# MISSION POSSIBLE

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

ENERGY TRANSITIONS COMMISSION

## REPORT SUMMARY

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## REPORT SUMMARY

## 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**
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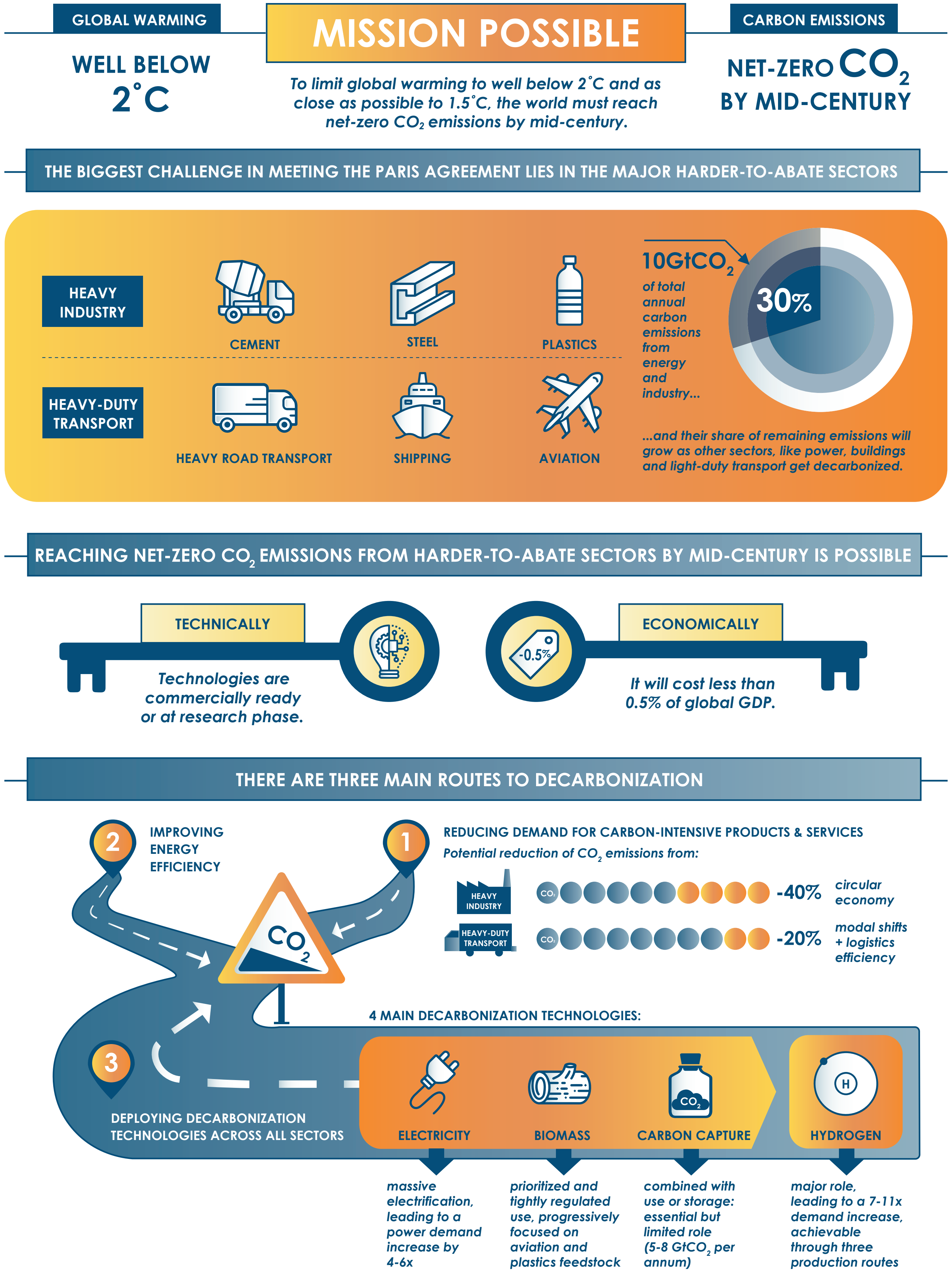



The Paris climate agreement committed the world to **limit global warming to well below 2°C and keep it as close as possible to 1.5°C above preindustrial levels.** The latest IPCC report[1] has warned the world of the major negative impacts on humanity and the planet of a rise in global temperatures 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.8);
B. How to manage the transition to net-zero $CO_2$ emissions in heavy industry and heavy-duty transport (p.20);
C. What policymakers, investors, businesses and consumers must do to accelerate change (p.24).

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 15.
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.
- **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.

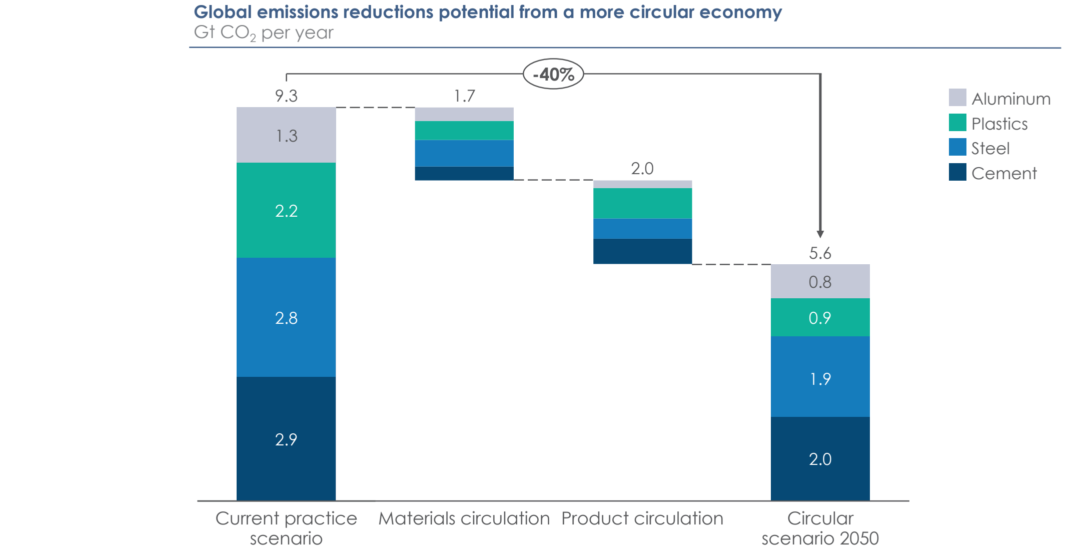
### Decarbonization technologies

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].

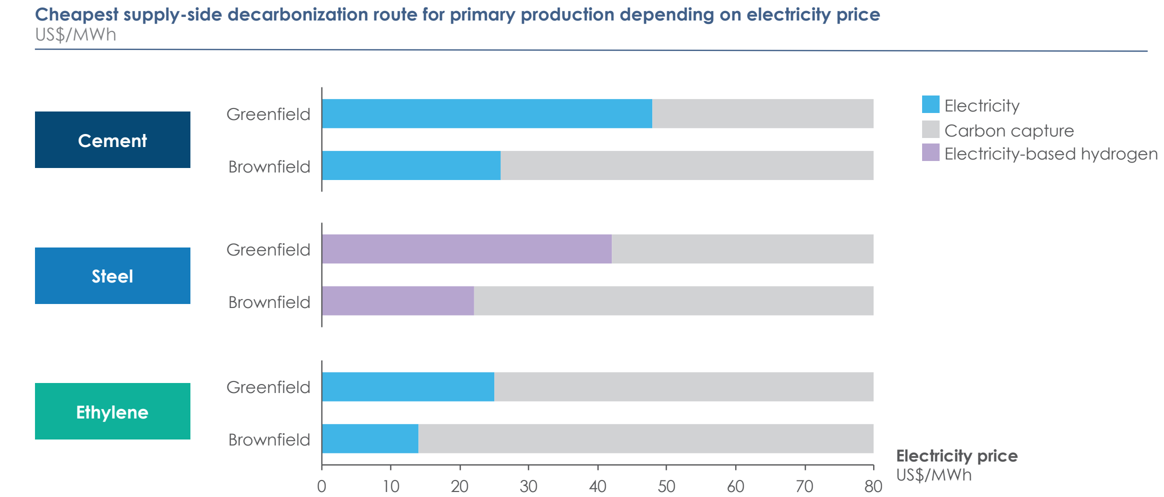
**A more circular economy can cut emissions from the harder-to-abate sectors in industry by 40% by 2050**




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

**Exhibit 1**

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




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 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)

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

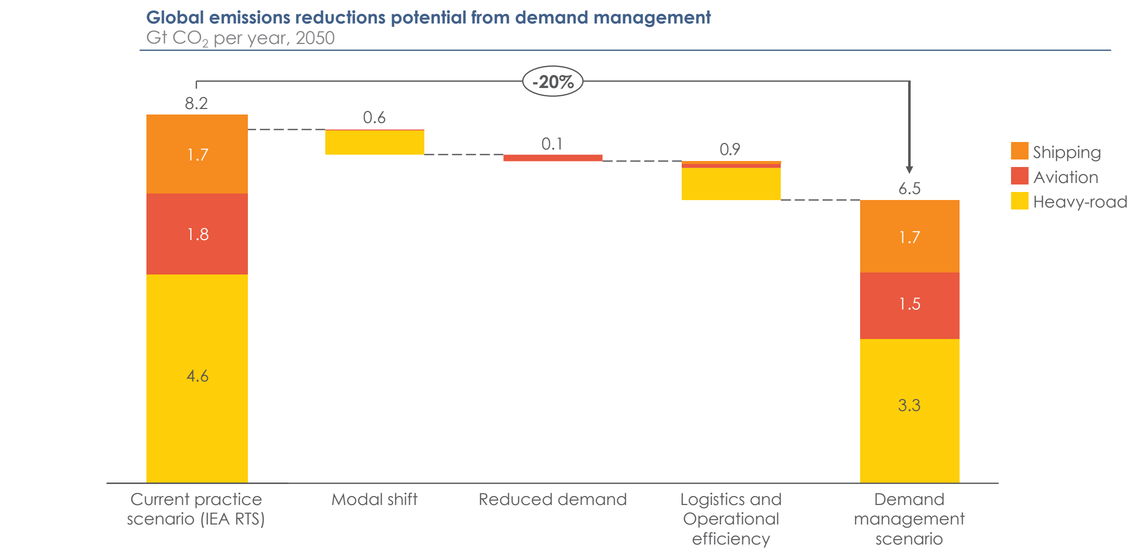
There are significant opportunities to **improve energy efficiency by 35-40% in the transport sectors** without radical changes in technology, and potentially more with technology breakthroughs. This potential will be particularly important in shipping and aviation, given the long lifetime of planes 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].

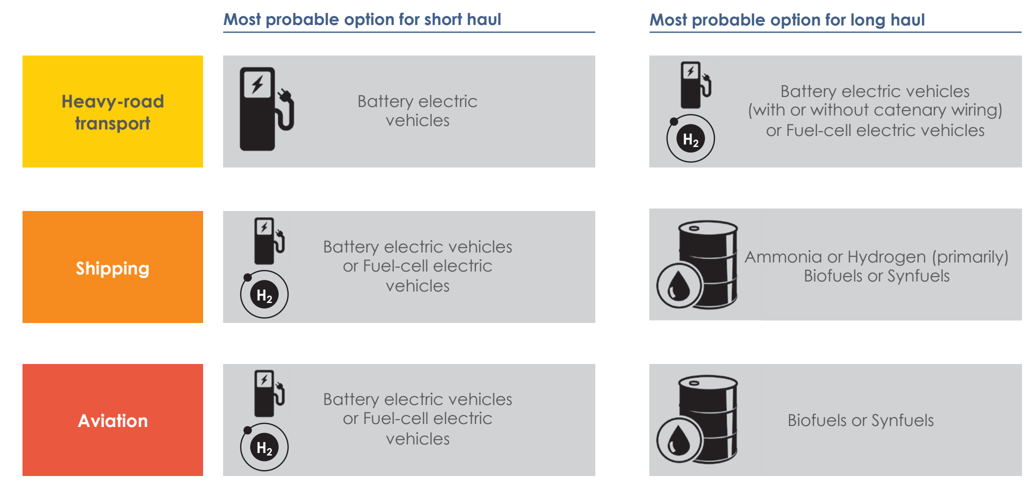
Even with these costs, and even if demand grows in line with business as usual forecasts, the maximum additional cost of decarbonized heavy industry and heavy-duty transport would only be **0.5% of global GDP by mid-century** [Exhibit 6]. The cost of running a net-zero-$CO_2$-emissions economy would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




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.

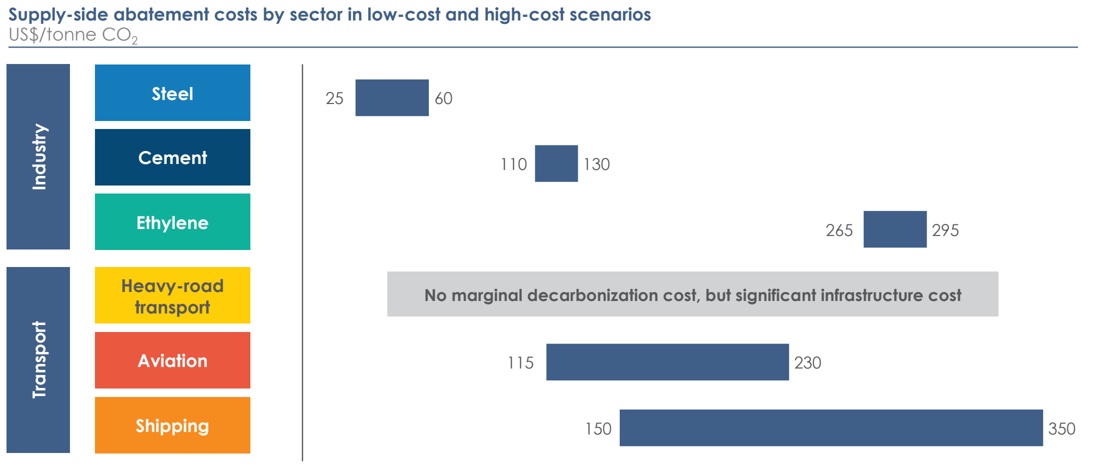
- **Demand management:** Greater recycling and reuse of materials within a more circular economy, combined with logistics efficiency and modal shifts in transport sectors, could reduce the decarbonization costs for harder-to-abate sectors by 40-45%, bringing them down to 0.15-0.25% of global GDP.
- **Future 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




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**

### 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].

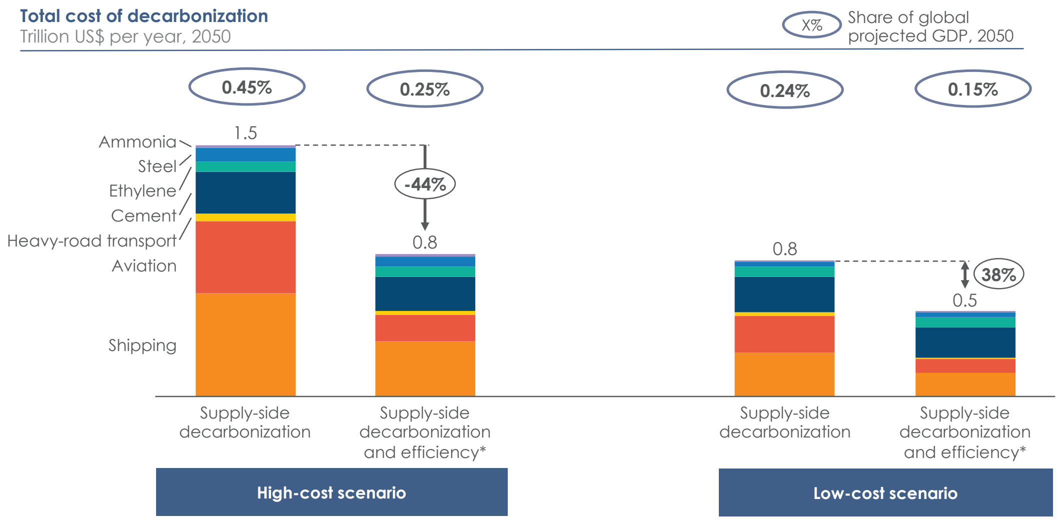
### Key implications for policymakers:

- 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**

13 McKinsey and Company (2018), *Decarbonization of the industrial sectors: the next frontier*
14 European Environment Agency (2018)

**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.
- **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.

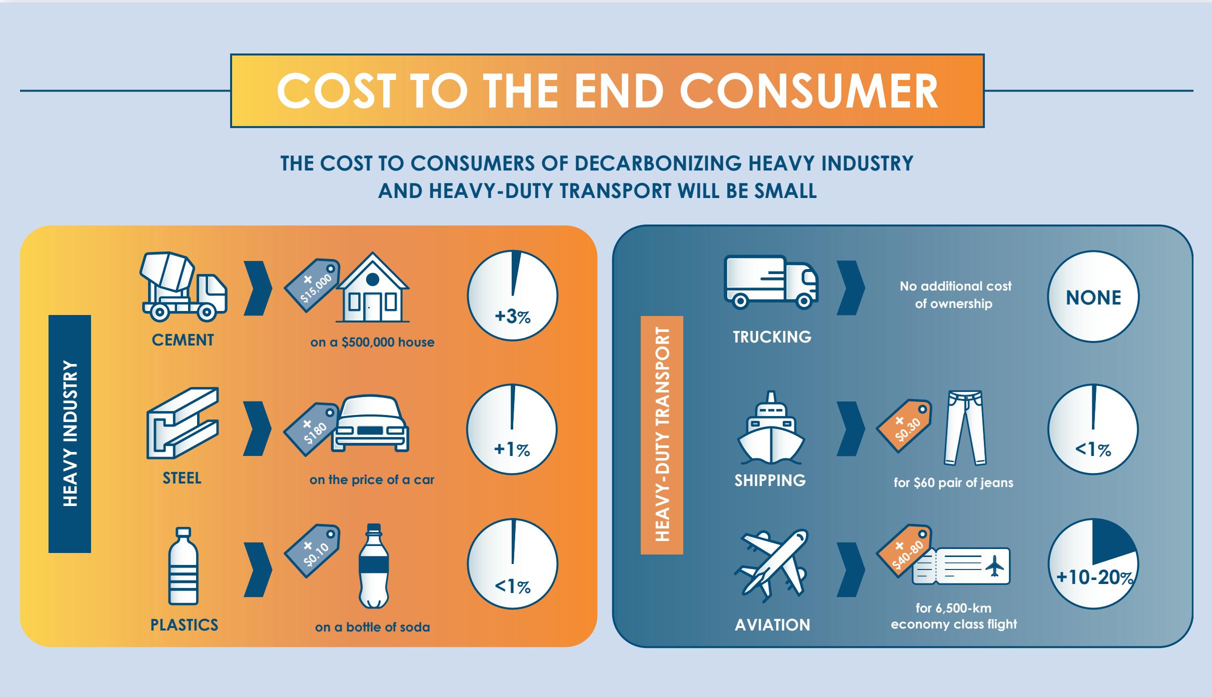



Exhibit 7

**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%) |
| Industry | Steel | +$120 per tonne of steel | +20% |
| Industry | Plastics | +$500 per tonne of ethylene | +50%* |
| Transport | Heavy road transport | No price impact | None |
| Transport | Shipping | +$4 million on typical bulk carrier voyage cost per annum | +110% |
| Transport | 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 750g$CO_2$ 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 1000g$CO_2$ 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 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 could 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).

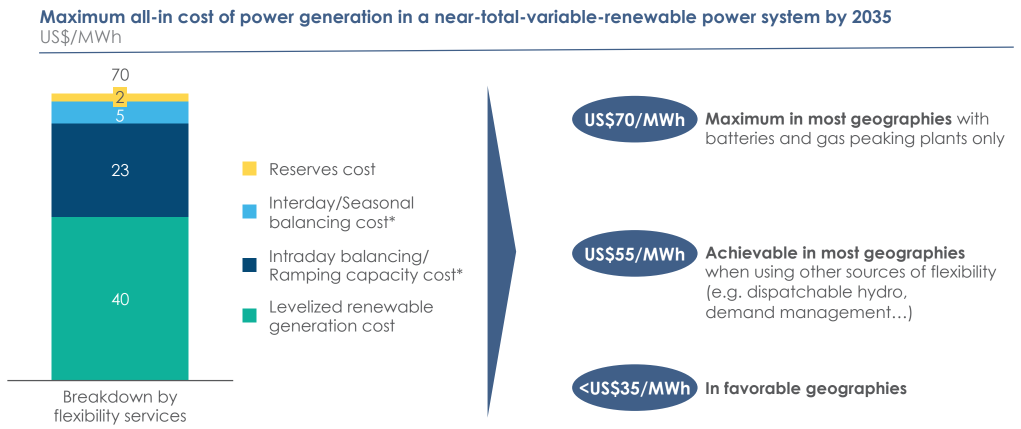
The key uncertainties relate to the supply of lignocellulosic material which could be sustainably harvested from forest crops (through a large-scale reforestation program, focused on degraded land in tropical countries), as well as to the availability of winter cover crops and algae-based products. Several 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.

**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.

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:

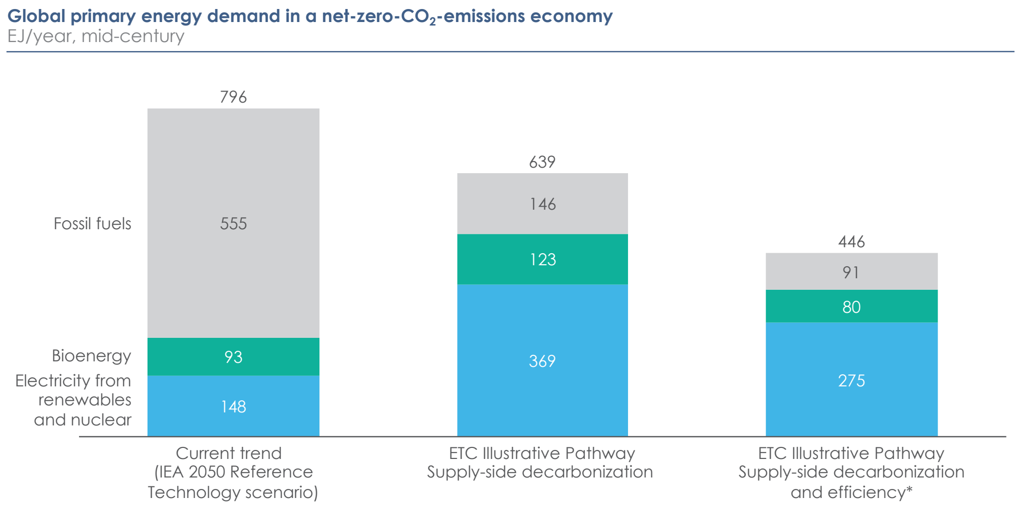
- Tight regulations on biomass sustainability are vital. This will likely exclude energy crops, which often compete with agriculture and ecosystem services, with some local exceptions like winter cover crops in temperate climates.
- The development and cost reduction of truly sustainable bio jet fuels 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 scale 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 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.

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.

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.

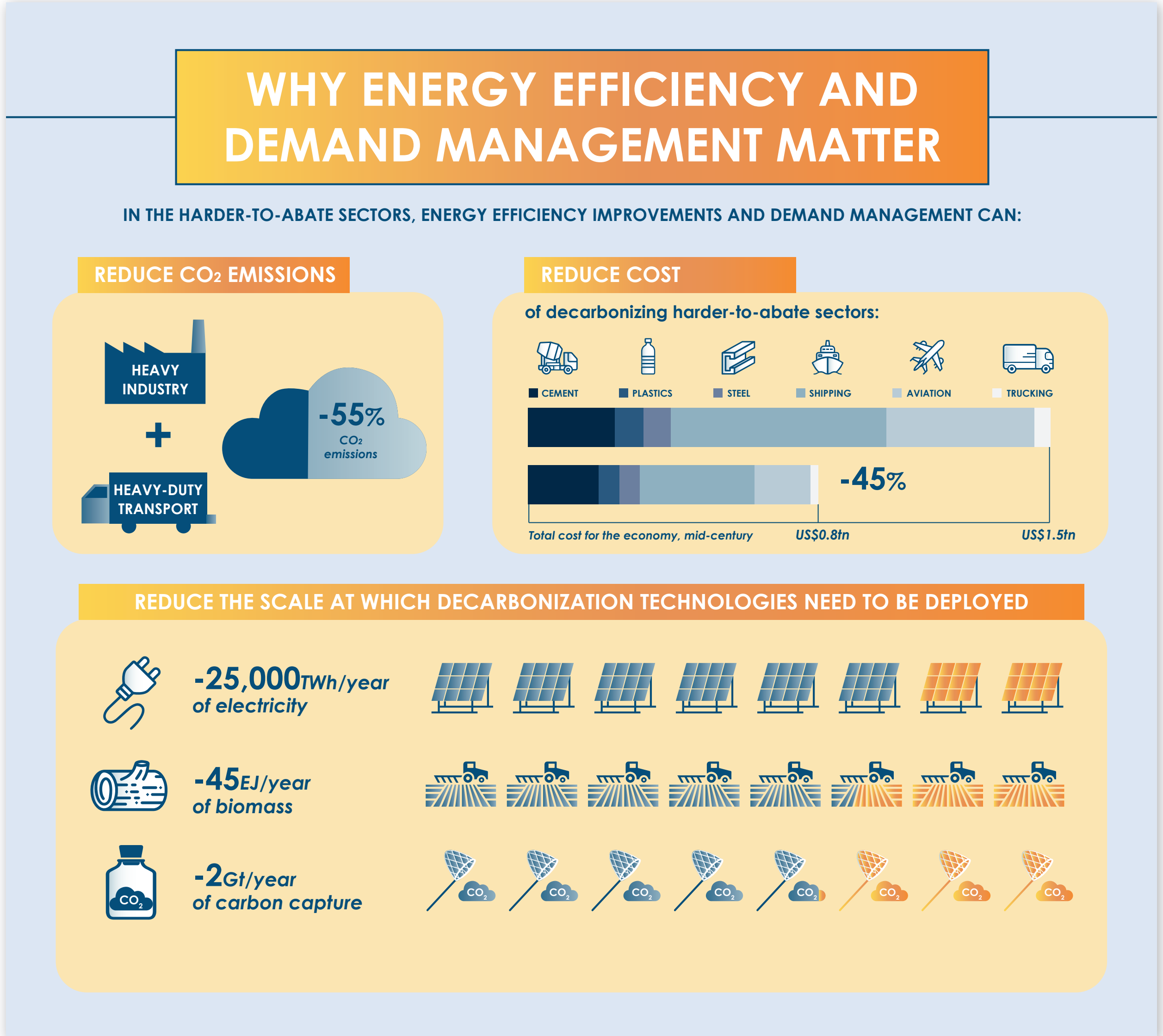



Exhibit 11

# 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).

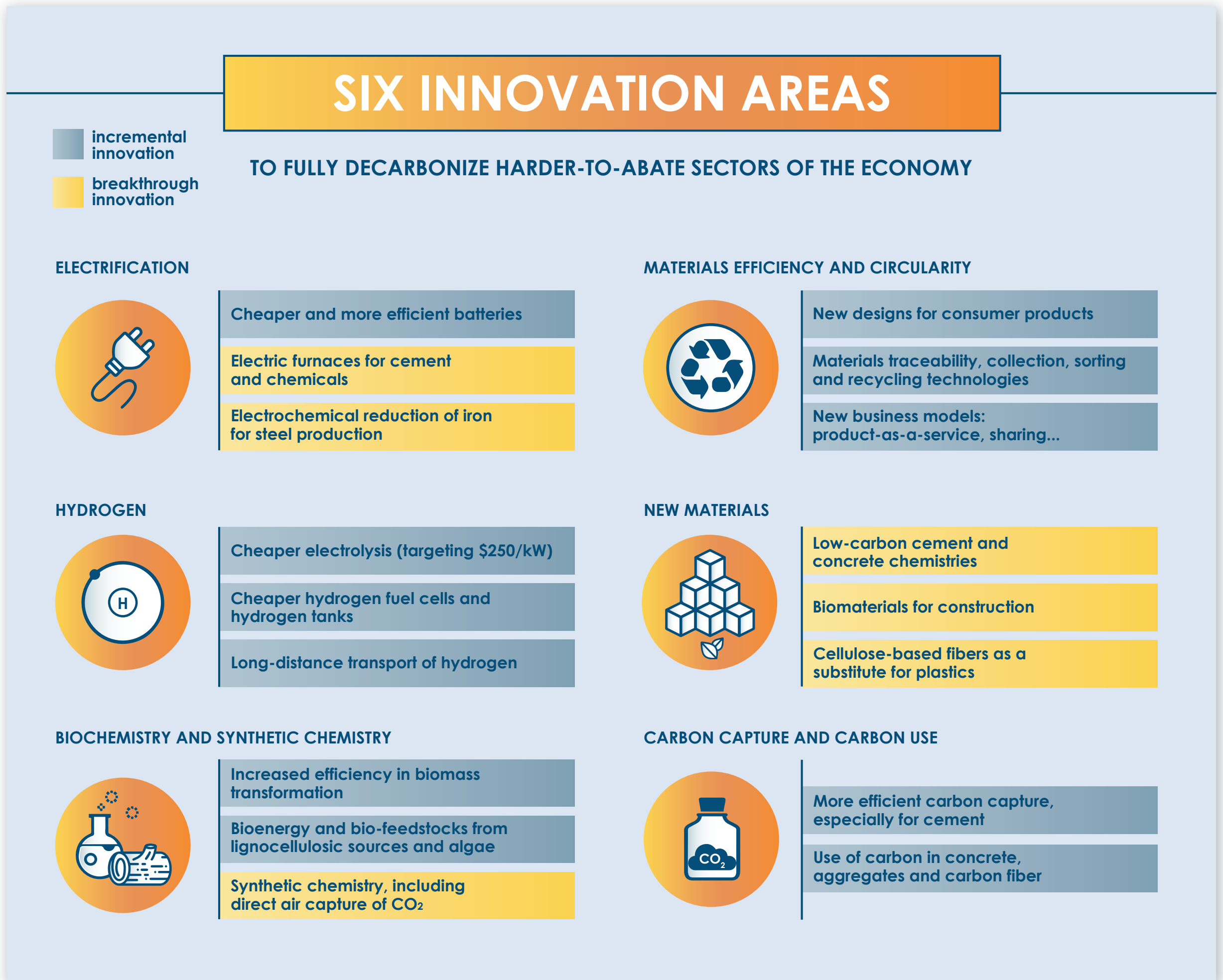



Exhibit 12

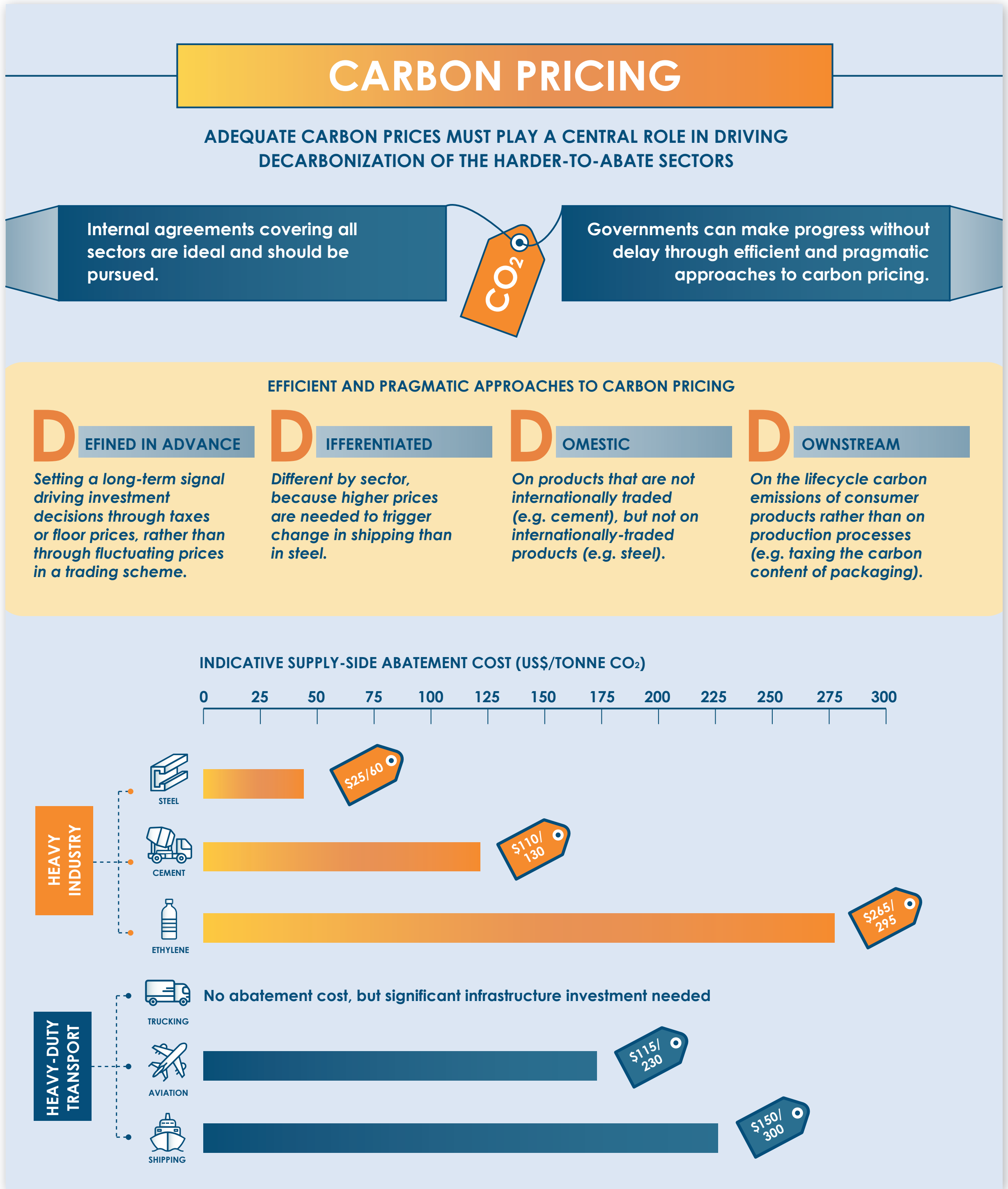



Exhibit 13

### 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 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).

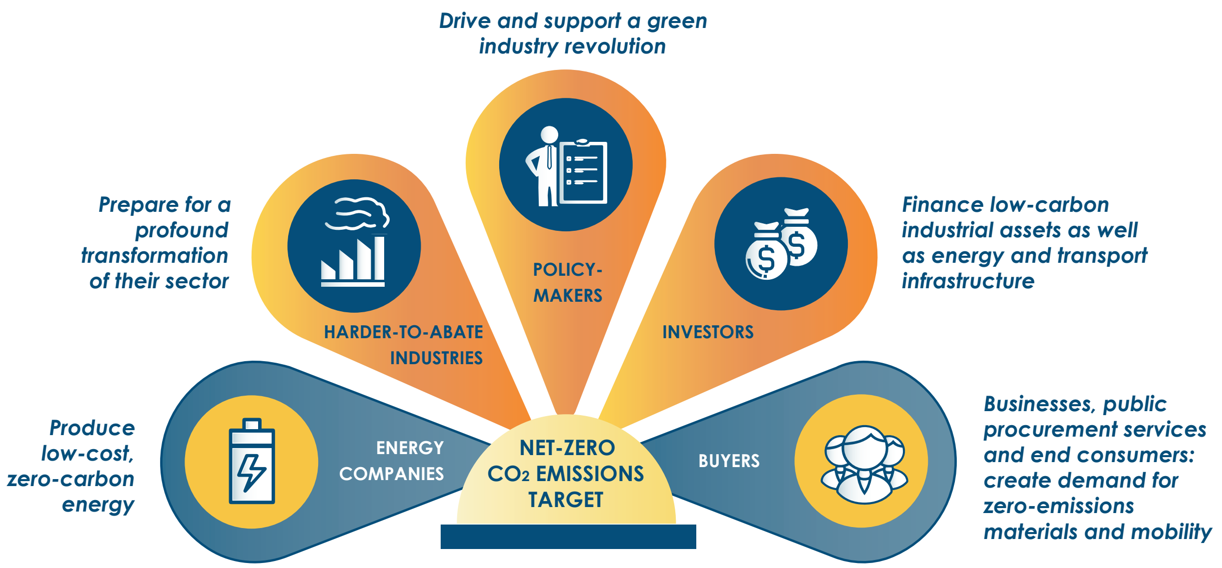
## WINNING THE CLIMATE WAR

**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




| 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.* |

www.energy-transitions.org