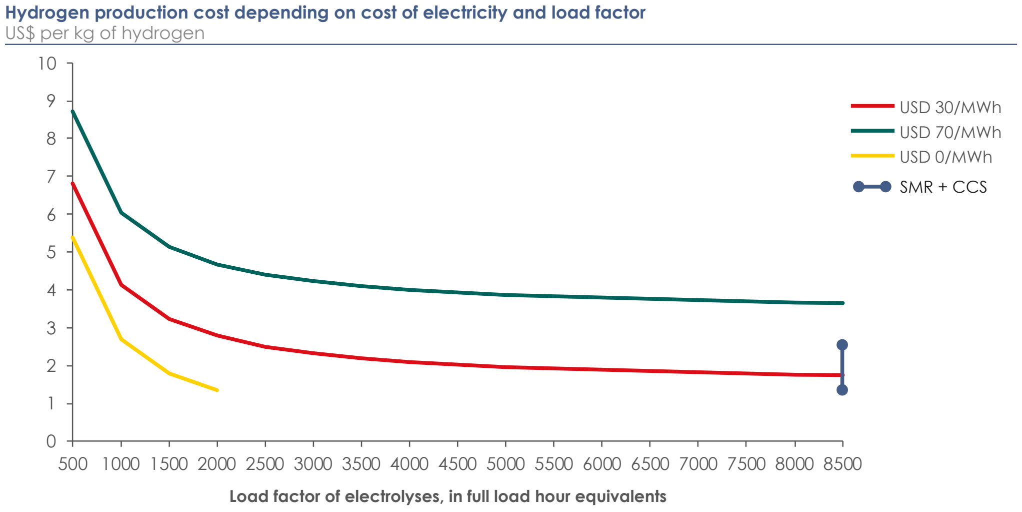
Land availability constraints

There is **sufficient wind and solar resources available in-land globally to generate the entire power demand required** in the world**.** Delivering 100,000TWh/year of electricity entirely with solar PV would require a land area of about 1.3–1.7 million km², which represents **around 1% of the global land area**[7]. If it were possible to deploy floating panels at sea, the surface required would be less than 0.3% of total earth surface.

However, **huge variations in wind and solar resource by region** imply major differences in the yields and costs of renewables. Solar and wind energy are likely to be available in some locations (e.g. Chile, Mexico, Western China, the Sahara and the Middle East) at generation costs below US$20/MWh, but generation costs in many other regions will certainly exceed this level [Exhibit 6.8].

In addition, **large differences in population density** have important implications for the feasible scale of renewable (in particular solar) deployment,

Producing hydrogen from electrolysis may already be cost-competitive with the traditional SMR route in locations with low renewable electricity costs



Assumptions: electrolyzers CAPEX US$450/kW, WACC 7%, 30 years lifetime, 70% efficiency
Source: Adapted from Philibert, C. (2017), REFI, Insight Papers, IEA, Paris, *Producing hydrogen from renewable energy*

Exhibit 6.7

---

[5] ETC-CPI (2017), *Low-cost, low-carbon power systems*
[6] Philibert, C. (2017) REFI, Insights Paper, IEA, Paris, *Producing hydrogen from renewable energy*
[7] Assuming 1.2-1.7ha/GWh/annum based on NREL (2018), *Land-use Requirements for Solar Power Plants in the United States*.

given competition with other land uses, in particular agriculture. China would only need to use about 1.7% of the land area of its five sparsely populated western provinces to meet its entire current electricity demand from solar power. But for Bangladesh to support equivalent electricity use per capita with solar energy alone would require 6-8% of its entire land area to be devoted to solar panels in a country where almost all land is already intensively used to grow food.

Several countries will therefore require **additional baseload zero-carbon power generation**, with lower land consumption and higher capacity factors, in the form of biomass plants (with or without carbon capture), fossil fuels plants combined with carbon capture, or nuclear.

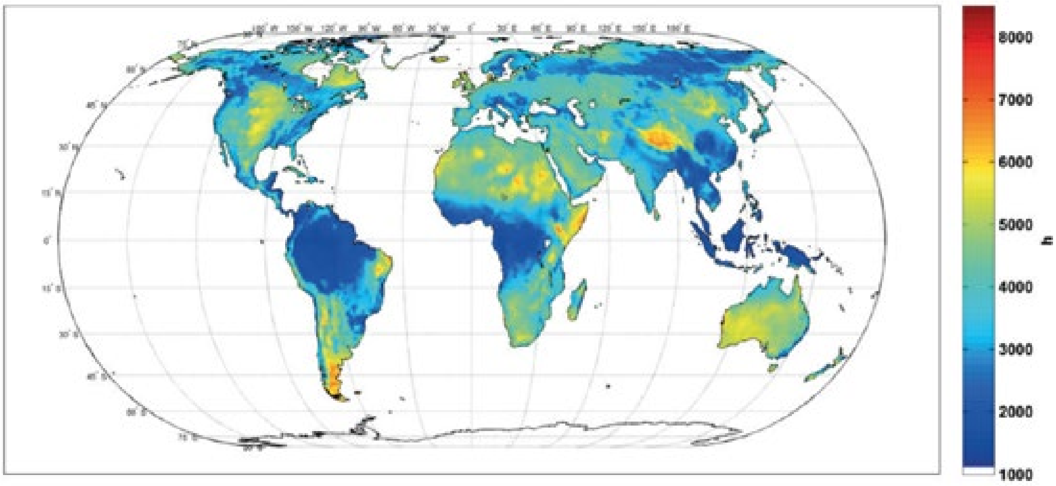
Constraints on mineral supplies to support battery deployment

If global auto and trucking fleets were entirely electrified, **required battery capacity could reach about 660TWh**[8]. The crucial question is whether limits to the available mineral supply will constrain either the feasible eventual scale of electrification or the pace at which electrification can grow given any bottlenecks in production capacity. Concerns are often expressed about the supply of lithium, rare earths and cobalt.

Our key conclusions are that:

- In the long term, **lithium resources** will be sufficient to meet massive electrification, provided effective markets and technologies develop for recycling/reuse of battery cells and material. Any temporary supply bottlenecks are unlikely to produce large price spikes that would disrupt rapid progress towards vehicle electrification. But securing lithium supply is all the more important as lithium-ion batteries are projected to remain the dominant technology in the future.
- The availability of the 17 elements collectively known as **"rare earths"** – some of which play a role in some types of electric motors as well as in batteries – is unlikely to be a serious medium/long-term impediment to wider electrification. Moreover, the current dominance of China in rare earths supply – which has raised concerns about potential Chinese dominance of battery technology – is likely to reduce as a result of investments in other regions. The adverse local environmental impacts of rare earth mining and refining, meanwhile, can be dramatically reduced via the adoption of tight controls and best practice processes.
- The biggest concern over the short to medium term is the availability of **cobalt**. While total cobalt resources are in principle sufficient to

Availability of wind and solar resources differ significantly by region



Source: IEA (2017), *Renewable Energy for Industry* (Adapted and based on Fasihi, Bogdanov and Breyer (2016), *Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants*)

Exhibit 6.8

---

[8] Assuming 3.1 billion light-duty vehicles with batteries of 70kWh and 0.4 billion heavy-duty vehicles with batteries of 600kWh.

support wider electrification, 60% of current production is concentrated in the Democratic Republic of the Congo. This raises concerns about security of supply, potential corrupt practices, and local environmental damage, in a country with imperfect governance which may suffer further political instability. Disruptions to supply could produce significant price increases over the next 5 to 10 years. Technological developments to reduce or eliminate the need for cobalt within batteries are therefore a high R&D priority.

Any pressure on these resources could in any case be significantly reduced by:

- **Innovation in battery chemistry** to decrease the cobalt and lithium density per cell;
- The development of markets and processes which will ensure **maximum recycling/reuse** of batteries and their components;
- **Reducing demand for heavy road transport** (in particular through greater logistics efficiency and modal shift) by adopting a circular vision of mobility and developing car sharing. In their latest report, Material Economics show that adopting a car sharing business model could decrease the number of cars by ~75% and designing for durability has the potential to increase car lifetime by 60%[9].

Other environmental constraints: copper and water

While massive growth in electricity and hydrogen demand will create significant increases in demand for copper and water, our analysis does not suggest serious resource constraints:

- More extensive electrification will increase the demand for copper, which is used in electricity transmission and distribution systems. But our analysis of total resources and production potential **does not suggest any significant constraint on growth in copper use**[10], and alternative materials like aluminum might play a substitution role in any case.
- Finally, large supplies of water will be needed to support large-scale production of hydrogen from electrolysis, and water is also used in some cases for solar PV panel washing, creating localized challenges in arid locations where solar yields are highest. But, on a global scale, a shift from a fossil-fuel-based energy system to one dominated by renewable energy will **significantly reduce the demand for water**, given the large quantities of water used in oil and gas production (particularly fracking) and in thermal power generation. Moreover, global water supply and demand issues are dominated by the agricultural sector, not by industrial or energy system use.

(II) A PRIORITIZED AND TIGHTLY REGULATED USE OF BIOMASS

The role of bioenergy and bio-feedstock in a zero-carbon economy is a complex issue, given **multiple potential sources of biomass, multiple different transformation mechanisms, and multiple end uses**. It will, in part, be driven by the evolving cost of different biomass sources and transformation processes relative to the costs of alternative low-carbon options.

But, the appropriate use of bioenergy and bio-feedstock also needs to reflect (i) **limits to the environmentally and socially sustainable supply of biomass**, given competing needs for food production and ecosystem services, and (ii) the **lifecycle carbon emissions** across the production, distribution and use of bio-based products. Moreover, bioenergy typically produces less than 1% of the energy that solar power can produce per hectare, making electricity-based solutions more effective where available and technically feasible. Accordingly, the appropriate role of bioenergy will vary by region in the light of different biomass resources.

Our analysis suggests the following broad conclusions to guide public policy and business strategy:

- **Bioenergy can play a significant role** in the energy transition, but sustainable sources may be **limited to 70EJ per annum** by mid-century.
- **Tight sustainability regulations** are indispensable to ensure that the use of bioenergy and bio-feedstock truly reduces carbon emissions (over the lifecycle of the bio-based product) and does not have other environmental impacts, in particular deforestation, competition with food production, or threats to ecosystems and biodiversity conservation.
- **Biomass use should therefore be prioritized** in sectors with least low-carbon alternatives, in particular, aviation and chemicals.
- **Bioenergy is likely to be more expensive than fossil fuels**, implying that significant carbon prices will be required to drive its use in many applications.

---

[9] Material Economics (2018), *The Circular Economy, a powerful force for climate mitigation*

[10] DBS Group Research (2018), *Copper and its Electrifying Future*

Sustainable supply of biomass

Estimates of the sustainable supply of biomass for the energy and industrial system vary hugely – with a range of studies suggesting figures from less than 50EJ to about 1200EJ per annum[11].

IEA estimates suggest that **about 70EJ could potentially be supplied by different forms of wastes and residues**[12], which would not require dedicating land to biomass production for the energy and industrial system. This entails 10-15EJ of municipal waste, 46-95EJ from agricultural wastes and processing residues (e.g. straw, corn stover and bagasse), and 15-30EJ of wood harvesting residues. These are the most clearly sustainable bioenergy resources, and are likely to be the lowest-cost resources too. Supply is however limited by availability of waste. Municipal waste might increase with urbanization, but could also be reduced through better waste management and higher rates of sorting/recycling. As for crop and wood residues, a sufficient share (e.g. 70%) of the residues needs to be returned to the soil to maintain soil quality, avoiding increased use of urea-based N-fertilizers, which release CO_2 during use.

The wide variation in overall biomass supply estimates then reflects different assessments on the **availability of land that could be dedicated to the production of biomass for energy and feedstock** in one of the following forms:

- **Oil plants and sugarcane** produce the highest energy yields per hectare, and are the easiest to convert into biofuels, but are grown on scarce arable land (11% of the world's land surface[13]), directly competing with food production – ideally, future bioenergy production should therefore avoid reliance on any of these crops.
- There may, however, be significant potential in some regions to grow **"winter cover crops"** on arable land which would otherwise lie fallow over the winter. The Ecofys report on biogas potential in Europe estimates that 130 Mt of biomass could be produced per annum by 2050 from second crops of maize or triticale (a wheat-rye hybrid) grown on 50% of all current wheat and maize crop land in Europe[14].
- **Pastureland** is more extensively available (25% of the global land surface[15]), but typical biomass yields per hectare are much lower.
- **Algae** may constitute an additional source of biomass for bioenergy and bio-feedstock, but developments are early stage and the true potential of this biomass source is yet to be refined.
- The greatest uncertainty lies in the availability of **lignocellulosic material harvested from forest crops**, either from energy-dedicated wood plantations, or (most probably) from residues of new forestry grown for other primary purposes (in particular natural carbon sequestration). This would require large-scale reforestation, and should be tightly monitored and controlled to prevent any risk of deforestation. Some recent studies suggest that there are 800 million ha of depleted tropical forest land on which it would be possible to grow fast-growing species such as poplar and willow, in rapid cycle rotation. The critical importance of forest-derived products has been greatly increased by recent progress in the production of biofuels and biogas from lignocellulosic sources, reducing previous dependence on oil crops (for biofuels) and limited waste supplies (for biogas).

Many factors are likely to significantly limit (and possibly prevent) dedicating land to the production of these energy crops, and therefore invite to caution:

- Population growth is likely to increase **land use requirements for agriculture**, especially if climate change impacts agricultural yields. Beyond land use, increased water scarcity due to climate change would also impose prioritization of agricultural requirements over use to grow biomass for energy and industry.
- It is imperative to **prevent further land use change**, in particular deforestation in tropical areas, both to preserve ecosystems and biodiversity, and to avoid large carbon emissions from the food and land use system.
- Achieving a zero-carbon-emissions economy will require some level of negative emissions from **natural carbon sequestration**, likely delivered through a massive reforestation program, in particular on degraded lands.
- This reforestation program could possibly go hand-in-hand with **the significant scale-up of timber production**, which would enable the substitution of carbon-intensive cement and steel in buildings and infrastructure by a high-performance, low-carbon (or even carbon-negative) building material.

---

[11] UKERC (2011), *Energy from biomass: the size of the global resource*

[12] IEA (2017), *Technology roadmap: Delivering Sustainable Bioenergy*

[13] UKERC (2011), *Energy from biomass: the size of the global resource*

[14] Ecofys (2018), *Gas for climate*

[15] UKERC (2011), *Energy from biomass: the size of the global resource*

Tight regulations on biomass sustainability are therefore vital. This will likely exclude many energy crops, which often compete with agriculture and ecosystem services, with some local exceptions like winter cover crops in temperate climates. Balancing these different considerations, the ETC suggests that **a sustainable biomass supply of 70 EJ could be produced each year, possibly going up to 100EJ** thanks to tightly-regulated reforestation efforts. We use these estimates to assess how potential priority demands compare with such a budget.

Lifecycle carbon emissions from biomass

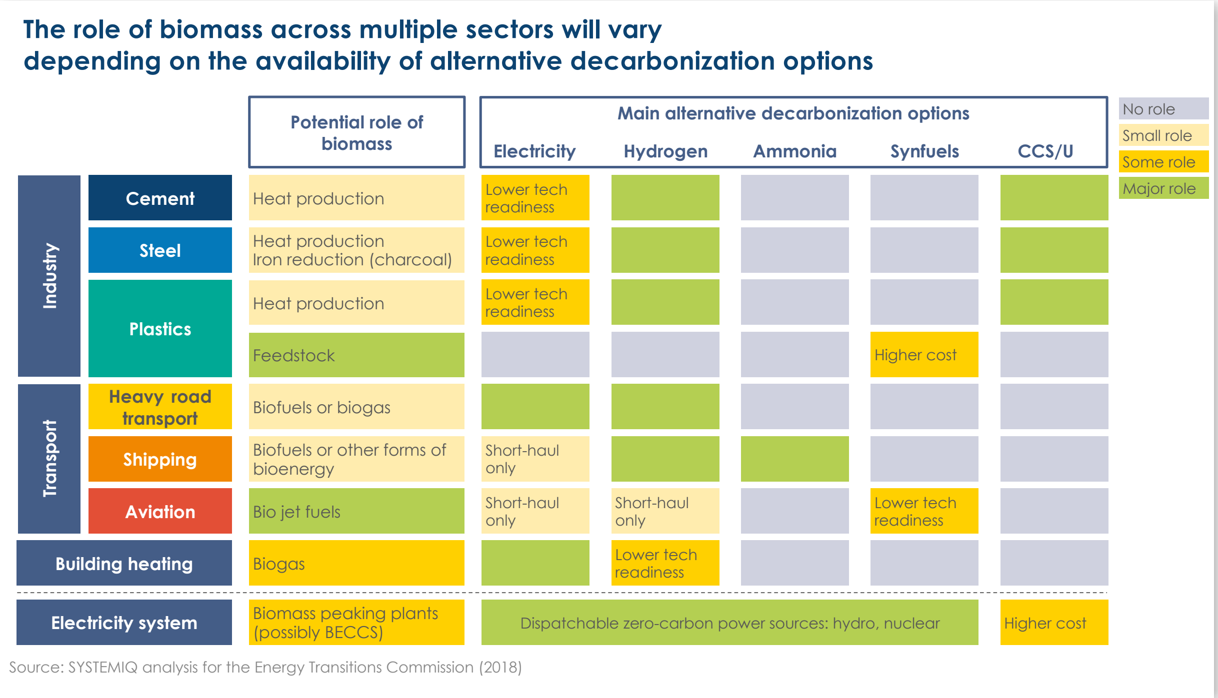
Biomass use could theoretically be carbon-neutral, if biomass production does not drive any harmful land use change, if it does not use any carbon-emitting N-fertilizers, and if all energy inputs to biomass harvesting, transportation and transformation were zero-carbon themselves.

However, these conditions are not necessarily met today, leading to **significant differences in lifecycle carbon emissions** for different types of bioenergy currently on the market. Estimates suggest that, while ethanol from Brazilian sugarcane delivers full lifecycle emission reductions of over 85%, ethanol from US maize may achieve only 10-30% reductions, and biodiesel from European rapeseed 50-65%[16].

Over time, emissions reduction from biomass use will likely improve as the economy decarbonizes and energy inputs to biomass production increasingly come from zero-carbon electricity or biomass itself. But the pace of that development is uncertain. There is therefore a danger that premature switching to bioenergy produces only limited emissions reduction if biomass use is not **carefully regulated and monitored**.

Priority uses of biomass

Multiple sectors, both easier-to-abate and harder-to-abate sectors, currently use – or have the intention of using – bioenergy or bio-feedstock to drive decarbonization. **A sustainable supply of 70-100EJ of biomass would be vastly insufficient to meet all the potential sectoral claims** on biomass from the energy, industry and transport sectors. **Biomass use must therefore be focused** on sectors where alternative decarbonization routes are least available [Exhibit 6.9].



The role of biomass across multiple sectors will vary depending on the availability of alternative decarbonization options

		Potential role of biomass	Main alternative decarbonization options				
			Electricity	Hydrogen	Ammonia	Synfuels	CCS/U
Industry	Cement	░ Heat production	🟨 Lower tech readiness	🟩	⬜	⬜	🟩
	Steel	░ Heat production Iron reduction (charcoal)	🟨 Lower tech readiness	🟩	⬜	⬜	🟩
	Plastics	░ Heat production	🟨 Lower tech readiness	🟩	⬜	⬜	🟩
		🟩 Feedstock	⬜	⬜	⬜	🟨 Higher cost	⬜
Transport	Heavy road transport	░ Biofuels or biogas	🟩	🟩	⬜	⬜	⬜
	Shipping	░ Biofuels or other forms of bioenergy	░ Short-haul only	🟩	🟩	⬜	⬜
	Aviation	🟩 Bio jet fuels	░ Short-haul only	░ Short-haul only	⬜	🟨 Lower tech readiness	⬜
Building heating		🟨 Biogas	🟩	🟨 Lower tech readiness	⬜	⬜	⬜
Electricity system		🟨 Biomass peaking plants (possibly BECCS)	🟩 Dispatchable zero-carbon power sources: hydro, nuclear				🟨 Higher cost

⬜ No role
░ Small role
🟨 Some role
🟩 Major role

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 6.9

---

[16] SYSTEMIQ analysis (2017), based on ADEME (2017) and other sources

In the harder-to-abate sectors, the demand for biomass will vary depending on the availability of a cost-effective alternative decarbonization option.

- In **aviation**, it is highly likely that decarbonization will require the development of either a biofuel or synthetic equivalent of jet fuel. The relatively low efficiency of synthetic fuels production would, at least initially, favor the biofuel route.
- In **shipping**, biodiesel or other forms of bioenergy may be a cost-effective alternative to hydrogen or ammonia (as substitutes for HFO) in existing ship engines in the short term, but cost reductions in hydrogen and ammonia production could progressively reduce the need for bioenergy use in the sector.
- In **road transport**, biofuels and biogas probably will not have a significant, long-term, cost-effective role, given the higher intrinsic efficiency of electric engines, and therefore of battery electricity vehicles (BEVs) or hydrogen fuel-cell vehicles (FCEVs).
- In **industry**, bioenergy could potentially play a decarbonization role through direct biomass use or biogas use for heat production. Sustainable charcoal can also technically be used as a reduction agent in steel. However, as explained in Chapter 2, there are alternative routes to supply-side industry decarbonization, via direct electrification, use of hydrogen, or carbon capture.
- Bioenergy may, however, be particularly important in the **chemicals sector**, where it could be used as a feedstock in monomer production, with the CO_2 absorbed in biomass growth offsetting not only production emissions but also end-of-life emissions.

THERE IS ENOUGH BIOMASS SUPPLY TO COMPLETELY DECARBONIZE AVIATION.

If not constrained by tight sustainability criteria, the biggest claims on biomass could actually arise from other sectors than heavy industry and heavy-duty transport:

- In **residential heating**, electrification – either through induction or heat pumps – may be the main route to decarbonization in many circumstances, in particular where heat pumps can deliver a major efficiency advantage. But, in regions facing large seasonal heating peaks, this may have very costly implications for peak electricity demand. Biogas may therefore play a complementary role, in some circumstances, with electricity producing baseload heating, while biogas covers heating peaks[17].
- In **electricity generation**, as we argued in *Better Energy, Greater prosperity*[18], it will, in future, be possible to build systems which are nearly completely dependent on variable renewables (at 85-90%). But, solid biomass or biogas may need to play a role in helping to provide the last 10-15% of peak seasonal supply, which may be very expensive to meet from other low-carbon power sources. Combined with carbon capture (as BECCS), this could potentially be a source of negative emissions.

Given limited global supply of biomass (i.e. 70-100EJ), our analysis suggests that:

- **There is enough biomass supply to completely decarbonize aviation.** This would require a maximum of 42EJ by 2050. This number could be lowered if synfuels are developed, and if energy efficiency and demand management are maximized.
- The second highest priority sector is likely to be **bio-feedstock for plastics**, but bio-feedstock **could not entirely substitute for fossil fuels**: 28EJ of biomass supply would be required to cover only 30% of feedstock needs. The strategy for plastics decarbonization must therefore combine an as complete as possible shift towards a circular model, with carbon sequestration – in the form of solid plastics placed in permanent, secure and leak-proof storage – and an as limited as possible use of bio-feedstock to compensate for inevitable losses in the value chain.
- **The biggest demands for biomass could come from residential heating** (28EJ of biomass input if biogas plays a significant role in residential heating), **and from biomass-based power generation** (34EJ if biomass-based power generation provides only 4% of global electricity

---

[17] The ETC has not done an in-depth analysis of pathways to decarbonize heating, but an initial literature review has been carried out to make it possible to integrate heating in the overall illustrative pathway developed for this report, and take into account implications for the required scale of different energy sources.

[18] Energy Transitions Commission (2017), *Better Energy, Greater Prosperity*

supply to help meet peak generation needs). It is therefore essential to minimize this need, especially in the power sector, by driving maximum progress of renewables, energy storage technologies and smart demand management.

- Combined, those four main applications are likely to eat up the full supply of sustainable biomass, therefore leaving **limited to no space for biomass use in other sectors**. Alternative decarbonization routes should therefore be prioritized, and public support to biomass development should transition away from non-priority sectors to high-priority sectors.

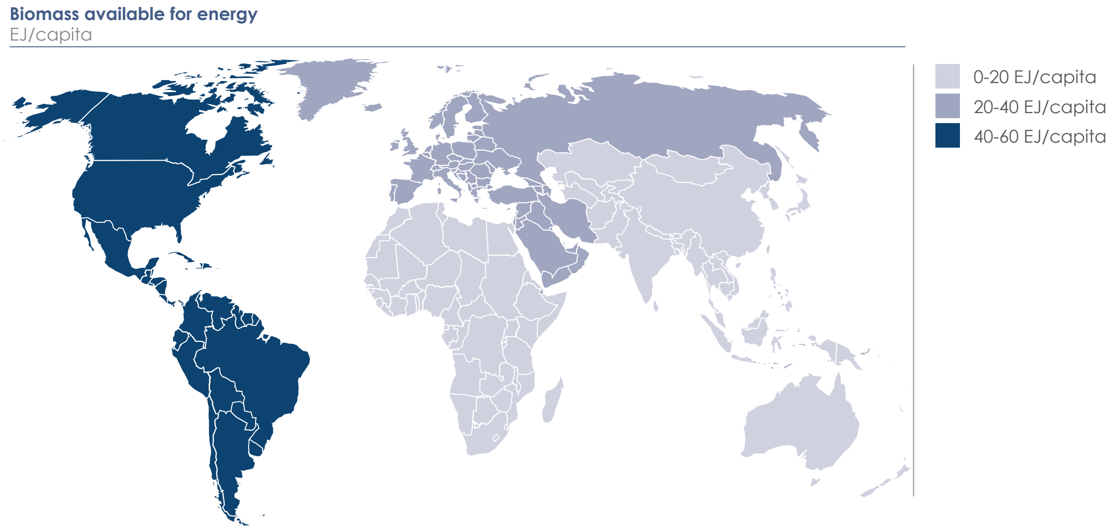
However, **biomass availability differs significantly from region to region** [Exhibit 6.10], which suggests that (i) there will likely be a development of international trade of biorefined products (biofuels and bio-feedstock) and (ii) there might be regions where local conditions provide a clearly sustainable supply for a larger portfolio of applications, and where biomass therefore continues to be used in non-priority sectors, especially in heating and power, to a greater extent than elsewhere.

Exhibit 6.11 describes an illustrative pathway to a net-zero-carbon economy that entails a maximum of 123EJ of biomass use across all sectors, prioritizing aviation and plastics, taking into account some biomass use in heating and power, and acknowledging that very limited biomass might still be used in some locally-specific circumstances in a broader range of applications. Importantly, energy efficiency improvement (across all sectors and in particular in heating) and reduced demand for carbon-intensive products and services (in particular for aviation) could **significantly reduce the amount of biomass required to reach net-zero emissions from 123EJ to 80EJ**.

Cost-competitiveness of bioenergy

Prospects for bioenergy costs are complex to assess because of (i) large differences in the cost of different biomass sources, (ii) significant regional variations, (iii) multiple possible transformation processes, with unclear cost trends, and (iv) uncertain impact of higher demand for scarce biomass resources on prices as the energy transition progresses.

Availability of biomass differs per region



Source: IRENA and UN in McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 6.10

Municipal waste is almost certain to be the cheapest biomass source (and indeed may be available at negative cost with processers paid to remove it), and biofuels or biogas made from municipal waste may therefore become available at costs fully competitive with fossil fuels or natural gas. But there are limited total quantities of municipal waste available. **Other categories of biomass can vary in cost** from as low as US$1-2 per GJ (for agricultural residues) to more than US$20 per GJ (for oil crops)[19].

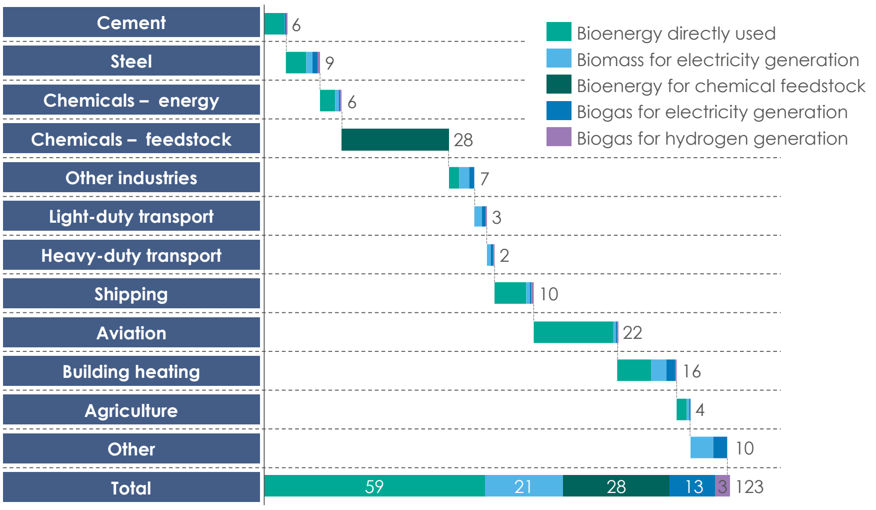
WASTE AND RESIDUES ARE CERTAINLY THE CHEAPEST BIOMASS SOURCE.

When considering both the cost of the biomass input and the cost of transformation, the costs of final bioenergy forms is particularly uncertain:

- Estimates of **liquid biofuel costs** (for transport applications and bio-feedstock) differ greatly and are changing as new technologies become available. Sugarcane-based ethanol is sold in Brazil at prices fully competitive with gasoline, but other road transport biofuels are still significantly more expensive. Meanwhile, current estimated costs of bio jet fuel production suggest a large cost premium over conventional jet fuel (e.g. 100%), but costs of production from municipal wastes are now falling quite rapidly and a price premium of 50% only appears in the realm of feasibility. Some estimates suggest that, even in the long term, biofuels would only be competitive with gasoline and diesel if crude oil prices rise above about US$60-US$80 per barrel. Given that oil prices are likely to decline over time, if demand decreases and prices are set by lower marginal cost producers, a carbon price will likely continue to be required to make biofuels cost-competitive.
- Similarly, **biogas** costs are significantly higher than natural gas costs, and almost certain to remain so. Ecofys estimates that current costs of US$108/MWh for anaerobic digestion derived biogas could fall to US$67/MWh by 2050, with significant reductions in production costs offsetting a slight

In a zero-carbon economy, bioenergy needs could reach up to 123EJ

Bioenergy input demand in a net-zero-CO_2-emissions economy
EJ/year, ETC supply-side decarbonization pathway



Source: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2018)

Exhibit 6.11

---

[19] SYSTEMIQ analysis, based on DataStream, EUBIA, Novozymes, Bentsen N.S. et al. (2006)

increase in biomass supply costs[20]. Costs for thermal gasification (which can be applied to some biomass sources, but not others) could be a still lower US$48/MWh. But this reduction will not be sufficient to make biogas cost-competitive with natural gas in the absence of a carbon price.

- The costs of **solid biomass** for use in electricity generation or industry vary greatly by specific location, but, in most regions, are likely to remain significantly more expensive than unabated coal or gas, and than renewables. In a power system dominated by cheap renewable power, biomass is likely to compete with coal or gas plants abated through carbon capture for the provision of peaking capacity. Current wood pellet prices in North-West Europe are about US$10 per GJ versus US$4 per GJ for hard coal, adding about US$40/MWh compared to the cost of fossil-fuel-based electricity. It could therefore be cost-competitive with abated coal and gas plants even without a carbon price, given that carbon capture would add US$45-55/MWh to generation costs[21].

It is therefore likely that **most forms of bioenergy will continue to cost significantly more than fossil fuel equivalents**, implying that significant carbon prices, or other forms of policy support, will be required to make them economic. Biomass-based solutions may also be more expensive than alternative decarbonization routes like electrification, hydrogen or carbon capture in some applications, where they would then naturally be driven out of the market.

(III) AN ESSENTIAL, BUT LIMITED, ROLE FOR CARBON CAPTURE

Most scenarios for limiting global warming to well below 2°C assume that carbon capture (combined either with use or storage) will play a major role. Many, in addition, assume that the use of bioenergy plus CCS (BECCS) will enable the global economy to achieve net negative carbon emissions in the late 21st century. For instance:

- Analysis of multiple climate mitigation models by the IPCC[22] shows that around two thirds assume that BECCS amounts to more than 20% of primary energy in 2100.
- The recently published Shell Sky scenario[23] anticipates that, by 2050, the world might be storing 5Gt of CO_2 per annum and using another 5.1Gt in CO_2-based products, with 1.8Gt of the total already by then deriving from biomass sources. By 2100, the scenario envisages 10.9Gt of carbon storage plus 8.3Gt of carbon usage.
- In *Better Energy, Greater Prosperity*[24], we described a median case (based on an analysis of 100+ existing 2˚C scenarios) in which the world might develop 7-8Gt of carbon sequestration per annum by 2040 (with a combination of carbon use, carbon storage and natural carbon sinks).

But there is a glaring **disconnect between these assumptions and the current pace of carbon capture development**. To hit 7-8Gt captured per annum by 2040, the world would need to build more than one hundred plants per year over the next 20 years, each with an annual capacity of 3Mt[25]. By contrast, after more than a decade of intense discussion of the necessity of and potential for carbon capture, total operating and planned CCS capacity is less than 40Mt per annum from 37 projects[26]. In the absence of large-scale deployment, **estimates of CCS costs for commercial deployment have, if anything, slightly increased** – in a decade during which solar PV costs have fallen by 77%[27].

In this context, there is **no current consensus about the necessary scale of carbon capture** to achieve the Paris objectives. Some believe that the declining cost of renewable electricity mean that carbon capture is no longer required. There are also concerns that large CCS/U assumptions are used in the public debate to justify large permanent fossil fuel production. Finally, there are concerns about the permanence, safety and environmental impact of underground carbon storage.

It is therefore essential to attempt a dispassionate analysis of the need and potential for carbon capture. The ETC's analysis indicates that **carbon capture is likely to play a significant role in some sectors, in particular cement, but with the total scale of deployment required being less than in many scenarios**:

- **The role for carbon capture in the power sector will likely be limited.** Even with significant scale

---

[20] Ecofys (2018), *Gas for climate*
[21] Global CCS Institute (2017), *Global costs of carbon capture and storage*
[22] IPCC (2018), *Global Warming of 1.5˚C*
[23] Shell (2018), *Shell Scenarios Sky – meeting the goals of the Paris agreement*
[24] Energy Transitions Commission (2017), *Better Energy, Greater Prosperity*
[25] Energy Transitions Commission (2017), *Better Energy, Greater Prosperity*
[26] GCCSI (2017), *The global status of CCS: 2017*
[27] Bloomberg New Energy Finance (2018), *Tumbling costs for wind, solar, batteries are squeezing out fossil fuels*

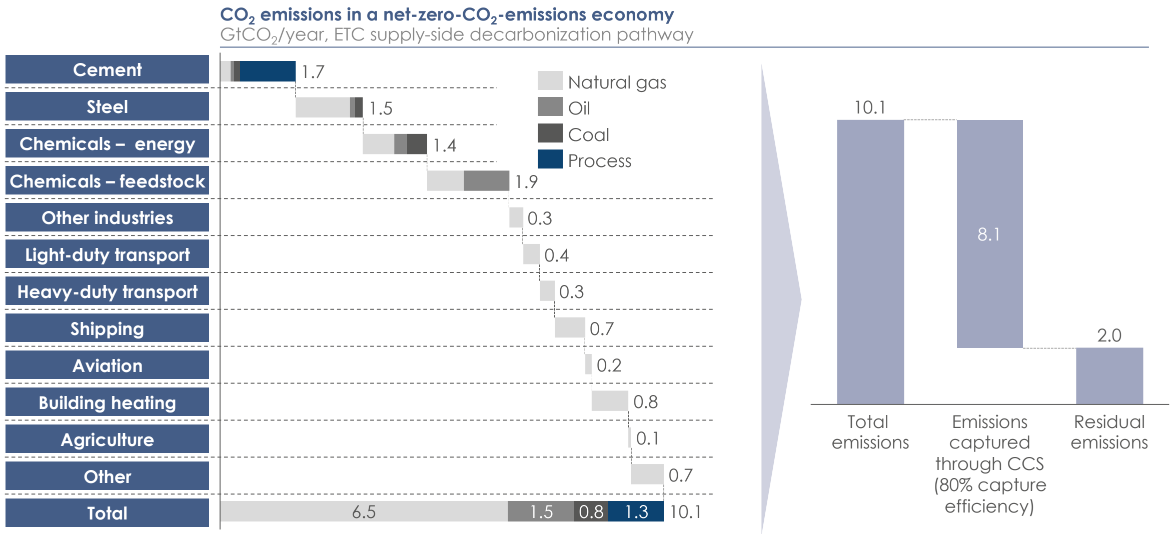
development, "nth of a kind" CCS installations are likely to add US$10-US$30 per MWh to the cost of generating electricity from coal or gas[28], leaving little opportunity for cost-effective deployment in an environment where the all-in cost of electricity will increasingly compete with fossil fuels even when no carbon capture cost is added. It could, however, still play a role in countries which face constraints on renewables deployment (as described in Chapter 7), and potentially for peak power generation, in power systems based at 85-90% on variable renewables (as described in Section II above).

- Carbon capture will, however, have **a crucial role to play in industrial decarbonization**. In the cement sector, it is likely to be the only feasible route to completely eliminate process emissions. In steel or chemicals, it may be the most cost-effective route to decarbonization in regions which do not enjoy abundant cheap wind and solar resources. The potentially low cost of capturing process emissions from steam methane reforming (SMR) may mean that hydrogen and ammonia will, in some locations, be more cost-effectively produced via SMR plus CCS than via electrolysis.
- It is important to note, however, that **carbon capture is not totally effective**, with about 10-20% of CO_2 likely to escape from capture installations. As a result, if CCS/U amounts to 8-10Gt per annum, there will be residual emissions of 1.5-2 Gt, which will need to be offset in the land use sector in order to achieve net-zero total emissions.
- Our illustrative pathway to a net-zero-carbon economy suggests **5-8Gt of CO_2 capture per annum may be required in 2050** [Exhibit 6.12].

This carbon could then, in turn, be used in CO_2-based products or stored in underground storage:

- There is a **significant opportunity to use CO_2, rather than transport and store it**. These opportunities are greatest in concrete (where absorbing CO_2 can improve product quality), aggregates and carbon fiber. Given that carbon capture will likely be essential to decarbonize cement production, and that the dispersed nature of cement production will increase the cost and complexity of CO_2 transport, this suggests a potentially significant role for integrated CCU projects across the cement, concrete and aggregates value chain. We

Up to 8Gt of CO_2 capture per annum may be required in 2050



Note: The ETC supply-side decarbonization pathway accounts for carbon capture on end-of-life incineration of plastics
Source: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2018)

Exhibit 6.12

---

[28] Global CCS Institute (2017), *Global Costs of Carbon Capture and Storage*

estimate that **1-2Gt could potentially be used** each year rather than stored in 2050.

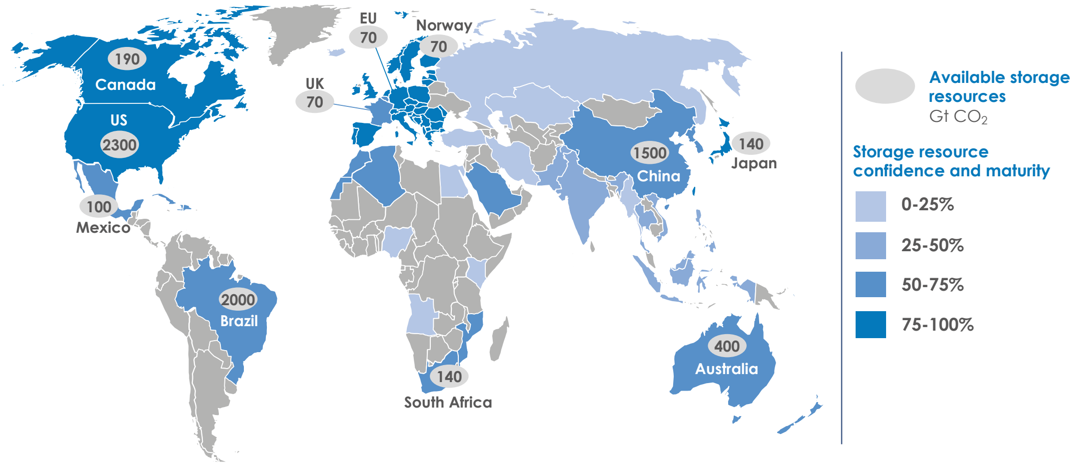
- Some underground storage will, however, be required, on a scale of 3-7Gt per annum. Leading institutions like the IPCC have concluded that **carbon capture and storage is technically feasible and likely to be safe enough** to play a role within an overall emissions reduction strategy, provided it is effectively regulated and monitored[29].
- **3-7Gt of geological carbon storage is certainly feasible on a global scale**, but the role of carbon storage will vary considerably by region, given major differences in available geological storage capacity [Exhibit 6.13].

However, achieving these volumes of carbon capture by mid-century would require a step change in the pace of deployment, which **will not occur unless governments play an active role** in:

- **Building social acceptance** of carbon transport and storage on the back of independent scientific evidence of their safety;
- Making carbon capture and storage economically viable through **carbon pricing**, as well as through appropriate insurance mechanisms;
- **Planning and regulating the deployment of carbon transport and storage infrastructure**, including deciding on the routes of carbon pipelines and ensuring tight regulation and monitoring of leakage risks.

These conditions are not yet met today. Immediate and forceful collective action from policymakers and industries is needed to meet them in the next 10 years. **If underground carbon storage is not developed**, meeting the Paris objectives would be a much greater challenge requiring (i) an even faster deployment of renewables and electricity-based solutions for industry than what is currently described in Chapter 7, (ii) the development and deployment of low-carbon materials (including breakthroughs in cement chemistries) to substitute for Portland cement, (iii) the development of carbon dioxide destruction technologies to treat remaining carbon emissions and (iv) greater amounts of carbon offsets from the land use sector.

Availability of CO_2 underground storage resources is still uncertain in some regions, but appears to differ significantly across the globe



Source: Global CSS Institute in McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 6.13

---

[29] IPCC (2005), *Carbon Dioxide Capture and Storage*; IPCC (2014)

A MAJOR ROLE FOR HYDROGEN

Hydrogen is highly likely to play a major, cost-effective role in the decarbonization of several of the harder-to-abate sectors, and may also be important in residential heating [Exhibit 6.14]. It could also play a role in flexibility provision in the power system. As a result, achieving a net-zero-CO_2-emissions economy will require a very significant increase in global hydrogen production: **from 60Mt per annum today to 425-650Mt by mid-century**, even if hydrogen fuel-cell vehicles play only a small role in the light-duty transport sector.

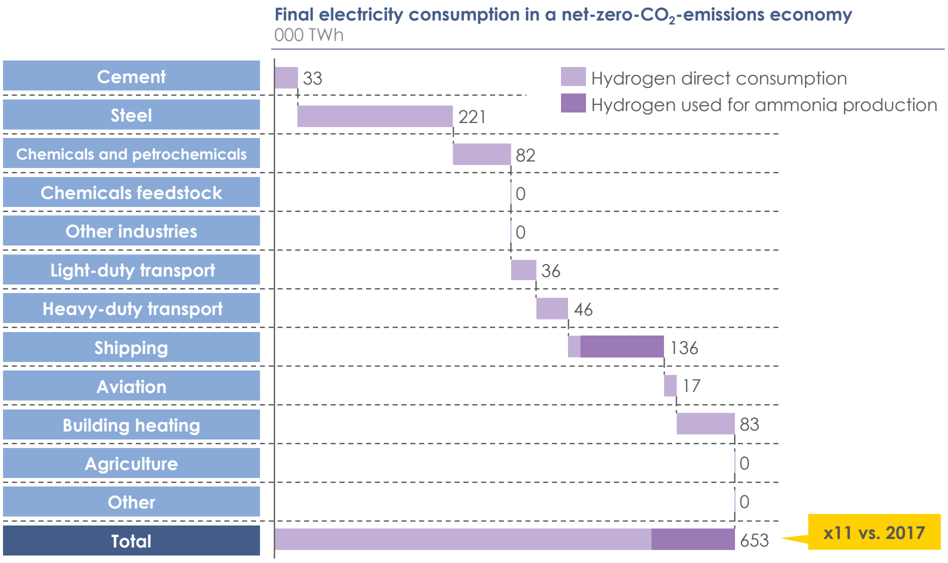
It is therefore essential to foster the large-scale and cost-effective production of zero-carbon hydrogen via one of three routes:

- **Electrolysis using zero-carbon electricity:** This will be increasingly cost-effective as renewable electricity prices fall, especially in the most favorable locations, and as electrolysis equipment costs decline. If 50% of future hydrogen demand were met by electrolysis, the total volume of electrolysis production would increase 100 times from today's level, creating enormous potential for cost reduction through economies of scale and learning curve effects.

- The application of **carbon capture to steam methane reforming**, and the subsequent storage or use of the captured CO_2: This may be one of the more cost-effective forms of carbon capture given the high purity of the CO_2 stream produced from the chemical reaction, if energy inputs to the process are electrified as the CO_2 stream from gas combustion is less concentrated. For hydrogen from SMR plus CCS to really be near-zero-carbon, however, carbon leakage in the capture process, as well as methane emissions throughout the gas value chain, would have to be brought to a minimum. If 50% of future hydrogen demand were met using SMR with carbon capture on the chemical reaction, the related carbon sequestration needs would amount to 2-3Gt.
- **Biomethane reforming**: SMR could also be made zero-carbon if biogas were used rather than natural gas, but is unlikely to play a major role, given other higher priority demands on limited sustainable biomass resources.

The ETC's illustrative pathway assumes a balanced mix of hydrogen production through electrolysis and SMR (50/50) and, within the SMR route, a 5% share of biomethane reforming.

In a zero-carbon economy, hydrogen consumption could be multiplied by more than 10



Source: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2018)

Exhibit 6.14

(IV) OVERALL CONCLUSIONS AND IMPLICATIONS

It is neither possible nor necessary to predict the precise balance of the three routes by which full decarbonization of the harder-to-abate sectors and of the overall global economy will be achieved. Indeed, the optimal balance between the different routes will vary by specific region, reflecting different natural resource endowments.

But, the ETC's illustrative pathways suggest some important conclusions [Exhibits 6.1 and 6.2]:

- There is a **major opportunity to reduce total energy demand** – and total carbon capture needs – by maximizing progress on energy efficiency, increasing logistics efficiency and modal shirt, and moving as rapidly as possible towards a more circular economy. Our modelling suggests that, while future final energy demand in 2050 might be 640EJ, this could be reduced **by as much as 30%** (to 445EJ) if all opportunities for energy efficiency and greater materials recycling and reuse could be seized. As Chapter 4 described, this would significantly reduce the cost of decarbonization. It would also reduce the likelihood that bioenergy demands breach sustainability limits or that carbon capture and storage is needed on an unattainable scale.
- Whatever the precise level of final energy demand, **electrification will be the dominant route to decarbonization**, with direct use of electricity accounting for 65-75% of final energy demand, and hydrogen and ammonia (in part produced from electricity) accounting for about 10-15%. Total electricity generation, whether for direct use, or for the production of hydrogen, ammonia or synthetic fuels, will need to **grow from around 20,000TWh today to 85-115,000TWh** by mid-century. This hugely increased electricity supply will have to be produced at 85-90% from direct zero-carbon electricity generation (i.e. renewables or nuclear) with only 10-15% coming from biomass or abated fossil fuel inputs.
- **Biomass demand could still amount to about 80-125EJ globally** (including plastics feedstock), with a lower bound that is slightly higher than the 70EJ of wastes and residues which are likely to be available by mid-century. This reveals that limiting biomass use within tight sustainability constraints will constitute a significant challenge. Solving that equation will require to:
  - Significantly increase the efficiency of biorefinery processes, in order to produce more final bioenergy with a fixed supply of biomass;
  - Grow sustainable forms of biomass supply beyond wastes and residues, with a particular attention to lignocellulosic sources, winter crops and algae;
  - Further reduce the need for biomass across sectors, in particular by leveraging energy efficiency and demand management opportunities, by developing alternative zero-carbon dispatchable power sources and new forms of energy storage in the power system, and by developing alternative decarbonization routes in other sectors.
- **Fossil fuels** are likely to still represent 20% of primary energy demand (90-150EJ), leading to 5-8Gt of carbon capture. Within that, natural gas would be predominant. With 13-30EJ, chemicals feedstock represents an important share of fossil fuel primary energy demand (from oil and natural gas). End-of-life management, recycling and secure landfilling would remove the need for 0.7-1.5Gt carbon capture on end-of-life incineration.
- If sustainable bioenergy resources turned out to be more constrained, or if carbon use and underground carbon storage could not reach the necessary scale, more intense electrification would be indispensable, which would be technologically possible, but would demand more investment and more forceful policies.

7

The path to net-zero carbon: Transitional issues and solutions

Chapters 2 to 4 argued that it is technically possible to eventually decarbonize each of the harder-to-abate sectors at only a small cost to the economy and consumers. Public policy and industry investment plans should therefore aim to achieve complete decarbonization of these sectors by mid-century, with **the developed world achieving net-zero carbon emissions by 2050 and the whole world by 2060.**

But policy and company investment plans also need to reflect the appropriate transition path from today to those endpoints. **Technical, economic and institutional challenges** lie in the way of a rapid transition to net-zero emissions, with important differences between sectors, in particular, between industry and heavy-duty transport.

In this chapter, we therefore consider:

i. The technical, economic and institutional challenges of the transition in harder-to-abate sectors;
ii. The feasible pace of deployment of renewables, and implications for the pace of electrification;
iii. The evolving role of biomass throughout the transition;
iv. The appropriate role of transitional solutions, in particular the use of natural gas and the purchasing of offsets.

(I) TECHNICAL, ECONOMIC AND INSTITUTIONAL CHALLENGES

Technical challenges

Many technologies described in Chapters 2 and 3 are still at the developmental stage and are not yet commercially ready. **Market readiness varies significantly from technology to technology.** For instance, electric trucks could be available and cost-competitive in the early 2030s, while cement kiln electrification is 20 years out. Complex hydrogen-based and electricity-based industrial processes (notably the electrification of high temperature heat and the direct reduction of iron through an electrochemical process) are among the least commercially ready technologies, which will particularly slow down the transition in industry. By contrast, technologies required to decarbonize heavy-duty transport (in particular battery, hydrogen and biofuels) appear to be closer to market readiness, which should facilitate the transition in those sectors. A key priority for policymakers and industry players is to accelerate the development and deployment of key innovations. The **innovation agenda for the harder-to-abate sectors** is described in detail in Chapter 8.

In addition to sector-specific technologies, Chapter 6 stressed that the decarbonization of harder-to-abate sectors will considerably increase demand for various forms of zero-carbon energy – in particular zero-carbon power, zero-carbon hydrogen produced either from electrolysis or from SMR combined with carbon capture, and sustainable bioenergy and bio-feedstock – and grow the need for carbon transport and storage infrastructure. Meeting a surge in demand from multiple sectors of the economy will require **a step change in the pace of deployment of these cross-cutting technologies**. Those key resources will be unevenly distributed across the globe, driving different decarbonization pathways in each geography, but also potentially redistributing competitive advantages across countries in different industries. Section 2 below examines in more detail the scale-up challenges for zero-carbon power and sustainable biomass, and the implications for transition pathways in harder-to-abate sectors.

Last but not least, our analysis suggests that, while the energy and industrial systems can get very close to net-zero by 2060, there may be **small residual emissions** (around 2Gt per annum) which would be very expensive to eliminate. These will arise in particular from:

- **Carbon capture**: Most carbon capture technologies enable the capture of 80-90% of the CO_2 stream from industrial processes, but capturing the last 10-20% is likely to be either near-to-impossible technically or extremely costly.
- **Biomass use**: Although very tight standards should aim to ensure that only sustainable biomass-based products, which are carbon-neutral or carbon-negative over their lifecycle, are used in a zero-carbon economy, there may be some uncontrollable residual lifecycle emissions in some cases.
- **End-of-life emissions from plastics**: End-of-life emissions from plastics can only be eliminated through bio or synthetic feedstock, which would be carbon neutral over their lifecycle. However, availability of these alternative feedstocks is limited. It will therefore be essential to manage the existing and future fossil-fuels-based plastics stock through mechanical and chemical

recycling, as well as secured end-of-life storage for solid plastic, to avoid end-of-life emissions. However, it may not be feasible to achieve 100% collection and management of end-of-life plastics, and some level of leakage may still occur.

To achieve a net-zero carbon economy, these residual emissions will need to be **compensated by negative emissions**, either within the energy and industrial system through BECCS, or from land use.

Economic and institutional challenges

In the absence of carbon prices, most decarbonization routes in the harder-to-abate sectors represent **a net cost compared to the high-carbon alternative**. Market forces alone will therefore not drive progress; and strong policies – combining carbon pricing, regulations, and financial support – are essential to create incentives for rapid decarbonization. In that context, **sectors which are exposed to international competition will be more difficult to shift** to zero-carbon technologies than others, given the risks on competitiveness if decarbonization costs were imposed (either through carbon pricing or through regulations) in one region and not in others. This implies the need for international policy coordination, or alternatively the use of downstream taxes, border tax adjustments and/or compensating mechanisms. Policy implications are described in Chapter 9.

In heavy industry, where assets have very long lifetimes, strong policy incentives might be required to **encourage early asset write-offs**. In steel, for instance, a switch from blast furnace reduction to hydrogen-based DRI is likely to require the scrapping of the existing plant before the end of its useful life. This issue is unlikely to apply to transport, given the considerably shorter lifetime of the truck and bus fleets, and the possibility to use a drop-in fuel in shipping and aviation.

Even assuming that carbon prices and regulations create clear financial incentives for the decarbonization of harder-to-abate sectors, the **upfront investment costs** for many zero-carbon technologies will likely be too important for individual industry players to bear, especially in sectors and companies facing low margins. Public support to investment (for instance through loan guarantees or repayable advances) will therefore be important to incentivize low-carbon investment.

Moreover, some industries, like shipping or construction, are so fragmented that **incentives are split**. Even cost-effective efficiency technologies and circular practices are not easily deployed. Innovative policy should strengthen incentives, for instance regulations imposed at port level or obligations for materials recycling.

Finally, although beneficial on an aggregate scale, **the transition to a zero-carbon economy will inevitably create winners and losers**. Policy should anticipate and compensate for the distributional effects of the transition through just transition strategies. Particular attention should be paid to:

- **International development support:** The increase in cost of intermediate products might be more difficult to bear in developing countries than in developed countries, in particular given that the biggest increase in demand for materials and mobility services are expected in emerging economies, where materials recycling will play a more limited role than in developed countries with already high materials stocks. MDBs and DFIs will therefore need to play a role in the financing of low-carbon infrastructure and industrial assets. The transfer of best available technologies to developing markets will also be essential.
- **Short-term impact of carbon prices on end consumers**: Even though, in the long run, zero-carbon products and services will be available at a very small additional cost for end consumers, carbon pricing could have a larger impact on the purchasing power of lower-income households in the short term by penalizing products and services with lower environmental performance initially conceived for lower-income market segments.
- **Impact on local employment and economic development:** The transition to a zero-carbon economy implies a restructuring of the industrial sector, which is likely to weaken some sectors and companies, with significant impact on employment in the regions where they are located. Policies ensuring the transition of the workforce – through early retirement or re-training – as well as the development of new economic activities in those regions will be particularly important to ensure that the zero-carbon transition is socially acceptable.

(II) POWER DECARBONIZATION AND ELECTRIFICATION

Pace of power decarbonization

Electricity – whether used directly or via hydrogen, ammonia or other electricity-based fuels – will play a major role in achieving a zero-carbon economy, and the total volume of both electricity and hydrogen production will need to increase dramatically during the course of the 21st century, from 20,000TWh today to about 100,000TWh by 2050. Given the scale of these future needs, **it is essential that public policies drive rapid growth in zero-carbon electricity supply** in order to both decarbonize existing electricity supply and support growing future demands for zero-carbon electricity.

Chapter 6 demonstrated that it is **in principle feasible to meet this surge in demand with renewable energy** and that the related claim on land use is not of the nature of constraining supply in the long term.

However, there could be **limits to the pace at which renewable electricity supply can be grown** in the medium term. To reach circa 90,000TWh of wind and solar power generation globally by 2050, and therefore meet roughly 90% of power demand through variable renewables, **the amount of new solar and wind capacity installed annually globally would need to increase by more than 10% per year every year until 2050**, which means doubling annual deployment every 7 years. Such exponential growth appears to be in the realm of feasibility, now that renewables are reaching cost-competitiveness, but it will require a step change in the scale of the renewable industry [Exhibit 7.1].

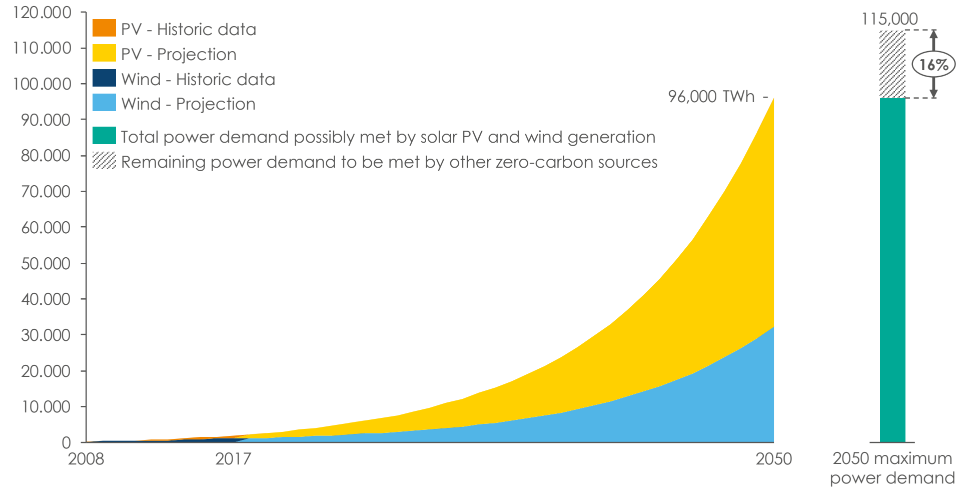
Moreover, there will be **significant regional variations**. For instance:

- Given current solar and wind deployment rates in the US, a continued acceleration of renewable deployment – with new-build capacity steadily increasing by 10% per year – could enable the country to meet roughly 90% of its 2050 power demand with variable renewables.
- By contrast, the pace of solar and wind deployment in India has historically been slower and the ramp up for these technologies is likely to be hindered by a weaker transport infrastructure, with losses currently above 15% in the national power grid. Meanwhile,

Global solar and wind power generation needs to grow exponentially in order to meet the expected power demand of a decarbonized economy

Power generation from solar PV and wind if annual deployment rates increase at 10% per year between 2018 and 2050

TWh/year



Source: Historic data: US EIA (2017) / Projection: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 7.1

power demand is expected to multiply by up to 7 (if energy efficiency is not significantly improved), driven by population growth, economic development and electrification of a broader range of applications. Even if new-built capacity steadily increases by 10% per year, the country would only be able to meet about 60% of its power demand with variable renewables.

Zero-carbon peak generation capacity will be required in all geographies to complement variable renewable power generation. Depending on local conditions, this could represent 10-15% of total power demand[1]. Peaking needs could be met by dispatchable hydro, biomass peaking plants and, although probably to a lower extent given the economics of peaking plants, by fossil fuels peaking plants combined with carbon capture or biomass peaking plants combined with carbon capture to create negative emissions.

In addition, several countries will likely require **additional baseload zero-carbon power generation** – in the form of biomass plants (with or without carbon capture), fossil fuels plants combined with carbon capture, or nuclear – if they are in one of two situations:

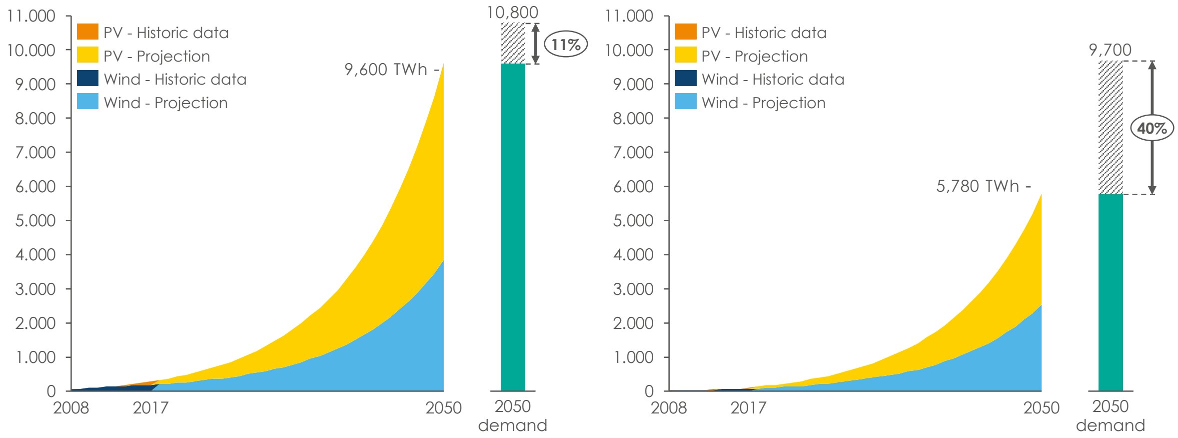
- They are unable to ramp up their renewable power generation fast enough to keep up with the pace of power demand growth.
- They face local land constraints and, for reasons of energy security, want to limit energy imports.

Pace of electrification

Today, many power grids around the world remain dominated by fossil fuel generation. Even if the deployment of wind and solar capacity accelerates, the transition to zero-carbon power systems will be progressive over the next three decades, in particular in the developing world. It is therefore possible that **immediate progress towards greater electrification could actually generate increased emissions** in the short term, if the electricity used comes from carbon-intensive sources.

Conversely, it is possible that **constraints on the pace at which transmission and local distribution grids** can be upgraded or charging networks rolled out might slow the pace of electrification even where feasible progress on the decarbonization of power generation would make electrification beneficial.

Given varying historic deployment rates and future demand growth, there will be important regional differences in how much of power demand can be met by variable renewables



US – Possible power generation from solar PV and wind in an accelerated renewable deployment scenario / TWh/year

India – Power generation from solar PV and wind in an accelerated renewable deployment scenario / TWh/year

Note: Projections based on annual deployment rates increasing at 10% per year from 2018 to 2050
Source: Historic: US EIA (2017) / Power demand in 2050: Shell Sky Scenario (2018) / Projection: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 7.2

---

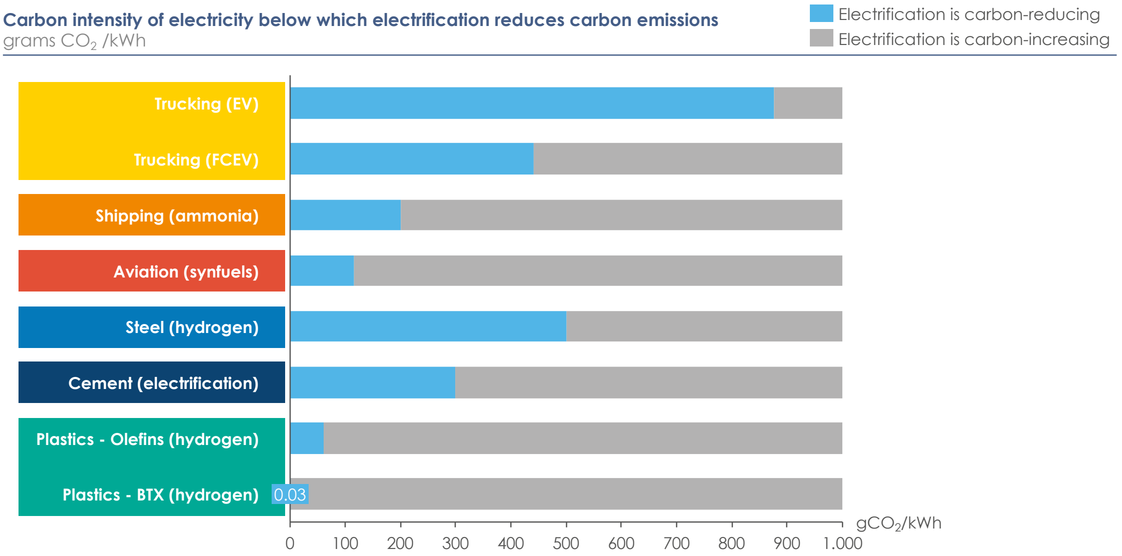
[1] ETC-CPI (2017), *Low-cost, low-carbon power systems*

The **optimal and feasible pace of electrification** should therefore be carefully thought through. If applications are electrified before electricity supply is decarbonized, the immediate impact can be an increase in emissions. Our analysis suggests, however, that while this danger might argue for moderating the pace of electrification of automobiles in some high-carbon developing countries, it is unlikely to place a limit on the appropriate pace of decarbonization of the industrial and heavy-duty transport sectors considered in this report.

The crucial question is, **how low the carbon intensity of electricity** (measured in grams of CO_2 per kWh) **needs to be** in order for electrification (direct or via electricity-based fuels) to produce a reduction in emissions [Exhibit 7.3].

- **In the case of surface transport** (whether autos, buses or trucks), electrification via battery electric vehicles reduces carbon emissions if electricity is generated with less than **875g/kWh**. If hydrogen is produced from electrolysis, the electricity used would need to be below 440g/kWh to make fuel-cell electric vehicles lower carbon than diesel or petrol.
- **In shipping**, the use of ammonia (produced from hydrogen from electrolysis) will be carbon-reducing if the electricity used is below **200g/kWh**.
- **In aviation**, any synthetic jet fuel produced from direct air capture of carbon plus hydrogen from electrolysis would need to use electricity with a carbon intensity below **115g/kWh** in order to ensure emissions reductions. This might imply that biofuels may need to play a greater initial role until electricity systems are extensively decarbonized.
- **In steel**, hydrogen-based DRI and electrowinning have breakeven points around **500g/kWh**.
- **In cement**, the electrification of kilns for Portland cement production can reduce emissions when the carbon intensity of electricity is below **300g/kWh**, while, with novel lower-carbon cement chemistries, the breakeven point would decrease to 70g/kWh.
- **For plastics**, there are different thresholds depending on the process, which are much lower than in other industry sectors given the very high energy intensity of those processes. For olefins production, it is possible to reduce emissions using a steam cracker with hydrogen when electricity carbon intensity is below **60g/kWh**. For BTX production, the threshold could be as low as are **0.03g/kWh**.

Electrification – direct or through the use of electricity-based fuels – only reduces carbon emissions if the carbon intensity of electricity is below a certain threshold



Source: Transport: SYSTEMIQ analysis for Energy Transitions Commission (2018) / Industry: Material Economics analysis for Energy Transitions Commission (2018)

Exhibit 7.3

These breakeven points need to be compared with the present carbon intensities of different electricity systems and their likely evolution over time. The relative carbon intensity to consider is a complex issue. In principle, what we need to know is the **average carbon intensity of the electricity**, which will be used as a result of a shift from a fossil fuel-based system to an electricity-based system (e.g. from an ICE truck to a BEV) **over the whole life of the newly purchased asset**. This could be:

- Higher than the current average carbon intensity of the electricity grid if the additional demand will be met, at the margin, by more fossil-fuel-based generation;
- But lower than the carbon intensity of the current marginal generator (usually fossil fuel) if the incremental demand will lead to new renewables investment and/or, for instance, if vehicles are charged, or hydrogen produced, at times of day when there is a surplus of renewable electricity supply;
- Lower than the current average grid intensity, if grid intensity is falling and will be lower on average during the lifetime of the relevant asset.

For these reasons, **the optimal timing of electrification cannot be mechanically determined by reference to current average grid intensity**, and carbon prices imposed on fossil-fuel-based power generation plus time-of-day electricity pricing have a crucial role to play in achieving an optimal way forward. Projected average grid intensity, looking forward over relevant asset lifetimes, can provide a useful initial indication of whether electrification is in danger of becoming "premature".

National decarbonization plans (set out for instance in Nationally Determined Contributions to the Paris Agreement) should integrate a **coherent vision of power decarbonization and electrification paths**. The picture is significantly different between developed and major developing countries:

- Almost all **developed economies** already have carbon intensities well below those at which direct electrification of surface transport is carbon-reducing, and most have plans which will take intensities down to the level at which even the most carbon-intensive indirect electrification routes (e.g. ammonia or synthetic fuels) will produce reductions in emissions. In developed economies, therefore, the pace of decarbonization of electricity should not be considered a reason for delaying moves to electrify either transport or industrial sectors (with the exception of plastics production). If, in some countries (e.g. Poland), there are any dangers that electrification might be premature, these should be met by accelerating electricity decarbonization, not by delaying the decarbonization of the harder-to-abate sectors.
- In some **developing countries**, however, immediate electrification, even in the most carbon-efficient form of direct electrification of road transport, could generate increased emissions in the short term. Thus, for instance, since Indian electricity generation is currently dominated by inefficient coal plants, with an average carbon intensity of over 1000gCO_2/kWh, any immediate and rapid shift towards electric autos, buses and trucks would not be appropriate, unless accompanied by policies to ensure that all incremental electricity generation comes from renewable resources. Even in China and India, however, carbon intensities could fall below the direct electrification breakeven point of 875gCO_2/kWh by 2030, with electric mobility then generating emissions reductions. Hydrogen and ammonia-based solutions could be carbon-reducing by 2040 to 2050, and even earlier if hydrogen production facilities were placed to utilize zero-carbon electricity.

Pace of investments in transmission, distribution and charging networks

We also need to consider whether limits to the **pace of necessary investments in transmission, distribution and charging networks** could slow down the feasible rate of electrification, even where the attainable pace of renewable (or other zero-carbon) power generation deployment would make it desirable. Our key conclusions are that:

- In principle **high-capacity long-distance transmission lines** can be designed and built rapidly enough (e.g. within two years) to ensure that the undoubted need for increased transmission grid capacity does not delay the feasible pace of electrification. But, in many countries, transmission investments can be delayed for many years by disputes about routing and design (e.g. whether above-ground or underground). Moreover, in developing economies, grids currently face significant losses and would have to be optimized while being expanded. It is therefore essential that (i) the need for additional transmission investment is anticipated far in advance to allow sufficient time for planning, public debate and decision-making, and that (ii) concerns about local environmental impacts are balanced against the need to decarbonize the economy.

- **Required distribution grid reinforcement** can also, in principle, be done in just a few years, and does not typically provoke the same opposition as some long-distance transmission projects. However, if significant reinforcement is required in many parts of the network simultaneously, this could create bottlenecks in project management and construction capacity. These needs should therefore be anticipated well in advance.
- **Charging infrastructure** – whether at medium speed (e.g. 7kW) for individual houses or on-street locations, or at high and super high speeds along major auto routes – could be rolled out at the pace required to support auto and truck electrification if appropriate policies were put in place.

In developed countries, grid reinforcement could represent a higher burden than in developing countries, where ongoing urbanization and grid deployment can be planned from the outset to enable a greater electrification of the economy.

In summary, it is essential for governments to develop **a coherent power strategy to mid-century** to accelerate the pace of power decarbonization, plan in consequence the electrification of a broader set of economic sectors, and anticipate related investment needs in the power grid.

(III) THE EVOLVING ROLE OF BIOMASS

The appropriate potential role of biomass in the economy is particularly difficult to define because of uncertainties over the total available supply of truly sustainable biomass resources, the full lifecycle emissions of biomass-based products, and their costs. Chapter 6 argued for **tight regulation and careful prioritization** of the use of biomass across different sectors of the economy.

The role of biomass during the transition to a net-zero-CO_2 economy will be shaped by two key dilemmas:

- In a world of limited sustainable supply of biomass for the energy and industrial systems, priority should eventually be given to aviation, where a zero-carbon equivalent of jet fuel will most likely be needed to decarbonize long-distance flights, and to plastics feedstocks, to compensate for end-of-life emissions of plastics. However, **many other sectors of the economy currently use bioenergy** as a route to lower CO_2 emissions, and could be disrupted if policies impose a phase out of biomass use in the short term.

- There are legitimate **concerns about the sustainability of some of the bioenergy forms currently on the market**, in particular first-generation biofuels from oil crops, which have arguably had reverse carbon emissions and negative environmental impacts. The development of bioenergy and bio-feedstock from lignocellulosic sources appears to be desirable to substitute for the least sustainable forms of biomass use. However, to avoid risks of deforestation or impact on biodiversity, this would have to come from agricultural and forestry wastes and residues, and **from newly planted forests**. Any significant expansion of bioenergy sourced from forested wood would therefore not be possible for about 15 years, even with fast-growing tropical forest crops.

The development of liquid biofuels faces a particularly tricky conundrum:

- On the one hand, **the faster large-scale production of biofuels develops, the faster costs will likely fall**, facilitating the decarbonization of those high-priority sectors. Large-scale development of biofuels for road transport in the short-term would therefore usefully drive the expansion of biorefining and reach economies of scale. Provided that tight sustainability standards are in place, this could boost, in particular, the development of biofuels from lignocellulosic sources or algae, as a substitute for the least sustainable biofuels currently on the market.
- On the other hand, it seems **unlikely that biofuels will play a significant cost-effective role in road transport over the long term** and subsidizing biofuels use in road transport today could potentially delay the switch from ICE vehicles to electric vehicles (either BEV or FCEV). If sustainability standards are not tightened, it could also grow the market for forms of bio-gasoline and bio-diesel that deliver only marginal emissions reductions and, in some cases, have seriously adverse environmental effects. This could be an argument for capping and eventually eliminating subsidies for road transport biofuels.

- For a few decades, though, and however rapidly new auto and truck sales switch to BEVs or FCEVs, there will be **a large stock of ICE vehicles on the road –** in particular in developing countries, where there is a fleet of second-hand vehicles – for which switching to biofuels would be a useful transition step.

Given these uncertainties and complexities, an appropriate bioenergy policy could entail:

- **Tightening the standards** that apply to lifecycle carbon emissions and broader environmental impact of bioenergy, in order to:
  - **Drive out of the market the least sustainable bioenergy products**, in particular those derived from oil crops competing with agricultural land and/or leading to deforestation;
  - **Ensure that any use of wood crops**, in both tropical and temperate forests, comes from newly planted forests that does not compete with other ecosystem preservation and biodiversity imperatives.
- **Restructuring current road transport biofuel mandates** to encompass a diversity of low-carbon fuels, including electricity and hydrogen;
- **Gradually removing support schemes for biofuels for road transport over the next two decades**, at a pace compatible with the feasible pace of road transport electrification, which will differ between developed and developing countries;
- **Establishing as rapidly as possible "green fuel" mandates for the aviation sector** to ensure that bio or synthetic jet fuel production rapidly achieves sufficient scale to drive cost reductions, even if biofuels use in road transport begins to decline.

(IV) TRANSITIONAL SOLUTIONS

Given the complexities and the challenges of the transition to net-zero CO_2 emissions in the harder-to-abate sectors, the use of transitional solutions can be appropriate to enable short-term emissions reduction in sectors where the end-state solution will take time to be deployed, **as long as they do not delay the progression to fully decarbonized solutions.** Transitional solutions are therefore particularly appropriate in heavy industry, where many zero-carbon solutions are not yet market ready; whereas they are likely to play a smaller role in transport, given the relative ease of transition to either electric vehicles (in trucking) or biofuels and synfuels (in shipping and aviation).

This section covers two main transitional solutions: the use of natural gas as a lower-carbon transition fuel and the use of offsets.

The appropriate role of natural gas as a transition fuel

Switching to natural gas could play a valuable role as a transition option achieving significant useful – though only partial – emissions reductions, provided methane emissions throughout the gas value chain are tightly controlled. Indeed, **gas combustion can produce about 50% less emissions than coal and switching from oil to gas would deliver more limited reductions (5-20%)**.

But these **climate benefits can be reduced significantly or even disappear if methane leakages in the gas value chain are above 1-3%** (depending on applications), given that methane is itself a very powerful greenhouse gas. Leakage rates in the US have been estimated at circa 1.5% by official figures and up to 2.3% according to recent studies, with rates of 5% or more reported in individual cases from some natural gas systems. Robust global estimates are lacking, but rates may be higher in less intensively monitored and less well maintained natural gas systems than in the US. **Bringing those emissions below 1%** (in total across upstream, midstream and downstream activities) **is a precondition to the use of natural gas as a transition fuel** on a large scale, but also a significant challenge for the industry. Leakages can in principle be eliminated through tight controls and appropriate investments in known technologies. The oil and gas industry has already taken commitments, in particular via the Oil and Gas Climate Initiative (OGCI) to reduce upstream methane leakages to 0.2%. But further progress will only occur if very tight regulations and monitoring are imposed.

Provided methane emissions are significantly reduced, the **appropriate use of natural gas will vary by sector** depending on:

- When the end-state solution will be commercially available;
- How fast gas use can be deployed;
- Whether there are any risks of lock-in into a non-zero-CO_2-emissions trajectory, especially due to the build-up of gas infrastructure.

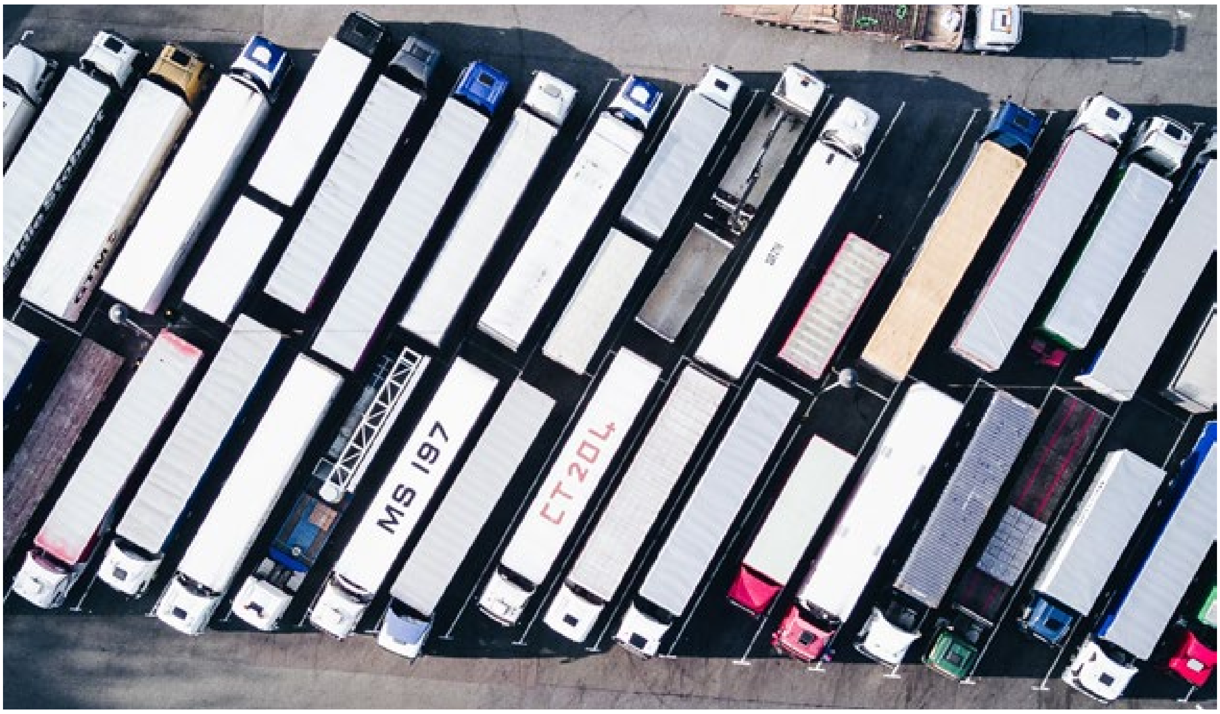
In particular:

- **In industry**, there are **significant opportunities to switch from coal to gas**, particularly in China, where coal is used as a feedstock in chemicals production, as well as the heat source in steel and cement production. This role is likely to be significant given long asset lives, the timescale at which we can expect most zero-carbon technologies for heavy industry to be available, and the probable slow pace of the industrial transition on brownfield sites.

- **In transport, the optimal role of gas is likely to be more limited**, given the relative ease to transition to either electric vehicles (in trucking) and biofuels or synfuels (in shipping and aviation). But, there may be a useful role of CNG as a transition fuel in long-distance trucking (while electric technologies cannot yet technically serve that range at competitive costs) and of LNG in shipping (while the cost of biofuels, synfuels or ammonia is still prohibitive).
- **In district heating,** meanwhile, gas may continue to play a significant role for many years in high-latitude countries with seasonal heating peaks, alongside greater electrification of heating. While the ETC has not looked in detail at the question of heat decarbonization, our initial analysis suggests that an optimal route to long-term decarbonization of heating may, in some countries, entail the integrated use of electrical heat pumps providing baseload heat, with continued use of gaseous forms of energy – either biogas or hydrogen – for which the existing gas infrastructure could be repurposed.
- **In power production**, as explained in Section II, there will likely be a continued role for gas-powered generation, combined with carbon capture, to complement power generation from variable renewable power systems, in particular to provide seasonal peak generation.

Accordingly, most scenarios for achieving well below 2°C assume that, over the next two decades, gas production and use should be more buoyant than coal or oil, which need to rapidly peak. In *Better Energy, Greater Prosperity*, for instance, we described a 2˚C scenario in which coal production falls by about 70% by 2040, oil by about 30%, but **natural gas production increases by 2% by 2040 and rapidly declines thereafter**. A 1.5˚C trajectory would impose earlier and/or sharper peaks in consumption across all fossil fuels.

The ETC's own illustrative pathway to a net-zero-emissions economy developed in 2018 presents a possible energy mix, in which **abated natural gas would provide roughly 18% of primary energy demand by mid-century** [Exhibit 6.2].



Indeed, to achieve a net-zero-carbon economy, **unabated natural gas consumption will eventually need to be phased out**. In transport, where carbon capture technologies are unavailable, this means completely phasing out the use of gas. In industry, continued gas use could be abated through carbon capture (combined with either use or storage). However, this would only be an imperfect solution given that current technologies typically capture 80-90% of the CO_2 stream only, leaving residual emissions of up to 20%.

Significant investment in gas production and distribution infrastructure, as well as gas-using equipment in the period to 2040, could make it more difficult to achieve the necessary rapid post-2040 reduction, **locking in the economy to emissions trajectory not compatible with a well below 2˚C** pathway and, even less, with a 1.5˚C trajectory. In that context, LNG can, in some cases, enable a fast route to partial decarbonization, while avoiding the large infrastructure investments required for gas pipeline development.

It is therefore essential that global and national strategies only allow for significant growth of natural gas as a transition fuel, and in particular for any new investment in gas infrastructure and long-lived assets such as shipping equipment, within the context of **long-term strategies to ensure phase-out of unabated natural gas** and progress to full decarbonization by:

- **Progressing to non-gas-based decarbonization options**, with, for instance, methane-based DRI transitioning to hydrogen, CNG/LNG use in shipping replaced by ammonia, or gas cement kilns electrified – which could entail the early write-off of some assets;
- **Replacing natural gas with biogas** – although global sustainable supply of biogas would constitute a constraint in the long term if it was to be used on the same scale as natural gas today;
- **Applying carbon capture** in the industrial applications using gas where it is possible.

The appropriate role of offsets

Since the marginal cost of decarbonization varies greatly among the harder-to-abate sectors and across the whole economy, the early stages of sectoral paths to net-zero could allow for the **temporary purchase of offsets** from other sectors of the economy or from the land use sector[2]. This will often be a cheaper way to achieve emissions reductions than to push early decarbonization within the harder-to-abate sectors themselves, at a time when full decarbonization technologies may not yet be available. These schemes (sometimes labelled "market-based measures") will also create **incentives to search for longer-term decarbonization solutions** by facing sectors with a marginal price of carbon.

In practice, some **existing sectoral strategies** (e.g. for the aviation industry) assume that, over the next decades, the sector will achieve flat emissions by purchasing carbon offsets, only later (after 2027 in the case aviation) achieving emission reductions within the sector itself.

The easier-to-abate sectors, in particular power generation, can provide lower-cost abatement options than harder-to-abate sectors and be a source of carbon credits within emission trading schemes such as the European ETS. However, the total volumes of carbon emissions allowed within these emissions trading schemes should be tightly capped and declining at a pace compatible with the Paris climate objective. This implies that, by mid-century, there will be almost no remaining potential for such purchases, as most sectors will have been fully decarbonized.

The food and land use systems could also provide up to 20Gt of abatement opportunities per year at cost of US$10/$tCO_2$ or less by changing land use patterns, avoiding deforestation, increasing new forestation, and other mechanisms to create natural carbon sinks. For instance, negative-cost opportunities potentially lie in changes in agricultural practices that would increase carbon capture in the soil while improving yields[3].

- The purchase of offsets from food and land use systems by harder-to-abate sectors could provide a **valuable source of financing to support investment in more sustainable land use**. A step change in private investment in sustainable food and land use is indeed required, both to ensure that land use change can play a major role in carbon sequestration and to deploy economically, socially and environmentally sustainable land use models that balance the competing demands on land use (agriculture, managed forests, carbon sequestration, renewable deployment, biodiversity…).

---

[2] Legal disputes related to how to account for carbon emissions reductions from offsets which are traded internationally outside of regulated emissions trading schemes are not covered in this report.

[3] SYSTEMIQ analysis (2017)

Illustration 7.1 – CORSIA: a carbon offsetting and reduction scheme in aviation

Agreed by the International Civil Aviation Organization Assembly (ICAO, a specialized agency of the United Nations) in October 2018, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is the world's first global, sector-wide market-based climate measurement. A total of 73 ICAO members, representing more than 87% of the international aviation activity, have volunteered to take part in CORSIA.

During the initial pilot phase (2021-2023) and first voluntary phase (2024-2026), operators that use air routes between voluntary states will have to offset their CO_2 emissions(which will be calculated by applying the annual sectoral increase in carbon emissions to the 2018 baseline emissions of each individual company). This will create a powerful incentive for emissions reduction within the aviation sector, while also creating space for a transitional solution through the use of offsets, most probably from the land use sector.

Moreover, to establish a reference scenario for later offsetting requirements, a global baseline of CO_2 emissions from international aviation activity is to be established and finalized by 2020. This baseline will then be used to measure progress over the following decades.

As part of this programme, all airlines operating international flights will have to monitor and report fuel consumption and emissions from January 2019. These measurements will be key to provide a reliable dataset to calculate the sectoral 2020 emissions baseline. To kickstart this, the ICAO launched a successful training programme (ACT-CORSIA) in July 2018, which had over 500 participants across 250 airline companies.

Company-level baselines will then be used to set detailed targets that airlines will need to comply with from January 2021.

- There are, however, major challenges in ensuring that the purchase of offsets generated from land-use change truly does result in incremental carbon emission reductions, and tight regulation needs to be put in place to **ensure that the development of natural carbon sinks does not create adverse environmental externalities**, for instance in terms of biodiversity.

A separate issue is **whether these offsetting opportunities should remain in the long term**:

- The **full decarbonization of easier-to-abate sectors** of the economy will eventually limit the opportunities for emissions trading within the energy and industrial system to the sole negative emissions produced by the use of bioenergy combined with carbon capture (BECCS). This use will, in turn, be constrained by limited availability of biomass, as well as the possible difficulties to significantly scale underground carbon storage given social acceptability issues (as explained in Chapter 6).
- There will also be **limits to the total scale of carbon sequestration** from land use, in particular to the total scale of reforestation, given other claims on land use for food production and other human activities.

It is therefore vital that **offsetting schemes are perceived as a transition strategy only**, with plans in place to drive all sectors eventually to as close as possible to net-zero emissions "in themselves". The ETC's analysis demonstrates that the technologies to achieve this are available and would only impose a small cost on the global economy. Our analysis also suggests, however, that, while the energy and industrial systems can get very close to net-zero by 2060 globally – and by 2050 in developed economies –, there may be **small residual emissions** (around 2Gt per annum) which would be very expensive to eliminate. These would arise from leakages from carbon capture, uncontrollable use of biomass which would not be fully carbon neutral, and remaining end-of-life emissions from plastics escaping recycling or secure storage. A **small long-term role for negative emissions from land use or BECCS** may therefore be indispensable.

CHALLENGES AND OPPORTUNITIES FOR DEVELOPING COUNTRIES ON THE ROUTE TO NET-ZERO

Chapters 2 and 3 highlight that, in the next decades, most of the growth in materials production and heavy-duty transport is expected to take place in developing countries, specifically within India, South-East Asia and Africa. This creates a specific set of challenges and opportunities for these regions on the route to net-zero CO_2 emissions.

Opportunities to limit growth in demand are likely to be lower and of a different nature in developing countries than in developed economies. Indeed, Europe or the US have already built up their stock of materials and reached a somewhat stable level of cement, steel and plastics per capita. They are therefore in a position to maximize materials recycling to a much greater extent compared to developing countries, where growing primary materials production will be essential to support economic growth and urbanization. Material Economics estimate that CO_2 emissions from heavy industry could be reduced by up to 56% below business-as-usual projections in Europe by 2050, but only 40% on average globally.

Conversely, the fact that developing countries will go through a significant **build-up of their urban infrastructure, industrial capacity and transport fleet** over the next decades could represent a major opportunity to "get things right the first time" by immediately planning for infrastructure that will be adapted to the energy and industrial system of the future and by leapfrogging to best available practices and technologies.

With regards to infrastructure, urbanizing countries have the opportunity to **anticipate the need for a strong power grid**, with both long-distance transmission lines and local distribution networks conceived to enable a significant level of clean electrification. By contrast, it may be more difficult to strengthen the last-mile distribution network to enable electric vehicle charging in cities like London, where one has to dig holes in the roads to access the existing network. This is also true for the transport infrastructure, which can already be developed with electro-mobility and modal shift opportunities in mind.

Similarly, whereas the stock of housing and commercial buildings can be difficult to retrofit in existing cities, developing countries could take advantage of best available practices and technologies to be **more efficient in their use of carbon-intensive construction materials** and to build buildings which will be energy-efficient in use. These are, in principle, opportunities that could lower the cost of construction (by lowering materials requirements) as well as building operational costs.

Finally, the McKinsey analysis indicates that **the cost of building a greenfield decarbonized industrial plant will likely be much lower than the cost of decarbonizing a brownfield plant**. As they build up their industrial assets over the next decades, developing countries therefore have the chance to immediately adopt the most energy-efficient industrial processes for new plants, opt for zero-carbon technologies when they are already available today, or design plants that could easily be shifted to zero-carbon solutions.

There will, however, be obstacles to the ability of developing regions in Asia and Africa to fully take advantage of these opportunities, which could in principle lower the overall cost of their transition to zero-carbon energy and industrial systems:

The additional cost to the end consumers of decarbonizing heavy industry and heavy-duty transport, although modest, is likely to have a relatively **greater impact on the purchasing power of low-income households** in developing countries. These distributional effects might call for accompanying budgetary measures.

Developing countries also tend to **import cheaper, second-hand equipment**, vehicles and industrial assets from developed countries. These, by definition, are neither the most energy-efficient, nor the lowest-carbon technology options, and may create a lock-in effect in higher-carbon solutions. For that reason, developing countries might use transitional solutions, such as the use of biofuels in ICE vehicles, for a longer period than developed countries.

Institutional weaknesses and the importance of the informal sector might also make it **more difficult to plan for and control major developments in terms of urbanization** and energy provision. One of the difficulties to deploy clean electrification in countries like India and Brazil will, for instance, be the currently high level of losses on the electricity grid.

The shift away from fossil fuels in coal-rich countries like India will most probably have a **local impact on employment and economic development in the regions where fossil fuels production is currently concentrated**. Developing just transition plans that enable the transition of the workforce to new economic activities will therefore be key to the social acceptability of the transition.

Access to capital will be essential to overcome these difficulties. In countries which have historically suffered from relative capital scarcity due to country-related risks perceived by investors, this calls for a major role for development finance institutions, who should drive investment in low-carbon infrastructure, zero-carbon energy provision and low-carbon industrial assets, through direct investment and blended finance mechanisms that can de-risk private investment.

8

Agenda: the innovation Technology developments and potential game changers

In Chapters 2 and 3, we argued that there are **feasible pathways to decarbonize each of the harder-to-abate sectors** at a moderate cost to the economy and to end consumers. In some cases, however, we noted that further technology developments would be required to **bring key technologies to commercial scale deployment**, addressing engineering complexities and driving down costs. Some of these technologies are closer to market readiness than others. But the main routes to decarbonization described earlier, and the costs set out in Chapter 4, reflect approaches where technical feasibility is undoubted and do not assume any fundamental breakthroughs in basic research and lab-based development.

Exhibit 8.1 presents a summary of key domains where **incremental performance and cost improvement** of existing technologies are essential to facilitate commercial scale deployment. Exhibit 8.2 presents a summary of key areas where **innovations are further away from market**, and require significant development, demonstration and piloting over the next 15 years to bring them to market readiness by the 2030s or 2040s.

In parallel, it is almost certain that within the next 50 years, **currently unforeseeable technological breakthroughs will significantly change the optimal pathway to decarbonization** and result in costs significantly below those described in Chapter 4. Due to their nature, such developments cannot be described in advance. But the probability that they will occur will be increased if forceful public policy makes reaching net-zero carbon emissions from the harder-to-abate sectors non-negotiable. It is possible to identify some areas of technology where current R&D suggests that major breakthroughs are in principle possible, which, if they were achieved, would have major implications for decarbonization routes and costs.

Investment in these technologies will be primarily driven by the private sector, provided that appropriate policy levers create strong incentives for decarbonization. But **public innovation support** could also play a role, which will be different based on the level of technology readiness of different innovations. This is described in further details in Chapter 9.

Incremental innovation is needed to ensure the deployment of key technologies at scale

Innovation area	Key incremental innovation needed to decarbonize the harder-to-abate sectors	Indicative target
Materials efficiency and circularity	New designs for consumer products	Average car weight: -60% vs today
	Materials traceability, collection, sorting and recycling technologies	Plastics recycling: 50% of end-of-life plastics
	New business models: product-as-a-service, sharing...	Cars used as sharing vehicles: >60% of fleet
Electrification	Cheaper and more efficient batteries	Lithium ion batteries: US$100/kWh
Hydrogen	Cheaper electrolysis	Electrolysis equipment: US$250/kWh
	Cheaper hydrogen fuel-cells and tanks	Fuel-cells: US$80/kW
	Long distance transport of hydrogen	International H_2 transport: US$2c/kWh
Biochemistry and synthetic chemistry	Increased efficiency in biomass transformation	Solid biomass to fuel efficiency: 50%
	Bioenergy and bio-feedstocks from lignocellulosic sources and algae	Cost premium of biofuels: <50%
Carbon capture and use	More efficient carbon capture, especially for cement	Capture efficiency: 95%
	Use of carbon in concrete, aggregates and carbon fiber	Cost-competitive CO_2-based products

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 8.1

(I) ENABLING GREATER EFFICIENCY AND CIRCULARITY

Achieving the potential for energy efficiency across all the harder-to-abate sectors and driving materials efficiency and circularity will require innovation in three major areas: equipment/ product design, materials processing systems, and business models.

Equipment/Product design

The lifecycle carbon emissions of a piece of equipment or product can indeed be highly impacted by its design, as design drives material requirements, operational efficiency and the ability (or not) to repair, dismantle and recycle the product at end-of-life. Encouraging innovation in this space will require **creating strong incentives for face designers and manufacturers for them to take into account the impact of their products lifecycle.** Product standards and extended producer responsibility can be key tools to achieve this objective.

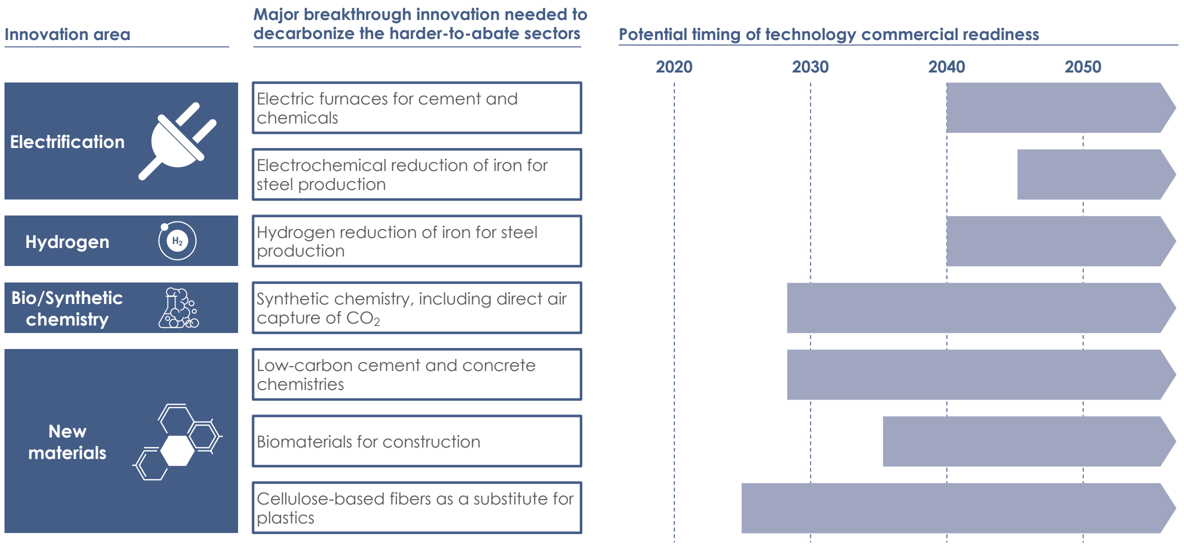
Innovation in product design can:

- **Increase energy efficiency**: Optimizing aerodynamics of cars, trucks, airframes or ships allows major energy use reduction. In shipping, the Energy Efficiency Design Index, implemented by the International Maritime Organization and labelling all new vessels since 2011, stimulates innovation for energy efficiency at the design phase by giving transparency on the relative energy efficiency of a ship compared with the average in its range.
- **Enable the use of new low-carbon fuels:** In aviation, the adoption of hydrogen is dependent on radical redesign of air frames, as it implies a repositioning of hydrogen tanks and rethinking of the engine structure.
- **Improve materials efficiency and circularity**: Conceiving buildings, vehicles, house appliances or packaging in a way that reduces over-specification of materials, extends the lifetime of the product (due to greater sturdiness and ability to repair), and facilitates end-of-life dismantling, sorting and recycling of materials. This can also entail the use of new high-strength materials that reduce the amount of materials input required to deliver the same performance.

Materials processing systems

In parallel to R&D efforts dedicated to products, technology development on how materials are handled from manufacturing to end-of-life are also key to enabling greater materials efficiency and

Breakthrough innovation could considerably facilitate and accelerate full decarbonization



Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 8.2

circularity, driving down carbon emissions from virgin materials production. In particular:

- At the manufacturing or construction stage, new techniques can be developed to **reduce waste from production.**
- With the help of digital technologies, developing a **system to trace materials** is a prerequisite to ensure that the carbon and recycled content of end products can be known, which, therefore, would enable them to develop a premium low-carbon offer that compensates for higher production costs of green products as well as regulate and/or tax products accordingly.
- At end-of-life, **improving product dismantling, materials sorting, and recycling techniques** is essential to enable greater material circularity. This entails greater automation of dismantling (which should already be facilitated by better product design) and materials sorting. It also demands innovation in metallurgy and chemical techniques, which would enable greater and higher-quality materials recycling, in particular, by separating constituents of composite materials, removing impurities in the waste flow, and developing recycling techniques that can absorb mixed materials flows (such as chemical recycling in plastics).

Business models

Finally, Chapter 2 describes how demand for materials can be reduced, sometimes significantly, by new behaviors and practices which increase the lifetime of products and/or enable more intensive use (so that the same level of service can be offered with a lower quantity of underlying products). For businesses, this entails a shift from a linear towards a more circular business model:

- **Service-based (rather than product-based) business models:** For instance, instead of selling cars, a company can sell kilometers travelled, by renting cars that remain owned by the company itself. This enables greater control over fleet management, improving the lifetime of the car. The same can be envisioned for materials use in, for instance, buildings: the steel could remain owned by the steel manufacturer, who would then have the responsibility to ensure its durability throughout its lifetime, as well as dismantle and recycle it at end-of-life.
- **Sharing business models:** Car sharing and shared office spaces constitute two obvious examples of business models that increase stock utilization, therefore, limiting the number of cars or office buildings required in the economy.

(II) BRINGING NEW ELECTRIFICATION TECHNOLOGIES TO MARKET

Direct electrification is likely to play a crucial role across the transport sector and be an option to decarbonize some industrial processes.

- **In the transport sector**, batteries and electric engines are considered to be well developed technologies. But, **cost reductions and progress on performance**, particularly in terms of charging speed and energy density, will determine the extent to which long-distance trucking, shipping and aviation can, at some point in time, be electrified. A key short-term objective should be to drive further cost reduction of lithium ion batteries to achieve the US$100/kWh by 2025 (as predicted by BNEF) or earlier. This would make trucking electrification clearly cost-competitive over many distances. A second short-term objective should be to achieve superfast charging with a lower negative impact on the lifetime of batteries, as superfast charging currently significantly degrades the durability, which loose efficiency over time.
- **In the industry sectors, the commercial readiness of different electrification technologies varies depending on the sector**. Electric arc furnaces can already be deployed and improved in steel production, in particular for scrap recycling, whereas electric furnaces for deployment in the cement and chemicals industries are still under development. Electrochemical iron ore reduction constitutes an even earlier-stage technology, which is unlikely to be market ready before the late 2050s. Bringing those technologies to market should be a key focus of R&D projects in these sectors.

PRODUCTS SHOULD BE DESIGNED TO FACILITATE END-OF-LIFE DISMANTLING, SORTING AND RECYCLING OF MATERIALS.

Potential game changer: New battery technology

Our analysis of the transport sectors in Chapter 3 assumes that the cost of lithium ion batteries will continue to fall, decreasing below US$100/kWh by 2025. But we have not assumed any **breakthroughs in terms of battery energy density**, with current-state lithium ion batteries unable to go above about 260Wh/kg[1]. Improvements in battery density could have very significant effects on optimal decarbonization paths.

Very significant improvements (e.g. about a factor of 6) would be required to challenge our assumption that international flight will continue to require either a liquid hydrocarbon or the use of hydrogen. But, if only moderate improvements (e.g. factor of 2 to 3) could be achieved, this would already:

- Greatly accelerate the pace at which automobiles, light vans and buses would become electric;
- Make electric trucking feasible even for longer distances, potentially squeezing out a major role for hydrogen fuel-cell vehicles in long-distance trucking;
- Significantly extending the range and aircraft size for which battery-powered flight is a feasible option, in particular if airframes were radically redesigned to allow the optimal use of electric engines;
- Similarly extend the distances over which coastal shipping, RoPax and medium distance cruising would go down the battery electric route.

Given the huge economic benefits derived from more dense batteries, a very large sum of investments is now being devoted to **exploring a range of alternative battery technologies**, with over US$14 billion of battery-related investments in the last two years and a three-fold increase of patent filing since 2010[2]. Many informed experts believe one of these routes is highly likely to deliver major improvements in density, or in feasible charging rates, within the next 10 years. There is therefore a significant chance that our scenario for transport electrification will prove to be conservative.

Exhibit 8.3 presents the **major innovations in battery technology**, focusing on improvement energy density, charging performances and safety. R&D efforts are currently focused on three major innovations to answer unmet needs of the current generation of batteries: silicon-based anodes, solid-state electrolysis and advanced-cathode chemistries, which all increase energy capacity and voltages. Alternative technologies will also likely develop for niche applications: flow batteries could become the technology of choice in bulk storage systems, as this technology provides an exceptional lifetime of up to 100,000 cycles but can only be used for stationary purposes due to its low energy density[3].

Potential game changer: Electrochemistry

Current chemical industry production methods have approached their practical performance limits. Therefore, new disruptive technologies are needed in order to provide solutions to decarbonize production beyond incremental manufacturing improvements. In particular, full, scalable and cost-competitive electrification of heavy industry would require breakthrough innovation in electrochemistry. **Supplying heat through electricity instead of hydrocarbon fuels is a major challenge** and can today be done in several ways[4]:

- For low-to-medium temperatures, **heat pumps** using electricity and excess heat, and mechanical vapor recompression for steam, are a well-known but not yet competitive technology. Several research projects are working at increasing these promising technologies' overall efficiencies.
- **Electric furnaces** are a known technology, which can be used to produce the high temperatures needed in heavy industry. It is already widely used in, for instance, scrap-steel production, but still needs to be developed for other applications.
- **Advanced electro-thermal technologie**s – including induction, infrared radiation, electromagnetic radiation, microwave heating, radio waves, ultraviolet light, electron beams and plasma technologies for all temperature ranges – constitute the least developed set of technologies.

Opportunities for electrifying the industrial harder-to-abate sectors vary depending on the sector and require major developments in technology:

- **In cement**, application of microwaves and induction energy could present alternative to fossil fuels or bioenergy for heating and drying in cement kilns, but these options are today far from scalability.
- **In the steel industry**, short-term efforts are focused on deploying electric arc furnace production, for scrap-based steel production as well as for DRI-based production (which currently operated with gas, but could be

---

[1] Janek J. And Zeier W. (2016), *A solid future for battery development*

[2] Arthur D. Little (2018), *Future of batteries*

[3] Arthur D. Little (2018), *Future of batteries*

[4] Swedish Energy Agency, SP Technical Research Institute of Sweden and Chalmers University of Technology (2017), *Industry's electrification and role in the future electricity system: a strategic innovation agenda*

switched to hydrogen). In the long term, however, the molten oxide electrolysis process (electrowinning) could allow the reduction of iron ore using only electrical energy. This process would offer an alternative to hydrogen-based DRI and could simplify the production process and significantly reduce energy consumption[5].

- **In the chemical industry**, electrochemical production processes could be deployed before the 2030s, based on electro-technology substitutes for distillation (including adsorption and membranes).

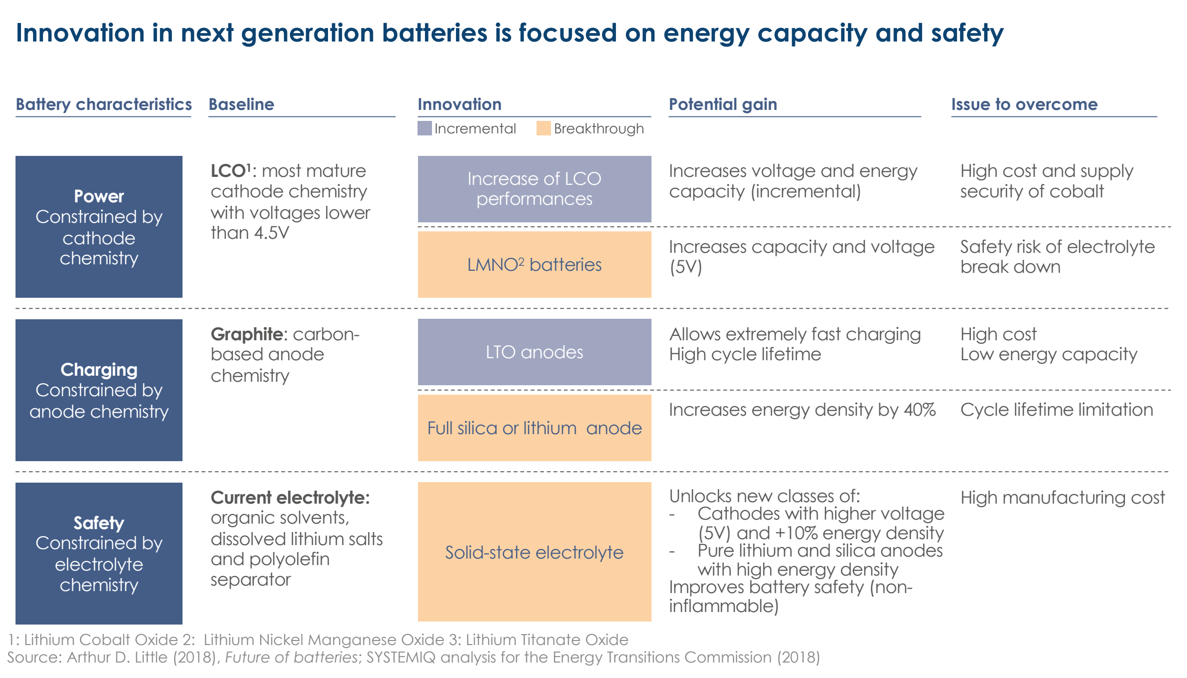
(III) DRIVING DOWN THE COST OF HYDROGEN-RELATED TECHNOLOGIES

Given the major role that hydrogen will almost certainly play in a zero-carbon economy, it is crucial to reduce the cost of hydrogen use and production.

On the production front, there are **two main routes to produce zero-carbon or near-zero-carbon hydrogen**. Electrolysis using a zero-carbon electricity input is likely to become the dominant route over time, especially in regions with favorable wind and solar resources. Steam methane reforming combined with carbon capture offers an alternative route, which may be more cost-competitive in the near future, but would still imply some residual greenhouse gas emissions, from carbon leakages at capture stage and from (hopefully reduced) methane leakages across the gas value chain.

The pace and the extent of **cost reductions achieved in hydrogen production and distribution**, regardless of the production route, will be a key driver of the scale of the hydrogen economy. It will not only impact the scale of direct hydrogen use in transport and industry, but also drive the deployment of hydrogen-based fuels, in particular, ammonia in shipping and synfuels in shipping and aviation.

- In this context, a key priority should be to **drive down the cost of hydrogen electrolysis** to achieve US$250/kW in the 2030s. This will primarily occur as a result of scale deployment, but research into new technological approaches to anode, cathode and electrolyte design also have a role to play. Innovations such as Polymer Electrolyte Membrane (PEM) or solid oxide electrolysis could achieve higher power density and cell efficiency, hence ultimately reducing operational costs, provided they overcome the limiting factor of cell lifetime and material costs.



Innovation in next generation batteries is focused on energy capacity and safety

Battery characteristics	Baseline	Innovation ▨ Incremental 🟧 Breakthrough	Potential gain	Issue to overcome
Power Constrained by cathode chemistry	**LCO**[1]: most mature cathode chemistry with voltages lower than 4.5V	▨ Increase of LCO performances	Increases voltage and energy capacity (incremental)	High cost and supply security of cobalt
		🟧 LMNO[2] batteries	Increases capacity and voltage (5V)	Safety risk of electrolyte break down
Charging Constrained by anode chemistry	**Graphite**: carbon-based anode chemistry	▨ LTO anodes	Allows extremely fast charging High cycle lifetime	High cost Low energy capacity
		🟧 Full silica or lithium anode	Increases energy density by 40%	Cycle lifetime limitation
Safety Constrained by electrolyte chemistry	**Current electrolyte:** organic solvents, dissolved lithium salts and polyolefin separator	🟧 Solid-state electrolyte	Unlocks new classes of: - Cathodes with higher voltage (5V) and +10% energy density - Pure lithium and silica anodes with high energy density Improves battery safety (non-inflammable)	High manufacturing cost

1: Lithium Cobalt Oxide 2: Lithium Nickel Manganese Oxide 3: Lithium Titanate Oxide

Source: Arthur D. Little (2018), *Future of batteries*; SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Exhibit 8.3

---

[5] Swedish Energy Agency, SP Technical Research Institute of Sweden and Chalmers University of Technology (2017), *Industry's electrification and role in the future electricity system: a strategic innovation agenda*

- **Bringing the SMR plus carbon capture process as close to possible as net-zero carbon emissions**, while reducing its cost, should be another priority. This could entail electrifying the heat input to SMR (to remove heat emissions and ensure that only the relatively pure stream of process CO_2 emissions must be captured), improving the capture rate, and developing the downstream applications – either through use of carbon (see later in this chapter) or carbon storage.
- Another option that may prove a useful technology is **methane splitting**. Using methane (either from natural gas or biomethane) as a feedstock and electricity as energy source, produces hydrogen and solid carbon, thus not requiring carbon capture while using 3-5 times less power than electrolysis.

In parallel, expanding the use of hydrogen and hydrogen-based fuels will require a **decline in cost of key hydrogen-related technologies**. Objectives should include:

- Reducing the cost of **hydrogen fuel-cells** to achieve less than US$80/kW by 2025 for medium duty vehicles (vs. US$100/kW today)[6];
- Reducing the cost of **hydrogen storage** (e.g. tanks on board of vehicles, storage for refueling stations, hydrogen transport infrastructure…) – for instance, hydrogen tanks for medium duty vehicles should reach US$9/kW by 2025 (vs. US$15/kW today);
- Proving the feasibility and driving down the costs of **using ammonia in existing ship engines**, by finetuning the engineering of fuel handling and other ancillary equipment, and by developing technological solutions to NOx emissions;
- Reducing the cost of **hydrogen transportation and distribution**, which can today double the price of hydrogen and rule out centralized production from low-cost, large-scale electrolysis in favorable locations.

(IV) REVOLUTIONIZING THE CHEMICALS INDUSTRY THROUGH BIOCHEMISTRY AND SYNTHETIC CHEMISTRY

Beyond decarbonizing the chemicals production processes, the key challenge to fully decarbonize the chemicals industry, taking into account the lifecycle of its products, is to **address the embedded carbon,** which is released at point of use for fuels and N-fertilizers, and at end-of-life for plastics. There are two routes that can enable this:

- **Biochemistry**, which can be zero-carbon over its lifecycle provided that all feedstock and energy inputs to the biomass production and refinery process are zero-carbon, and that it doesn't create indirect carbon emissions from land use change (see Chapter 6 for greater details);
- **Synthetic chemistry**, which can be zero-carbon over its lifecycle provided the electricity input is zero-carbon and the CO_2 input comes from direct air capture.

---

[6] US Department of Energy (2018), *Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles*

In both cases, the product (fuel, fertilizer or plastics) still contains carbon, but its lifecycle impact in terms of carbon emissions to the atmosphere would be neutral.

Biochemistry

The key challenge in biochemistry is figuring out how to avoid the use of oil plants and other biomass sources which compete with food production, and instead use wastes or sources which can be produced in large quantities without competition with food production and/or threat to biodiversity. This includes, in particular, **lignocellulosic sources and algae** (or other plants grown in sea water).

Cost reductions in lignocellulosic biochemistry have recently come from breakthroughs in the application of the thermochemical (Fisher Tropsch) processes in small-scale plants close to sources of supply. This has proved a more cost-effective route than has been found through the enzymatic hydrolysis approaches, which until now have produced disappointing progress.

But looking forward to several possibilities, many of which depend on variants of genetic engineering, could become available, for example:

- Breakthroughs in development of enzymes which might enable the direct production of hydrocarbons from cellulosic sources;
- Genetic engineering of crops to grow on more arid lands or in seawater, which are in plentiful supply, including different types of algae.

Moreover, given the probable limited supply of sustainable biomass and the potentially disproportionate demands for biomass arising from multiple sectors of the economy[7], it is also particularly important to **improve the efficiency of biorefinery** to be able to deliver more bioenergy or bio-feedstock with a fixed level of biomass supply. Today, the efficiency process of biomass-to-biofuels transformation is about 40-50% and could usefully be driven up.

Synthetic chemistry

The production of **synthetic fuels** based on hydrogen input constitutes an alternative to biofuels. The tighter the sustainable biomass supply will be, the more important it will be to develop and reduce the costs of synthetic fuels, to be used in aviation, shipping, and as a feedstock to the chemical industry. Key challenges in the development of synfuels are:

- To reduce the **cost of the hydrogen input** (see dedicated subsection above),
- To increase the efficiency and reduce the cost of **direct air capture of CO_2**, and
- To improve the efficiency and reduce the cost of the **synthesis process**.

Recent announcements by the start-up Carbon Engineering indicate that direct air capture of CO_2 could cost less than US$100/t$CO_2$, producing synfuels at US$1 per litre[8].

Hybrids between engineered bio and synthetic routes are also been explored – for instance, processes to accelerate the photosynthetic capture of CO_2 directly into materials which are not naturally arising plants, but from which hydrocarbon solid or liquid fuels, or biogas can rapidly be produced.

If these breakthroughs in biochemistry and synthetic chemistry could be achieved, consequences would be:

- Significantly **greater overall potential role for bioenergy** and bio-based products, because sustainability constraints on biomass availability could be relaxed – in the case of biochemistry;
- Significantly **greater overall potential role for synthetic fuels** – in the case of synthetic chemistry;
- **Possible reduction in the cost of decarbonizing aviation, shipping** (where relative roles of ammonia versus biofuels/synfuels might shift towards the latter), **and chemicals** – in both cases.

(V) DEVELOPING NEW MATERIALS

Beyond materials circularity and supply-side decarbonization, an alternative option to reach net-zero carbon emissions from key materials – in particular, in the buildings and manufacturing sectors – is to **substitute carbon-intensive materials** (like cement, plastics or steel) by less carbon-intensive ones.

Within the cement sector itself, a key innovative area is the development of **new cement chemistries**. With a wide variety of new chemistries are being developed to replace limestone or clinker with other minerals, it is highly likely that some of these developments will play a role in driving cement decarbonization. Precise performance characteristics (for instance in terms of speed to harden and final strength) would also

---

[7] See Chapter 6 for further details.

[8] Keith, D.W. (2018), Joule, *A process for capturing CO_2 from the atmosphere*

ILLUSTRATION 8.1 - Substituting Portland cement: the example of Pozzolan cement

Cement is one of the most complex industry to decarbonize, requiring carbon capture and/or an entirely new chemistry. High Volume Pozzolan Cement (HVPC) can be manufactured blending traditional Portland clinker with pozzolan. It could be one of the most promising alternatives to substitute for conventional Portland cement.

The Energetically Modified Cement (EMC) Technology developed by EMC cement provides an equal or enhanced product that contains 50% fly ash and 50% ordinary Portland cement. Fly ash is usually sourced today from power and industrial plants that burn coal, but, as the economy decarbonizes, it could in the future be produced from pozzolan, a volcanic rock, which may be available across all continents.
This technology was first developed in 2005 and has since been demonstrated at commercial scale, through different projects and applications that include, for instance, both State and Federal highways in the US. These first projects have confirmed the competitive cost structure, technical performance and compliance with materials standards of this new chemistry.

Pozzolan cement can provide a 52% decrease in CO_2 emissions vs. conventional concrete. Recent technology improvements show that emission reduction potential could go up to 70%. It would, in any case, have to be combined with carbon capture on the remaining Portland cement production to enable the industry to get close to net-zero emissions.[1]

[1] Footnote text: EMC (2018), *Cement production emissions challenge and solutions*

have to be met to ensure adoption. Their potential impact may be limited, though, by the availability of required feedstock minerals:

- Minerals for making belite clinker are readily available, but potential emissions reductions are only about 10%.
- Calcium sulphoaliminate (CSA) or carbonization of calcium silicates (CACS) clinkers could deliver more significant emissions reductions (20 to 30%), but the required mineral inputs are somewhat less generally available.
- Magnesium-silicate-based cement could eliminate emissions entirely, but the required minerals feedstocks for these chemistries are much less available.
- Alkali/Geo-polymer-based-cements, in particular, pozzolan-based cements, may be the most promising way forward, as they could eliminate more than 70% of carbon emissions, and pozzolan (volcanic rock) is likely to be relatively more available than other minerals mentioned above.

Beyond new cement chemistries, **new concrete chemistries** using less cement input are also being developed, which can lead to significant reductions in cement use and potentially to cement-less concrete in the longer-term.

Beyond cement, alternative construction materials should also be explored. **Timber in principle could play a major material substitution role** in the buildings sector. Cross-laminated timber can be used as an alternative to concrete and steel in an increasingly wide range of building sizes timber. It would not only reduce emissions from cement and steel, by reducing demand for these materials, but also act as an effective carbon sink, storing the CO_2 absorbed during forest growth for as long as the building exists (and longer if the timber is then reused in new buildings). The constraint is the supply of timber currently available. If 25% of the 6.4 billion cubic meters of concrete used each year were replaced by timber, the market would need to increase total global forest cover by about 14% – a land area 1.5 times the size of India[9]. Moreover, even if starting a massive reforestation program today, there would be a lag of 30 years before the timber supply was available for construction.

New materials could also play a key role in reducing plastics use, for instance in packaging, textiles and manufacturing. In particular, **cellulose-based fibers could substitute for plastics**, which would likely require less biomass input than if using bio-based plastics, given efficiency losses in the biochemistry process.

---

[9] SYSTEMIQ analysis for the Energy Transitions Commission (2018)

Beyond these examples, unforeseeable breakthroughs in mineral-based and bio-based materials might, in the long-term accelerate the decarbonization of the economy.

(VI) DRIVING DOWN THE COST OF CARBON CAPTURE AND CARBON USE TECHNOLOGIES

As described in Chapter 6, carbon capture will likely be part of the solution mix in the industry sectors, in particular in cement.

Although some carbon capture technologies are already operated at industrial scale, these need to be **adapted to different applications**, and incremental innovation could improve their efficiency and cost. A particular challenge is to **reduce the level of leakage** happening at capture stage (which is currently around 10-20% depending on application) to make carbon capture solutions as close to net-zero-carbon-emissions as possible.

Today, two sets of technologies are commonly used:

- **Pre-combustion technologies** entail the separation of CO_2 before any combustion takes place (like in steam methane reforming) and usually produce higher-concentration streams which are easier to capture, but are more difficult to retrofit on existing combustion processes.
- **Post-combustion technologies** enable the capture of CO_2 from fossil fuels burnt in air (for instance within a power station, a steel production blast furnace or a cement kiln), and therefore is less efficient as flue gas consist not only of CO_2, but also of water, nitrogen and other trace gases with a variety of impurities.

Three alternative sets of technologies could make it technically easier to separate the impure CO_2 stream from other flue gases and require further development:

- **Oxy-combustion** involves capturing the CO_2 post-combustion, but with the combustion taking place in pure oxygen. In principle, this technology could be applied in any application where combustion currently occurs in air.
- **Chemical looping** involves oxidizing (burning) fuel by use of a metal oxide, which reacts with fuel, rather than air, to produce CO_2 and steam. However, these technologies are still in the very early stages of development, with a sole 150 kW pilot exploring chemical looping undertaken by SINTEF.

- **Using membranes to separate CO_2 from flue gas** would theoretically offer a lower energy penalty, flexible operation from a modular design, and therefore greater ease of retrofit, but this has only been tested on very small scales.

In parallel, **reducing the costs of different carbon use applications** would also facilitate the deployment of carbon capture across multiple industries, by offering a revenue stream for the CO_2. Cost reductions are likely to come from economies of scale and learning curve effects, which require deployment at scale. The key question, therefore, is how to achieve sufficiently large-scale deployment, through partnerships with key buyers, in the concrete, aggregates, and carbon fiber industries.

9

Driving progress through policy

The overall conclusion of this report is that there are different routes – including both demand management solutions and supply-side decarbonization technologies – which together could drive **total decarbonization of the harder-to-abate sectors, and thus of the whole economy, by 2050 in developed economies and by 2060 in developing economies,** at an acceptable cost to the overall economy and to consumers.

It is impossible and unnecessary to specify in advance what the precise balance between the different routes will be, but it is useful to identify those elements of the transition which are certain to play a significant role. The aim of policy in this context should be to provide a clear direction of travel, by establishing short-term incentives and long-term signals that will drive private sector action. It should **unleash a market-driven search for the optimal mix of solutions, while also ensuring strong support for those aspects of the transition which are certain to be needed.**

To achieve this, specific policies to decarbonize the harder-to-abate sectors should be designed within the context of **seven principles and priorities:**

- **Stretch emissions reduction targets:** Public policy should set stretching and legally binding targets to ensure that the whole economy reaches net-zero emissions in developed economies by 2050 and in developing economies shortly thereafter. Governments can do this with confidence that the costs of delivering such targets will be manageable. These targets should then be backed by precise national roadmaps, (to be included in the next iteration of the Nationally Determined Contributions to the Paris agreement), using a set of precise indicators and intermediary targets for each sector of the economy, including the harder-to-abate sectors.
- **Make the most of demand management:** In heavy industry, carbon emissions could be reduced by 40% if we achieve greater materials efficiency and circularity. Moreover, materials substitution could also bring additional carbon abatement opportunities. In heavy-duty transport, demand management and modal shifts could bring down the cost of decarbonization by a lower, but still useful, 20%. It is essential to seize these lower-cost abatement opportunities. Carbon pricing can partly drive reductions in demand for carbon-intensive products and services and make recycling more profitable. But dedicated regulations will also be required, in particular to increase collaboration on materials circulation across industrial value chains and to encourage modal shift.
- **Accelerate energy efficiency improvement:** Similarly, it is essential to drive energy efficiency across the economy in both the easier-to-abate sectors and the harder-to-abate sectors. This will allow for many low-cost abatement opportunities, which will reduce the costs of supply-side decarbonization. This must be a key priority in the next 10 years and many of the policy levers discussed below – in particular carbon pricing and regulation – will help drive efficiency improvement.
- **Drive a green industry revolution:** The decarbonization of the harder-to-abate sectors demands no less than an industrial revolution, driven by new forms of energy (primarily zero-carbon power and hydrogen), new industrial production technologies (for instance, electric furnaces) and new business models (in particular circular business models). To face this challenge and seek the economic opportunities that will be arising from this new industrial system, governments need to revive industrial strategies, supporting innovation and nascent industries.
- **Accelerate power decarbonization:** It is essential to drive decarbonization of electricity as rapidly as possible as well as plan for very significant increases in total zero-carbon electricity demand. This will be required to achieve a net-zero economy, even if significant improvements in demand management and energy efficiency are achieved.
- **Anticipate the distributional effects:** Policymakers should overtly recognize that there will be some cost to the consumers. For example, consumers might see an increase in aviation ticket prices versus business as usual, marginally more expensive autos, or slightly more costly

POLICY SHOULD TARGET NET-ZERO CO_2 EMISSIONS FROM ENERGY AND INDUSTRY BY MID-CENTURY.

plastic packaging. Most of these costs will be minor and will likely be acceptable. But they might have a greater impact on the purchasing power of lower-income households, especially in developing economies. Moreover, although beneficial on an aggregate scale, the restructuration of the industrial system will inevitably create winners and losers, impacting local economic development and employment in some regions. Governments, in recognition of this, should develop "just transition" strategies, including ways of minimizing or offsetting distributional effects through public spending.

- **Fostering collaborations amongst actors:** Because innovation is funded and shaped both by governments and the private sector, and because of the specific role of international organizations and NGOs in the climate change space, the road towards a net-zero-emissions economy will need collective efforts, alignment and collaboration from stakeholders of different natures.

Within this context, this chapter considers the specific public policies which will help drive change in the harder-to-abate sectors, covering in turn:

i. Carbon pricing;
ii. Mandates and regulations;
iii. Public role in infrastructure development;
iv. Public support for research, development and deployment of new technologies.

(I) EFFICIENT AND PRAGMATIC APPROACHES TO CARBON PRICING

Adequate carbon prices must play a central role in driving the decarbonization of the harder-to-abate sectors, and indeed of the whole economy. They can **simultaneously increase incentives to supply-side decarbonization, energy efficiency improvements, materials recycling and demand reductions.** Price signals are more important in the harder-to-abate sectors than they have proved to be so far in the power sector, precisely because of the multiplicity of possible routes to net-zero in each sector: governments need to unleash the power of markets to search for the optimal way forward. Carbon prices alone would not be a sufficient policy, but they are an essential part of the policy toolkit.

Existing carbon pricing schemes, like the EU-ETS, have begun to play a role in driving down carbon emissions, but three challenges have limited their effectiveness to date [Exhibit 9.1]:

- There is a danger that, if international agreement cannot be achieved, **imposing carbon taxes in one country could result in shifts in the production location of internationally traded goods** (e.g. steel or aluminum) **and services** (e.g. international flights), and create a "carbon leakage" issue – i.e. displace carbon emissions to other regions rather than eliminate them. This has often led to exceptions within carbon pricing schemes, including the EU-ETS, for sectors facing international competition. Many of the harder-to-abate sectors fall within this category.
- Very different marginal abatement costs per sector, together with high emissions caps in emissions trading schemes, mean that the resulting **prices may be far too low to provoke change in the higher-cost, harder-to-abate sectors.** The key challenge is to create strong enough financial incentives today to trigger the search for optimal decarbonization pathways, without imposing a disproportionate burden on sectors for which progress towards full decarbonization can only be gradual. Indeed, in some of the harder-to-abate sectors, in particular in industry, long-lived assets and lack of market readiness of decarbonization technologies mean that imposing high carbon prices today could produce very significant short-term increases in prices.
- The uncertainty on long-term prices in emissions trading systems do not provide a sufficiently strong long-term price signal to spur technology development over several decades.

It is essential to overcome these challenges if the world is to meet the Paris target. **An internationally-agreed carbon price covering all sectors of the economy remains ideal,** and it is vital for governments to jointly pursue it. However, policymakers should also recognize that, if the ideal is not possible, there is still an opportunity to make progress by strengthening existing emissions trading schemes and by developing complementary, imperfect, but still useful approaches to carbon pricing.

These pragmatic approaches could be:

- **Defined in advance:** Specific taxes or floor prices, increasing through time in a way that is defined in advance, can provide greater certainty to investors than fluctuating prices within emissions trading schemes, and thus more powerful incentives for innovation efforts which have a long-term horizon. Ideally, these mechanisms would be supported by a broad cross-partisan coalition and/or be legally binding to limit the political risks of these policies being overthrown by future governments.

- **Differentiated:** Differentiated carbon prices by sector – reflecting different marginal abatement costs and technology readiness – can be applied in the harder-to-abate sectors. This could be particularly relevant for shipping and aviation, where it would be possible to impose high carbon prices (above US$100/ tCO_2) to drive rapid decarbonization in the 2020s and 2030s. If this level of carbon price was uniformly applied to the industry sectors at the same time, it would significantly increase the price of materials in the short term, given that full decarbonization technologies are not yet commercially available in industry. Carbon prices on materials-producing industrial sectors should therefore be lower than carbon prices on heavy-duty transport, and differentiated prices for different materials would have to be thought through carefully to avoid distortions in the competition between materials.
- **Domestic/Regional:** The argument that carbon pricing can impact international competitiveness is valid in some internationally-traded sectors (e.g. steel), but largely not in others (e.g. cement, where low value-to-weight ratio makes competition almost entirely domestic). Carbon prices can therefore be implemented at national/regional level on those sectors which face less international competition, while exempting other internationally-traded goods and services. This is already the case in many existing carbon pricing initiatives [Exhibit 9.1].
- **Downstream:** To overcome international competitiveness issues, it is also possible to impose carbon taxes on the lifecycle carbon emissions of end-products rather than on the carbon emissions at production level. In practice, this enables to indirectly price carbon in materials regardless of where they have been produced and price carbon emissions from freight regardless of the route that the product has travelled. Similar downstream taxes are already applied in many countries in the form of excise duties on gasoline and diesel, which are effectively subject to a carbon tax whatever the location of crude oil production

Carbon pricing initiatives already exist in many countries, but they do not always cover all harder-to-abate sectors and their price levels are too low to drive change in those sectors

Type of scheme	Country/Region	Sectors	Year of implementation	Government revenue US$, 2017	Price level US$/$tCO_{2e}$
Carbon Tax	Norway carbon tax	All sectors and fossil fuels, including natural gas.	1991	US$ 1,652 million	4-64
	UK carbon price floor	Power sector	2013	US$ 1,241 million	25
	Mexico carbon tax	All sectors and fossil fuels, except natural gas	2014	US$ 624 million	0.4-3
	Spain GHG tax	Fluorinated GHG emissions only (HFCs, PFCs, and SF6) from all sectors	2014	US$ 217 million	25
Emission Trading Scheme	European Union Emissions Trading System	Power, industry (with some free allocations) & intra-European aviation	2005	US$ 6,850 million	16
	Switzerland Emissions Trading System	Industry and power sectors	2008	US$ 5 million	8
	USA Regional GHG Initiative	Carbon emissions from power plants. First mandatory ETS in the USA.	2009	US$ 198 million	4
	California Cap-and-Trade Program	Industry, power, transport and buildings sectors	2012	US$ 2,024 million	15
	Tokyo Cap-and-Trade Program	Industry, power, transport and buildings sectors	2012	US$ 2,487 million	3
	Guangdong Pilot ETS (China)	Industry, power and aviation sectors	2013	US$ 3 million	2

Source: SYSTEMIQ analysis for the Energy Transitions Commission (2018) / ETS: Emissions Trading System

Exhibit 9.1

and refining. The main challenge to implement such an approach is to ensure the traceability of the lifecycle carbon emissions of complex end products. Developing digital solutions to enable this traceability should therefore be a key focus for innovation.

Carbon taxes or emissions trading systems are currently in place or being planned in 70 jurisdictions worldwide, covering one-fifth of global emissions[1]. However, many of these initiatives entail carbon prices of less than US$10/tCO$_2$, which are too low to drive change in the harder-to-abate sectors[2] [Exhibit 9.1]. It is important **to build on existing schemes and to deploy additional pragmatic approaches to carbon pricing, while pursuing international efforts to develop global carbon pricing arrangements** covering as much of the economy as possible. These should aim for a steady build-up of prices to something like US$50/tCO$_2$ by 2030, US$100 by 2040, and US$200 by 2050.

Five immediate actions to start with:

- **Remove fossil fuels subsidies, both at production and consumption levels:** Fossil fuel subsidies and tax breaks still amount to an estimated US$373 billion in 2015 according to the OECD and IEA[3]. They create a "negative carbon price" which hinders decarbonization progress.
- **Introduce a US$100/tCO$_2$ carbon price on cement:** This can be done on a national or regional basis, given low international exposure of the sector, and would simultaneously drive carbon capture development, switch to zero-carbon heat, progress on less carbon-intensive cement and concrete chemistries, materials efficiency in construction, and materials substitution.
- **Introduce domestic or regional taxes on carbon emissions in aviation:** Within the countries or regions that have large volume of internal aviation, such as China, India, the US and the European Union, carbon taxes on aviation of about US$100/tCO$_2$ applied at full rate to domestic flights and with reduced rates to international flights (to avoid major diversion of international flights through alternative hubs), would create a strong incentive for the use of alternative fuels.
- **Impose carbon taxes on plastics incineration:** Avoiding end-of-life emissions from plastics is essential to achieve a net-zero economy. Taxes on plastics incineration would drive plastics recycling, either mechanical or chemical, which can be a key source of low-cost emissions reduction and generate new economic activities.
- **Impose a gradually increasing tax on cars which reflect the carbon intensity of the materials used:** The use of zero-carbon steel would add less than 1% to the price of a car and would therefore be acceptable by end consumers. Given the importance of the automotive market for the steel industry, such a downstream tax would create incentives for upstream decarbonization, without creating major international competitiveness distortions.

(II) MANDATES AND REGULATIONS

While carbon prices are essential, they are not a panacea and, in some cases, not the most powerful policy instrument. In particular, **price signals are often insufficient:**

- **In highly fragmented sectors** where incentives are split (for instance, shipping or the plastics value chain);
- **When buyers focus on the upfront cost of a product,** rather than total lifecycle costs, which is a known factor slowing down energy efficiency improvements and which could also hinder progress, for instance, in the adoption of electric drivetrains in trucking;
- **To drive change on topics that are multidimensional** (such as the sustainability of biomass) and can therefore not be captured by a single price point.

In those cases, mandates and regulations will often prove more effective than carbon prices.

Driving supply-side decarbonization through regulations

On the supply side, various types of regulations could accelerate the decarbonization of harder-to-abate sectors:

- **Energy efficiency standards** have been a key driver of improvements in automobiles and appliances, and are already being applied by the IMO to drive improvements in the energy efficiency of new ships, or by the European Union with the proposition of the EU's first-ever fuel economy standards for new trucks in 2018.
- Similarly, **green fuel mandates** have a key role to play in the transport sector. Governments or international organizations, such as ICAO or IMO, could supplement carbon prices with "green

---

[1] World Bank (2018), *Carbon Pricing Dashboard*
[2] World Bank (2018), *State and Trends of Carbon Pricing 2018*
[3] OECD (2018), *OECD Companion to the Inventory of Support Measures for Fossil Fuels 2018*

fuel mandates", which require airlines and ship operators to use a rising percentage of fuel from zero-carbon sources. Such mandates, if set in advance, could prove to be very powerful drivers of innovation and investment, since they make a certain pace of improvement non-negotiable.

- In addition, **regulations which ban the sale of diesel or gasoline ICE autos and, eventually, trucks** beyond given future dates, **and/or which ban their use in major cities,** could play a powerful role in driving change. While such bans are sometimes condemned as "blunt instruments", their very bluntness and certainty can galvanize product development and investment decisions from vehicle manufacturers. Moreover, bans within cities are likely to be demanded for local environmental reasons (to reduce local air pollution, noise and local heat effects) as well as for climate reasons.
- **Regulations on end products,** which can take the form of regulations on the carbon intensity of materials used in the product (e.g. in cars), on the lifecycle carbon emissions of a product (e.g. taking into account the carbon emissions from transportation of an imported food product), or on the recycled content of a product (e.g. of packaging). The key challenge to implement such regulations is to first ensure traceability of these different dimensions and then establish appropriate labelling.
- **Tightly defined sustainability standards** for low-carbon fuels (including bioenergy and hydrogen) are essential (i) to discriminate between different types of bioenergy (or hydrogen) that can have very different carbon footprints and (ii), for biomass, to prevent negative externalities in terms of land use change, deforestation, competition with agricultural land and impact on biodiversity. As described in Chapter 6, the carbon footprint of bioenergy and bio-feedstock varies significantly depending on the source of biomass, on the energy-intensity of its transformation, and on its impact on land use change. Similarly, the carbon footprint of hydrogen will vary depending on the production route – electrolysis, which can be zero-carbon, or SMR plus CCS, which can only be close-to-zero-carbon – and on the carbon intensity of the electricity input. Standards should therefore be based on robust lifecycle carbon accounting and assessment of other environmental impacts.

Driving the circular economy agenda

In parallel, there are very major opportunities to reduce emissions in the industrial sectors by using circular economy approaches and more efficient design to reduce materials use. **Achieving a dramatic increase in materials efficiency, recycling and reuse will require fundamental changes in the way the entire value chains operate**, for instance through changes in product and building designs (to avoid materials over-specification, and facilitate dismantling, sorting and recycling at end-of-life), improved materials processing systems (especially at end-of-life), and new business models based on greater durability and more intensive use of products (for instance via sharing practices).

Given the fragmentation of these value chains across materials producers, manufacturers, distributors, waste management companies etc., **achieving such changes will require a significant degree of value chain coordination,** which can be strongly incentivized by public regulation, in particular via:

- **Legally-binding recycling targets for local authorities,** which focus on both the quantity of materials collected for recycling and the quality of the waste flow (which matters to facilitate high-quality recycling rather than downgrading);
- **Regulations on the recyclability and recycled content of key products,** for instance packaging;
- **Standards on materials efficiency and durability,** especially in infrastructure, buildings and key consumer products, which avoid over-specification of materials use, ensure availability of components for repair and tackles the issue of programmed obsolescence in manufactured products;
- **End-of-life product recycling responsibility,** which creates incentives for the manufacturer to develop designs which make end-of-life dismantling, materials sorting and recycling possible – notably for household appliances, cars and trucks, and buildings.

Five immediate actions to start with:

- **Commit to ban diesel and gasoline ICE vehicles within the metropolitan territory of major cities, by 2030 for cars and by 2040 for trucks:** This can be a powerful signal sent by the C40 to the automotive industry to shift its attention to electric engines (either in BEVs or FCEVs). This commitment should go hand in hand with the deployment of recharging and hydrogen refueling infrastructure, and the development of the public transport infrastructure required to support urban mobility.

- **Establish green fuel mandates for aviation:** These mandates should impose a growing share of zero-carbon fuels through time, aiming for 100% by 2050. This effort could be led at a regional level first – on domestic flights, within regions with large volume of internal flights (such as China, India, Europe and the US) – and then expand globally, potentially under the auspices of ICAO.
- **Enforce mandatory recyclability and recycled content targets for plastics packaging:** Regulations are essential to both ensure that plastics-based products are conceived in a way that makes them recyclable (e.g. encouraging use of the major types of plastics rather than rare plastics, avoiding layering of different materials…) and to encourage uptake of recycled materials. These efforts could start with packaging, and later expand to more complex manufactured products.
- **Modify and strengthen existing construction standards:** Tight energy and carbon efficiency standards are already applied in most countries, but they consider the building's operational footprint rather than the footprint of the construction materials used. Existing standards should therefore be completed with increasingly tight targets on embedded carbon in construction materials. In parallel, they should shift from materials specifications to performance-based specifications, in order to reduce materials over-specification and enable the use of new low-carbon materials, such as new cement chemistries.
- **Tighten standards on bioenergy and biofuels:** Some of the bioenergy and biofuels that are currently in use, in particular, biofuels based from oil crops, only enable a limited (or even negative) reduction in carbon emissions compared to fossil fuel alternatives. Moreover, they have sometimes had significant negative externalities, particularly for deforestation. It is therefore urgent to tighten sustainability standards for biomass, based on robust lifecycle carbon accounting and on an assessment of non-CO_2 environmental impacts.

(III) PUBLIC ROLE IN INFRASTRUCTURE DEVELOPMENT

Chapter 4 described the significant, but clearly affordable, investments required to build a zero-carbon global economy. Most of these investments need to be made by the private sector, with public policy providing the carbon prices and regulatory incentives which will make those investments economic. But, there are **some investments in common infrastructure where governments need to play a coordination role,** and, to some extent, a direct investment role, to ensure sufficiently rapid development.

Firstly, it is vital to ensure sufficient investment in **the energy sector,** in particular, in:

- **The scale-up of renewable power production:** To meet a 5-fold increase in power demand globally with zero-carbon power will require a significant acceleration of wind and solar deployment, which will need to be supported by a fast-growing renewable industry. Government targets for renewable expansion constitute an important signal to drive private sector investment.
- **Long-distance power transmission and local power distribution:** The total incremental cost of transmission and distribution reinforcement to support greatly increased electricity demand and high penetration of renewables adds only moderately to the total cost of electricity. But appropriate public policy interventions will be required:
  - Deploying long-distance power transmission lines demands appropriate regulatory arrangements. It will constitute a greater challenge in developing countries that currently suffer from weaker grids with high levels of grid losses, like India or Brazil.
  - Investments in the local distribution networks will be differentiated in developed and developing countries. In rapidly urbanizing countries, it is essential to plan new city power networks for the higher levels of electricity demand and charging infrastructure that will be required in the future. Beyond this, all countries need clear regulatory structures and incentives to compensate distribution providers for necessary investment in distribution networks, and therefore ensure that investment occurs.
- **Port infrastructure and pipelines to transport new fuels like hydrogen and ammonia:** Hydrogen and ammonia could potentially be produced on a very large scale at low cost in favorable locations and then internationally traded. This might be supported by shipping of new fuels (on a similar model as LNG today), which would

require an adaptation of port infrastructure, or by long-distance pipelines. Several transportation options are for instance being tested between Australia and Japan.

The second priority in terms of infrastructure investment lies in the **transport infrastructure,** in particular:

- **The fast development of vehicle charging/refueling infrastructure:** As there is already an appetite to invest from the private sector, cities and government could use their regulatory influence to create a conducive environment for private investment in charging infrastructure and hydrogen refueling infrastructure – and only provide subsidies under specific circumstances[4].
- **The maintenance and strengthening of railway infrastructure:** The quality of the railway infrastructure, both for freight and for passenger transport, can be a key driver of (or, conversely, a blocking factor in) modal shift from heavy road transport and aviation. High-speed rail connections on a regional level are particularly important to reduce demand for short-distance flights.

Finally, governments have to play a key role in ensuring the development, when needed, of **secure carbon storage and pipelines to transport CO_2** from industrial capture sites to storage sites. As described in Chapter 6, carbon capture and storage is likely to play a limited, but essential role to achieve a net-zero economy. This will require the development of pipelines and storage facilities which will not be economic unless shared between multiple industrial companies and will not occur unless governments play a role in:

- Securing **public acceptance of CCS** by imposing sufficiently tight regulatory standards and monitoring on the transport and storage infrastructure to ensure its safety and permanence;
- Planning and approving the **routing of pipelines.**

Four immediate actions to start with:

- **Develop integrated clean power strategies:** These should anticipate and plan for a significant electrification of the economy, in particular, by accelerating the deployment of renewable power and of other forms of zero-carbon power (where needed to complete wind and solar generation on a baseload or peaking basis), adapting the pace of electrification of different applications to the pace of power decarbonization, and ensuring investment in the strengthening of the grid both in terms of long-distance transmission and in terms of local distribution networks.
- **Create a coalition of major international ports dedicated to new fuels:** This coalition could have the double aim of (i) developing the necessary infrastructure for international trade of hydrogen and/or ammonia (which may be a growing activity for international ports at a time when international trade of fossil fuels should gradually wind down to meet the Paris objectives) and (ii) developing a battery recharging and hydrogen/ammonia refueling infrastructure in ports, as these are likely to become dominant fuels for the shipping industry over time.
- **Create regional coalitions for the development of recharging and hydrogen refueling infrastructure:** These coalitions should bring together national and local policymakers, energy providers, the automotive industry and motorway concession companies to jointly plan for the necessary infrastructure deployment to support electromobility (including BEVs and FCEVs).
- **Establish a coalition for the development of carbon capture and storage in Northern Europe:** Such a coalition should bring together two to three European States, oil and gas companies, energy-intensive industry players and representatives of the civil society. Its initial aim would be to plan for the necessary infrastructure (including financing and risk sharing), drive its social acceptability and, once built, ensure a tight independent monitoring of the carbon infrastructure.

(IV) PUBLIC SUPPORT FOR RESEARCH, DEVELOPMENT AND DEPLOYMENT OF NEW TECHNOLOGIES

Accelerating innovation will be essential to achieve the decarbonization of the harder-to-abate sectors by mid-century. But, current innovation systems are poorly connected, with little coordination between public and private R&D, and there is **no clear global R&D agenda to deliver a full decarbonization of the economy by mid-century** that would be shared by both public and private actors. Mission Innovation[5] could, in principle, be the platform developing such an innovation agenda, but has not yet been able to establish itself as the reference point across all sectors engaged in the energy transition.

---

[4] Clinton Climate Initiative (2018), *Policy options for electric vehicle charging infrastructure in C40 cities*

[5] Mission Innovation is a global initiative of 23 countries and the European Union that aims to dramatically accelerate global clean energy innovation. As part of the initiative, participating countries have committed to seek to double their governments' clean energy research and development (R&D) investments over five years.

Governments should therefore, through Mission Innovation and through their own public innovation strategies, **encourage technology development against a set of mission-driven criteria, based on the innovation agenda described in Chapter 8**. This innovation agenda distinguishes between (i) innovations where the basic science is known and where further progress could almost certainly be achieved – and costs be reduced – if sufficient scale of investment occurred, (ii) those where more fundamental research in underlying chemistry or engineering are required to bring technologies at scale, and (iii) those where game-changing improvements are possible, although they are at very early stages of development.

Public support has a different role to play at each stage of technology development:

- **For proven technologies** that now need to be deployed at scale to achieve economy of scale and learning curve effects, **most of the investment should come from the private sector**, but governments could usefully facilitate financing (for instance via tax breaks, loan guarantees, reimbursable advances) and use public procurement to create demand for "green" products and services. The example of renewable power shows that initial subsidies and price guarantees played a crucial role in driving scale deployment, which unleashed such economy of scale and learning curve effects that the need for subsidy is now rapidly declining. Given the multiple technologies required to support the decarbonization of the harder-to-abate sectors, it will be less easy to apply this principle, since less easy to define the very small number of technologies (i.e. the equivalent of wind and solar power) which will undoubtedly be required. But there could be still an important role for "nascent industry" policies which would focus on technologies or products meeting specific carbon-intensity targets in different sectors.
- **For technologies under development** that need to be brought to commercial readiness, **public innovation support could play a key role in de-risking and accelerating private sector R&D efforts**. Joint R&D projects, supported by public innovation funding, will be key to drive these technologies to market. The HYBRIT project described in Chapter 2 is one example among many for such an initiative. Governments can also provide greater certainty on future prices and market opportunities in for example 10 or 15 years, by using commitments on public procurement to guarantee future prices for an initial level of demand (e.g. guaranteeing a minimum price for zero-carbon bus procurement by 2025 or for low-carbon cement for public buildings by 2035).
- Finally, **public sector R&D** has an essential role to play to **foster radical technology breakthroughs** with respond to energy transition challenges, focusing on priority areas of research and working towards specific quantitative objectives 10 to 15 years ahead.

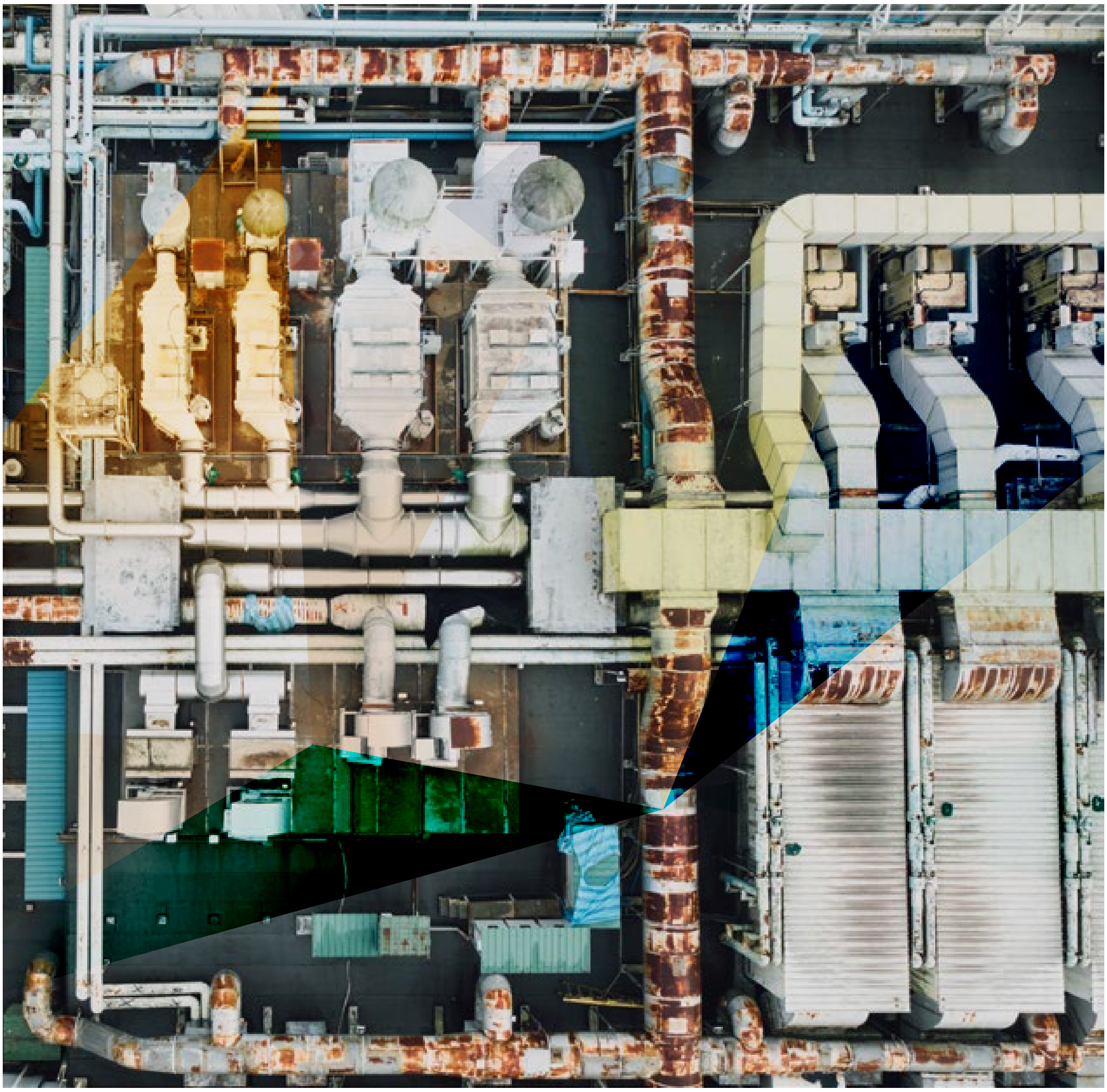
A specific challenge, especially for the least market-ready technologies, lies in bridging public research with private sector R&D, i.e. ensuring that early stage innovations (including those arising from public research) are connected to established companies in the energy, industry and transport sectors, which have the financial means, technical expertise, commercial know-how and market knowledge to rapidly bring those innovations to market. Encouraging knowledge sharing and R&D spending is particularly difficult in the capital expenditure-driven, low-collaboration environment of heavy industries. To solve this challenge, governments can fund joint public-private R&D efforts, create spaces and structures for project incubation that aim to link early-stage innovators with established companies, and create a market for low-carbon innovation, especially through public procurement, that will be large enough to trigger interest of major companies.

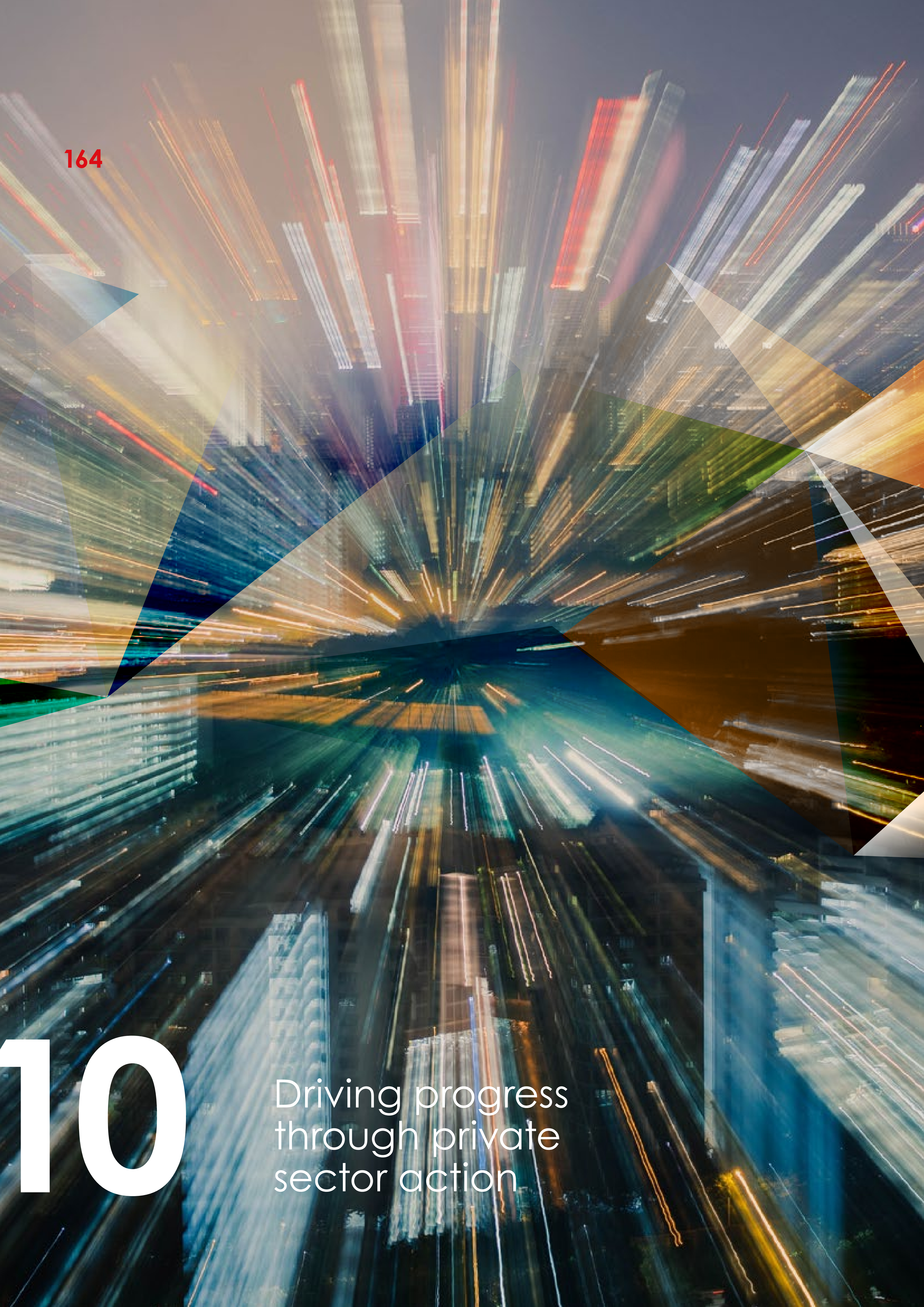
Four immediate actions to start with:

- **Develop and agree on a global zero-carbon innovation roadmap:** In the same way as the Sustainable Development Goals constitute a reference point for public, private and civil society organizations, we need a zero-carbon innovation roadmap that would define clear innovation targets essential to enable the world to achieve net-zero CO_2 emissions by mid-century. This could be orchestrated by Mission Innovation, building on its existing clean energy agenda, or be extended by a UN body.
- **Ensure that innovation in materials can benefit from clean energy innovation support:** The impact that new low-carbon materials (for construction, packaging, textile…), materials efficiency and materials circularity can have on CO_2 emissions reduction is significant.

Those innovation priorities should therefore be considered as part of the global innovation agenda to achieve a zero-carbon economy.

- **Launch a series of Global Innovation Challenges focused on the harder-to-abate sectors:** To ensure that R&D efforts are focused on achieving the key innovation targets described in Chapter 8, mechanisms like Global Innovation Challenges can be powerful tools to focus the creativity of researchers on climate-related missions, source and shed light on existing, early-stage innovations that could provide an answer to key sustainability challenges.
- **Ensure that public R&D spending, including spending committed through Mission Innovation, is channeled in priority to public-private R&D projects:** To achieve net-zero by mid-century, the key challenge is to not only develop the portfolio of innovations required to fully decarbonize the economy, but also to accelerate its commercial deployment. Commercial deployment, in turn, if established companies are party to these innovations, as they have the financial means, technical expertise, commercial know-how and market knowledge to rapidly bring those innovations to market.





10

Driving progress through private sector action

A strong policy framework will be of particular importance to drive decarbonization in the harder-to-abate sectors of the economy, where reducing carbon emissions will most likely represent a net cost, especially during the first decades of the transition. In that context, **market forces alone will not drive progress, but they can and should plan for it.** Awareness of the climate-related financial risks and opportunities is growing in the investor community as well as in the business community. Climate change will indeed impact the risk-return profile of companies, either directly due to the physical impacts of climate change, or indirectly due to climate-driven policy changes (such as carbon pricing) and to the development and deployment of new technologies, which will not only drive emissions reductions, but could also potentially disrupt the markets they are entering. **The private sector therefore needs to anticipate and prepare for the profound changes in the business environment and the industrial system which are foreseeable and to which they will need to adapt eventually.**

This will likely **require greater collaboration within each harder-to-abate sector and across their respective value chains,** in order to remove the "first-mover disadvantage" which could arise if a single company started to bear the cost of decarbonization while competitors continued to operate business as usual. These collaborations should focus on pre-competitive stages that can de-risk further company-level investments in decarbonization efforts, for instance by developing decarbonization roadmaps and targets, creating low-carbon standards or jointly exploring early-stage innovations. Such initiatives should conform with anti-trust policy. As decarbonization solutions and technologies get closer to market readiness, though, they will move into the field of market competition.

This chapter covers in turn what actions can be taken by:

i. Industry associations and initiatives in harder-to-abate sectors;
ii. Individual companies in harder-to-abate sectors;
iii. Major buyers of materials and mobility services, including major corporates, public procurement services and end consumers;
iv. Public and private investors.

(I) THE RESPONSIBILITY OF TRADE ASSOCIATIONS AND INDUSTRY INITIATIVES IN HARDER-TO-ABATE SECTORS: RAISING AMBITIONS

Many industry initiatives are already driving climate-related efforts across the harder-to-abate sectors. Examples include – but are not limited to:

- The **Cement Sustainability Initiative** (CSI)[1], which has been driving efficiency progress in the cement industry since 1999 and recently released a technology roadmap for a low-carbon cement industry in partnership with the International Energy Agency[2];
- **ResponsibleSteel**, which was recently established to create a standard for responsible steel covering a broader spectrum of social and environmental issues, including carbon footprint;
- The **International Air Transport Association (IATA),** which developed the industry roadmap aiming at a 50% reduction in carbon emissions by 2050 relative to 2005 levels (described in Chapter 3)[3];
- **The Global Maritime Forum,** which orchestrated, in October 2018, the signature of a call for action in support of decarbonization from 34 CEOs from across the maritime industry;
- **In the trucking industry,** which is highly fragmented, global initiatives have not yet emerged, but **local initiatives exist,** like the North American Council for Freight Efficiency (NACFE).

Those industry initiatives usually operate one step ahead of the industry trade associations, which represent a broader set of companies and therefore, by nature, tend to have a greater level of inertia.

Across sectors, current mobilization has usually taken the form of:

- **Climate-related industry announcements with varying levels of tangible commitments:** These can send a powerful signal to both policymakers and the rest of the industry on the desirable and likely direction of travel, but their real-life impact can sometimes be limited.
- **Sectoral roadmaps compatible with 2˚C trajectories:** These constitute an important first step in defining a joint vision of a decarbonization pathway, backed by industry players, that can inform policymaking. However, they do not currently lay out a pathway to net-zero carbon emissions within the harder-to-abate sectors themselves.

---

[1] Historically hosted by the World Business Council for Sustainable Development, the Cement Sustainability Initiative has announced its merger with the Global Cement and Concrete Association in August 2018.
[2] IEA & CSI (2018), *Technology Roadmap, Low-carbon transition in the cement industry*
[3] IATA (2013), *Technology Roadmap*

Given the urgency of making tangible progress to meet the target of net-zero emissions by mid-century and the likelihood of increased policy pressure and investor pressure on harder-to-abate sectors in the run up to this mid-century deadline, **the level of ambition of these industry efforts now need to be raised.** Industry initiatives in heavy industry and heavy-duty transport can, in particular:

- **Develop roadmaps to net-zero carbon emissions by mid-century:** These should build on existing low-carbon roadmaps in the sectors where they exist, aim for as close as possible to net-zero CO_2 emissions without relying on offsets from the land use sector (except to compensate for residual emissions from leakages in carbon capture installations and some uncontrollable end-of-life emissions), and include a strategy on the use and later phase out of transitional solutions such as lower-carbon fuels.
- **Develop cross-sectoral initiatives,** bringing together producers and buyers of carbon-intensive materials and mobility, to:
    - **Develop low/zero-carbon labels:** These can be used by buyers to differentiate between products and potentially enable producers to get a premium price for low/zero-carbon products. It will result easier to develop a label for distinct materials (e.g. biofuels, steel, cement) than for complex products (e.g. low-lifecycle-carbon -emissions buildings). Some of the most difficult implementation challenges will include the traceability of materials and of their lifecycle emissions, how to differentiate primary from recycled materials, and how to gradually increase ambitions over time.
    - **Create a demand for low/zero-carbon products and mobility services:** These could, for instance, take the form of a partnership between airlines, airports and travel agencies to develop a zero-carbon flight offer (which could progressively substitute for offsetting schemes) or of a long-term commitment from the automotive industry to purchase zero-carbon steel by 2040. Such schemes would often require some form of label on which product differentiation can be based.
    - **Support materials circularity:** Increased materials circularity can only be achieved through greater collaboration between all players across the materials value chains: producers, manufacturers, consumers, waste collection and sorting industries, recycling industries… Exchanges between these players could, for instance, lead to smarter product design enabling higher-quality recycling or waste collection schemes better adapted to the requirements of the recycling industry.
- **Develop early-stage innovation funds:** These could be co-funded by multiple industry players and could invest in pre-competitive research and development focused on decarbonization technologies which are 20 years away from market. Such joint funds would de-risk early investment in potential technological breakthroughs. The OGCI Climate Investments, announced in 2016 by the Oil and Gas Climate Initiative, has a similar ambition.

Finally, it is essential for industry associations to **align corporate lobbying with the net-zero-carbon-emissions agenda,** by not opposing and preferably actively using their lobbying capacity to support a set of policies (including carbon prices and regulations) which are necessary to drive progress in their sectors.

Illustration 10.1 – NACFE: Driving change in a fragmented industry

Improving the fuel efficiency of trucks could reduce carbon emissions from the sector by 30-45%. Achieving this potential is particularly crucial to reduce emissions over the next 10-15 years, as ICE vehicles powered primarily by fossil fuels are still likely to dominate the market. It could also save millions in fuels for the trucking fleets. The North American Council for Freight Efficiency (NACFE) works with the trucking industry, technology providers and manufacturers to double US freight efficiency. They aim to accelerate adoption of efficiency technologies by increasing confidence in those technologies and highlighting their benefits, sometimes on the back of commercial-scale testing. NACFE has already published 15 Confidence Reports that evaluate over 60 fuel efficiency technologies. They disseminate this knowledge and raise awareness through workshops which bring together key industry players and technology leaders to facilitate shared learning on efficiency technologies.

(II) THE RESPONSIBILITY OF COMPANIES IN HARDER-TO-ABATE SECTORS: PREPARING FOR THE FUTURE

To an even greater extent than the industry associations and industry initiatives, **companies in the harder-to-abate sectors need to prepare for the profound changes in their business environment** that they are likely to face, for the growing investor pressure on climate-related risks and for the increasing policy pressure on carbon emissions. Many leading companies in those sectors have already started to invest in this transition, especially in energy efficiency improvement and in R&D projects to develop and pilot key decarbonization technologies. Some have taken specific commitments to climate-related initiatives (like the RE100[4]), to science-based targets or, for the boldest companies, to net-zero emissions by a certain date.

These efforts should be pursued and accelerated. Policy changes, combined with the development of climate-related industry initiatives, should progressively reduce the competitiveness risks associated with being the first mover. Conversely, some companies might be in a position to **develop a first-mover advantage,** depending on their positioning on the market.

The portfolio of actions that can be taken by companies in harder-to-abate sectors includes:

- **Committing to tightened science-based pathways:** Companies in harder-to-abate sectors need to prepare for the full decarbonization of the economy and therefore develop clear plans to reach net-zero CO_2 emissions by mid-century. These plans can be informed by industry roadmaps. Most importantly, they should feed into their long-term business strategy and shareholder reporting.
- **Investing in R&D projects:** These projects should focus on the key innovation priorities outlined in Chapter 8 with the objective of demonstrating key technologies and piloting them on a commercial scale. These are likely to require collaboration across value chains, in particular the involvement of energy producers (who can supply zero-carbon power, hydrogen or biofuels) and of equipment providers.
- **Developing partnerships across their value chain to develop materials circularity:** Through collaborations with manufacturers and end users of the materials they produce, heavy industries can ensure that they retrieve these materials by their end of useful life and ensure their recycling. These efforts can potentially give rise to new business models based on materials-as-a-service, in which materials producer would retain ownership of materials throughout use, and therefore have both the responsibility and ability to manage the stock of materials.
- **Developing regional partnerships in industrial clusters:** These partnerships can aim to develop greater industrial symbiosis, which can take the form of an industrial facility using the wastes or byproducts of another one as a raw material of feedstock, of a joint facility to produce and/or store zero-carbon energy, or of a joint investment in shared CO_2 transportation and storage infrastructure.

(III) THE RESPONSIBILITY OF BUYERS: CREATING DEMAND FOR ZERO-EMISSIONS MATERIALS AND MOBILITY SERVICES

A key driver of change in the harder-to-abate sectors will be the existence – or lack thereof – of an initial demand for "green" materials and mobility services, i.e. buyers who might be willing to accept a premium price during the early stages of the transition period. This initial demand is essential to drive economy of scale and learning curve effects, which would then make zero-emissions products and services increasingly cost-competitive and accessible to a broader range of consumers.

Voluntary commitments from major buyers of materials, logistics services and business flights have a role to play in creating this initial demand. Two major types of buyers are to be engaged: (i) **major corporates,** which are committed to reducing their direct and indirect carbon emissions, and (ii) **public procurement services,** who play a particularly important role in the construction sector.

Voluntary commitments to "green purchasing" already exist. Campaigns like the RE100 (commitment to 100% renewable energy) and EV100 (commitment to 100% light-duty electric vehicle) are, for instance, gaining traction across a diverse group of companies and organizations who aim to improve their carbon footprint.

Similar initiatives could be envisioned in the harder-to-abate sectors:

---

[4] RE100 is an initiative run by The Climate Group through which companies commit to buy a 100% of their energy supply from renewable sources.

- **In heavy road transport,** the EV100 commitment could be expanded to an EV100+ commitment to 100% light-duty and heavy-duty electric vehicles (BEVs or FCEVs). Moreover, major cities, via the C40, could drive the heavy road transport market by committing to 100% electric buses (BEVs or FCEVs) by 2035. As described in Chapter 3, similar targets adopted in Chinese cities are currently driving down the cost of batteries.
- **In aviation,** major consumers of business flights, and the travel agents through which they operate, could commit to green flights purchase as an alternative to buying offsets to compensate for business air travel.
- **Across all freight transport modes,** global logistics companies could, with the support of a coalition of major clients, commit to tracking and gradually lowering the carbon intensity of their services over time, possibly developing a premium "low-carbon logistics" offer, which could attract a growing number of clients as it develops and becomes more cost-competitive.
- **In the construction sector,** the public sector, who is the single most important buyer of buildings and infrastructure, could play a significant role by developing "green" procurement in buildings – taking into account not only the operational efficiency of the building, but also the lifecycle carbon emissions of the construction materials – with, for instance, increasingly tight carbon intensity targets for the materials used in publicly-funded construction projects. In parallel, a combination of major corporates and leading architecture firms could initiate a demand for zero-lifecycle-carbon-emissions buildings in the high-end office space market.
- **In steel,** a powerful demand signal could come from the automotive industry, if 4-5 major automotive manufacturers were to commit to purchasing zero-carbon steel by 2040.
- Finally, **in the plastics value chain,** major manufacturers and retailers could choose to commit to recyclability targets, recycled content targets or lifecycle carbon emissions targets for their plastics-based products, therefore encouraging the chemicals industry to innovate.

Implementing these commitments, however, **will require greater traceability of the carbon intensity** of kilometer travelled, in the transport sectors, and of the lifecycle carbon footprint of materials, in construction and manufactured products. The former will be easier to put in place than the latter, given the complexity to track materials as they are transformed and incorporated into products and as they are then distributed from manufacturing to retail and all the way to the end consumer.

Due to the length of these value chains, and with the exception of aviation and some subsectors of shipping (cruise ships) and heavy road transport (buses), **the harder-to-abate sectors are not directly exposed to consumer pressure.** However, adequate labelling of lifecycle carbon intensity of products (e.g. cars, appliances) and services (e.g. flights) could create traceability and be a powerful tool for consumer awareness. It could facilitate the creation of a "green offer" at a premium price for end consumer products, which may be positively received given that the cost impact of decarbonization on consumer prices is likely to be relatively small.

Illustration 10.2 – Apple demands zero-carbon aluminum

In May 2018, Apple announced a collaboration with aluminum producer Alcoa and mining company Rio Tinto to develop zero-carbon aluminum. Apple has the ambition to one day produce a product that would be free of greenhouse gas emissions, and is therefore exploring how to reduce carbon emissions in its supply chain. It has already reduced the emissions from aluminum used in its smartphone by 83% using recycled aluminum and virgin aluminum produced in plants powered by hydroelectricity. This project aims to achieve even further reductions. Alcoa and Rio Tinto will create a joint venture, called Elysis, to develop a new zero-carbon smelting process. The project will enable Alcoa to bring to market a technology that the company has been developing since 2009, which uses advanced conductive material (instead of fossil-fuel-based carbon) to remove oxygen from aluminum oxide during the smelting process. Although Apple won't have shares in the joint venture and "only" brings US$10 million investment to the table (out of US147 million), it is the strong market signal coming from the company that catalyzed this collaboration. It benefits from the strong support of the Canadian and Quebec governments, which are investing US$47 million, i.e. more than Alcoa and Rio Tinto are jointly investing (US$43 million). The Quebec government will even take a small 3,5% share in the capital of the new company.[5]

---

[5] GreenBiz (2018, May 11), *Why Apple is getting cozy with aluminum giants Alcoa and Rio Tinto*

(IV) THE RESPONSIBILITY OF INVESTORS: SHIFTING FINANCE FLOWS IN THE INDUSTRIAL SECTORS

This report lays out a vision of key transformations of the energy and industrial system which need to happen – and are likely to happen – if the world is to meet the objective of keeping the rise in world temperatures well below 2˚C and as close as possible to 1.5˚C. As such, it constitutes a portrait of the world to come and **reveals a map of where existing industries are likely to be disrupted and where promising investment opportunities are arising.** We hope it can inform investment decisions from development finance institutions, institutional investors and venture capitalists.

Investment opportunities in low-carbon infrastructure and in zero-carbon power, in particular renewables, are already known, but this report highlights the considerable scale to which they might grow by mid-century with the full decarbonization of the economy. New investment opportunities will also probably arise in the key innovation areas described in Chapter 8. Finally, investors might want to pay particular attention to the companies – in the heavy industry and heavy-duty transport sectors, as well as in their value chains – which will take advantage of low-carbon innovation in materials, products and business models to shape up a new competitive edge.

To date, **climate-related risks and opportunities in the industry and transport sectors have been given relatively less attention than those in the energy sector.** The transition challenges in the harder-to-abate sectors raise specific questions, such as how to finance gradual decarbonization processes (which might therefore not be able to access tightly-defined green finance capital) or whether to invest in transitional solutions which could create emissions lock-in or stranded assets risks. Exploring these issues constitutes a key challenge for public and private investors alike. The European Commission has recently launched an initiative to define the EU taxonomy for sustainable finance, which will come to fruition in 2019 and will constitute a major reference point. This type of analysis and framework will arm public and private investors to better:

- **Evaluate the climate-related risks and opportunities** of their investments, going beyond the energy sector and **focusing on the industry and transport sectors;**
- **Develop strategies to shift their investment portfolio through time,** to ramp up investment in low-carbon infrastructure, facilitate the transition of industrial assets to low-carbon technologies, and design appropriate financing mechanisms for investing in assets with a stranding or emissions lock-in risk;
- **Develop a range of "green investment" products** with different risk-return profiles, going beyond ESG criteria and possibly relying on a new credit ratings system which would take into account decarbonization strategies alongside financial rating criteria.

Development finance institutions, in particular, will play a crucial role to facilitate these low-carbon investments in developing countries, through policy development, public investment, and private capital mobilization via blended finance mechanisms.

CONCLUSIVE REMARKS

The Energy Transitions Commission believes it is possible to achieve the near-total decarbonization of harder-to-abate sectors of the economy by mid-century, significantly increasing the chance of limiting global warming to 1.5˚C. Succeeding in that historic endeavor would not only limit the harmful impact of climate change; it would also drive prosperity through rapid technological innovation and job creation in new industries, and deliver important local environmental benefits. National and local governments, businesses, investors and consumers should therefore urgently take the actions needed to achieve this objective.

Acknowledgements

The team that developed this report has comprised:

Adair Turner (Chair), Ajay Mathur (Co-Chair), Faustine Delasalle (Program Director), Tugce Balik, Laetitia de Villepin, Saira George, Thea Jung, Sachin Kapila, Isabel Lewren, Jeremy Oppenheim, Ricardo Santana (SYSTEMIQ); Per Klevnäs, Anders Ahlen, Cornelia Jonsson (Material Economics); Arnout de Pee, Eveline Speelman, Maaike Witteveen (McKinsey and Company); Tristan Smith, Carlo Raucci (University Maritime Advisory Services).

The team wants to thank the ETC network for their active contribution:

Gardiner Hill, Towns Martin, Michael McMahon, Thomas Parson, Saurabh Sachdeva, William Zimmern (BP), Vivian Au, Vian Davys (CLP), Ashwani Pahuja (Dalmia Bharat Cement Limited), Diane Gilpin, Rebecca Heaton (DRAX), Grégory Bartholomé, Arthur Baux, Rose Delannoy, Adeline Duterque, Soizic Legoff (ENGIE), Michael Ding, Olivia Sang (Envision), Florence Bachelard-Bakal, Isabel Blanco, Harry Boyd-Carpenter, Cristian Carraretto, Alex Chirmiciu, Beauman Christopher, Damin Chung, Philip Good, Adil Hanif, Benedicte Kariger, Duncan Kernohan, Dimitri Koufos, Frederic Lucenet, Gianpiero Nacci, Rika Ishii, Rafael Rashid, Tara Shirvani (European Bank for Reconstruction and Development), Dries Acke, Tom Brookes, Pete Harrison, Simon Wolf (European Climate Foundation), Francis Sullivan (HSBC), Inger Kristin Holm, Nina Lillelien, Bjørn Kjetil Mauritzen, Rønnaug Sægrov Mysterud, Berit Sande, Ivar Valstad (Hydro), Ben Murphy, Lee Thornton (IP Group), Isabella Neuweg (London School of Economics), Kieran Coleman, Alastair Dick, Mark Grundy, Ned Harvey, Adam Klauber, James Mitchell, Mike Roeth (Rocky Mountain Institute), Emmanuel Normant (Saint Gobain), Sandrine de Guio, Philippine de T'Serclaes, Emmanuel Laguarrigue, Vincent Petit (Schneider Electric), Jean Cadu, Shantanu Chatterjee, Robert Cooper, Nigel Dickens, Alexandra Ebbinghaus, Katharina Gruenberg, Scott Hartman, Mallika Ishwaran, Greg Kamla, Jean-Paul Lange, Wilfried Maas, Jennifer Reilly, Steve Schofield (Shell), Gabriella Larsson (Statnett), Bertrand Magne (Sustainable Energy For All), Rebecca Brook, Anne-Caroline Duplat, Alessandra Kortenhorst, Janike Reichmann, Deborah McSkimming, Hettie Morrison, Clare Oh (SYSTEMIQ), Abhishek Goyal, Ashok Kumar, Peter Quinn (Tata Sons), Mrinal Mathur, A K Saxena, Girish Sethi, Thomas Spencer (The Energy and Resources Institute), Reid Detchon (United Nations Foundation), Mikael Nordlander (Vattenfall), Murat Isikveren, Kamila Waciega (Veolia), Jennifer Austin, Dean Cambridge, Jennifer Gerholdt, Robin Knight (We Mean Business), Craig Hanson, Karl Hausker, Leo Horn-Phathanothai, Jennifer Layke, Justin Mundy (World Resources Institute)

We also warmly thank the many experts who have taken part in the consultation process on our initial findings:

Patrik Akerman (Siemens), Nils Aldag (Sunfire), Gavin Allwright (International Windship Association), Graham Backhouse (Yara), Rebecca Bell (Scottish Carbon Capture and Storage), Niels Berghout (IEA), Carl Berninghausen (Sunfire), Vishal Bhavsar (One UltraTech), Tord Bjørndal (Statoil), Daniel Boehner (Audi AG), Javier Bonaplata (ArcelorMittal), Martina Bosi (World Bank Group), Jose Botello Martinez (Repsol), Philippe Boulanger (H2V Industry), Robert Boyd (The International Air Transport Association), John Bradshaw (International Chamber of Shipping), Jennifer Brown (Environmental Defense Fund Europe), John Bruce (Carbon Engineering), John Buckingham (BMT Defence Services), Keith Bushell (Airbus), John Bustnes (Swerea), Karl Buttiens (ArcelorMittal), Pierpaolo Cazzola (IEA), Yang Chen (World Bank Group), Johannah Christensen (Global Maritime Forum), Caterina Cilfone (World Economic Forum), Keith Coleman (Feed Algae), Fiona Collin (World Bank Group), Bryan Comer (ICCT), David Connolly (Jorvtega Marine), Dominique Copin (TOTAL), Beverley Cornaby (University of Cambridge Institute for Sustainability Leadership), Stef Cornelis (Transport & Environment), Stephen Cornelius (WWF), Jonathon Counsell (International Airlines Group), Ted Crozier (Climate KIC), Marianne Csaky (Alaska Airlines), Jim Davies (International Airlines Group), Nicholas de Cristofaro (Solidia), Femke De Jong (Carbon Market Watch), Marine d'Elloy (CCS Association), Guillaume de Smedt (Air Liquide), Ben Dixon (SYSTEMIQ), Haldane Dodd (Air Transport Action Group), Karl Downey (CRH), Phil Drew (Brunswick Group), Jill Duggan (University of Cambridge Institute for Sustainability Leadership), Lamberto Eldering (Statoil), Gabriela Elizondo (World Bank Group), Jeffrey Engler (Wright Electric), Geraint Evans (ETI), Emily Farnworth (World Economic Forum), Aurélie Favier (ETH Zurich / EPFL), Tom Fern (Brunswick Group), Araceli Fernandez Pales (IEA), Phillipine Fonta (WBCSD / CSI), Pierre-Etienne Franc (Air Liquide), Sam Friggins (Committee on Climate

Change), Guilhem Gaillarde (MARIN), Miguel Garcia Claro (Bombardier), Steven Gillard (Boeing), Lucy Gilliam (Transport & Environment), Michel Gimenez (Lafarge Holcim), Adam Goff (ClearPath), Arturo Ardila Gomez (World Bank Group), Matt Gorman (Heathrow Airport), John Green (Royal Aeronautical Society), Johan H. de Jong (MARIN), Fredrik Haag (International Maritime Organisation), Guillaume Habert (IBI), Sebastien Harquel (Embraer Foundation), Carrie Harris (International Airlines Group), Jon Hart (Rolls Royce), Karl Hauptmeier (Sunfire), Bill Hemmings (Transport & Environment), Emile Herben (Yara), Cait Hewitt (Aviation Environment Federation), Emily Hickson (B Team), Anne-Claire Howard (Better Coal), Leigh Hudson (British Airways), Edmund Hughes (International Maritime Organization), Kris Hyde (ITM Power), Lars Ingolf Eide (Research Council of Norway), Tom Einar Jenson (SYSTEMIQ), Marte Jerko (Yara), Peter Johansen (World Bank Group), Harald Justnes (SINTEF), Andreas Kammel (Volkswagen Truck & Bus AG), Henry King (Unilever), Stephanie Michelle King (Novozymes), Jan Kjetil Paulsen (Bellona), Jesper Kloverpris (Novozymes), Alan Knight (ArcelorMittal), Bernhard Kohl (Voestalpine), Matthias Komander (MAN), Nicolas Kraus (Hydrogen Europe), Alex Kremer (SYSTEMIQ), Janne Kuivalainen (ABB), Felix Kybart (MAN), Anna Larsson (Wallenius Wilhelmsen Logistics), Luke Law (Sustainable Aviation), Pharoah le Feuvre (IEA), Stefan Lechtenböhmer (Wuppertal Institut), David Lee (Manchester University), Harry Lehmann (German Environment Agency), Johanna Lehne (Chatham House), Yvonne Leung (WBCSD / CSI), Peter Levi (IEA), Erik Lewenhaupt (Stena Line), Tom Lorber (CIFF), Mats Lundberg (Sandvik), Nic Lutsey (ICCT), Atle Lygren (EMC Dev), Madadh Maclaine (ITM Power), Mark Major (SLoCat Partnership), Chris Malins (Cerulogy), Anand Marathe (Mahindra), Beatriz Martinez Romera (University of Copenhagen), John Mastoris (TITAN Cement), Peter Matrai (SYSTEMIQ), David Mazaira Martinez (Repsol), Alan McKinnon (Kühne Logistics University), Joris Melkert (TU Delft Faculty of Aerospace Engineering), Ewa Merchell (Valence Solutions), Christina Mestre (Transport & Environment), Christa Michelet (WWF), Chris Millman (Carnival Coorporation), Russel Mills (CIFF), Theo Mitchell (Bellona), Kjell Moljord (Statoil), Ned Molloy (GSCC Network), Sean Monkman (Carbon Cure), Carlos Monreal (Plastic Energy), Justin Moore (Boeing), Brian Moran (Boeing), Douglas Mulhall (EPEA), Ron Munson (Cogentiv Solutions), Andrew Murphy (Transport & Environment), Ana Musse (Petrobas), David Nelson (CPI), Robert Niven (Carbon Cure), Peter Nuttall (University of South Pacific), Carlos Ocampo (Novozymes), Manuela Ojan (Heidelberg Cement), Aoife O'Leary (Environmental Defense Fund Europe), Justin Ong (ClearPath), Gerard Ostheimer (WBCSD), Kahina Oudjehani (Bombardier), John Page (The Brookings Institute), Katharine Palmer (Lloyd's Register), Doug Parr (Greenpeace UK), Nikita Pavlenko (ICCT), Karl Peet (SLoCat Partnership), Hermann Pengg (Audi AG), Kelsey Perlman (Carbon Market Watch), Cedric Philibert (IEA), Brendan Pierpont (CPI), Nikoleta Piperidou (Synnogy), Janez Potočnik (SYSTEMIQ), Emma Price-Thomas (ArcelorMittal), Aliette Quint (Air Liquide), Henk Reimink (World Steel Association), Alastair Rennie (Yoenergy), Felipe Rodriguez (ICCT), Nils Rökke (SINTEF), Vladimir Ronin (EMC Dev), Joyashree Roy (IPCC Report), Esha Sar (WBCSD / CSI), Ashok Sarkar (World Bank Group), Brad Schallert (WWF), Michael Scharpf (Lafarge Holcim), Noah Schlosser (SunFire), Charles E. Schlumberger (World Bank Group), Renske Schuitmaker (IEA), Tom Schuler (Solidia), Karen Scrivener (EPFL), Stephanie Searle (ICCT), Aniruddha Sharma (Carbon Clean Solutions), Yoni Shiran (SYSTEMIQ), Volker Sick (CO_2 Sciences/ University of Michigan), Christoph Sievering (Covestro), Bjørn Simonsen (NelHydrogen), Ottar Skagen (Statoil), Irena Spazzapan (SYSTEMIQ), David Stangelo (Carbon Engineering), Claus Stig Pedersen (Novozymes), Sigmund Størset (SINTEF), Tom Strang (Carnival Coorporation), Peter Styring (University of Sheffield), Trude Sundset (Gassnova), Brian Sweeney (Calix), Ruma Tavorath (World Bank Group), Russell Tew (Borealis), Rachel Thompson (Gatwick Airport), Chris Thorne (Energy Technologies Institute), Alysia Tofflemire (Boeing), Alexander Tremel (Siemens), Ernesto Sanchez Triana (World Bank Group), John Vanderley (University of São Paulo), Patricia Vangheluwe (Plastics Europe), Gabrielle Walker (Valence Solutions), Nicholas Walters (World Steel Association), Luke Warren (CCS Association), Sheila Watson (FIA Foundation), Matthew Wenban-Smith (ResponsibleSteel), Keith Whiriskey (Bellona), Eliot Whittington (University of Cambridge, Institute for Sustainability Leadership), Benjamin Wickert (Siemens), Daniel Williams, Jorn Paul Winkler (THIIINK), Charlotte Wolff-Bye (Statoil), Alex Zapantis (GCCSI)

www.energy-transitions.org