Executive Summary

Making Mission Possible

Delivering a Net-Zero Economy

September 2020

Version 1.0

Energy Transitions Commission

Making Mission Possible

Delivering a Net-Zero Economy

The Energy Transitions Commission (ETC) is a coalition of global leaders from across the energy landscape: energy producers, energy-intensive industries, equipment providers, finance players and environmental NGOs. Our mission is to work out how to build a global economy which can both enable developing countries to attain developed world standards of living and ensure that the world limits global warming to well below 2°C and as close as possible to 1.5°C. For this objective to be reached, the world needs to achieve net-zero GHG emissions by around mid-century.

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

The Making Mission Possible report was developed by the Commissioners with the support of the ETC Secretariat, provided by SYSTEMIQ. It brings together and builds on past ETC publications, developed in close consultation with hundreds of experts from companies, industry initiatives, international organisations, non-governmental organisations and academia. The report draws upon analyses carried out by Climate Policy Initiative, Copenhagen Economics, Material Economics, McKinsey & Company, Rocky Mountain Institute, The Energy and Resources Institute, University Maritime Advisory Services, Vivid Economics and SYSTEMIQ for and in partnership with the ETC, as well as a broader literature review. We reference in particular analyses from the International Energy Agency and BloombergNEF. We warmly thank our knowledge partners and contributors for their inputs.

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 organisations 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.linkedin.com/company/energy-transitions-commission
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A prosperous net-zero-emissions economy by mid-century is Mission Possible

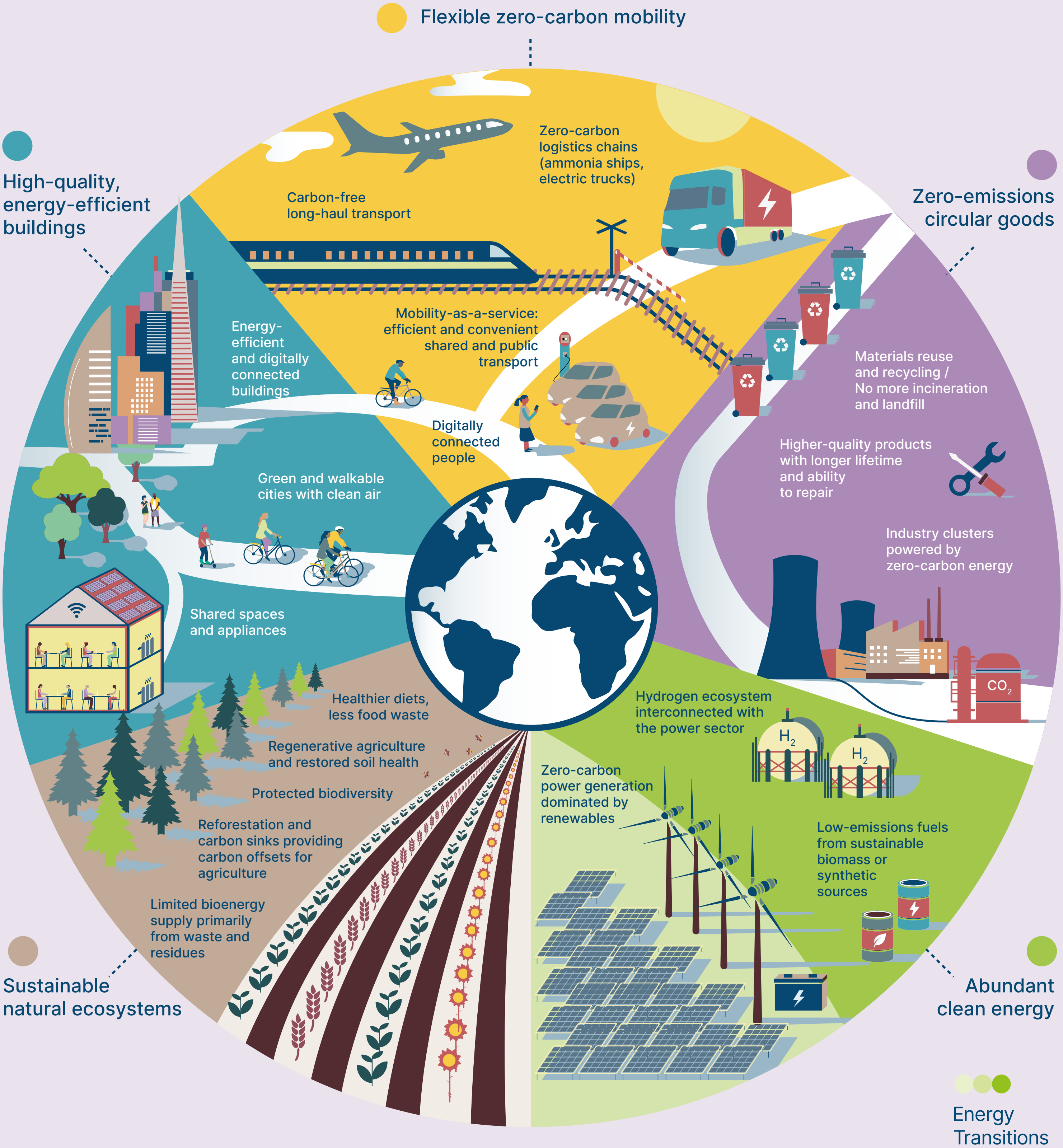
High-quality, energy-efficient buildings

Flexible zero-carbon mobility

Zero-emissions circular goods

Abundant clean energy

Sustainable natural ecosystems



Energy Transitions Commission

The **Energy Transitions Commission** (ETC) is a coalition of global leaders from across the energy landscape: energy producers, energy-intensive industries, equipment providers, finance players and environmental NGOs. Our mission is to work out how to build a global economy which can both enable developing countries to attain developed world standards of living and ensure that the world limits global warming to well below 2°C and as close as possible to 1.5°C. For this objective to be reached, the world needs to achieve net-zero GHG emissions by around mid-century.

Over the last four years, the ETC has issued several reports addressing different dimensions of the decarbonisation challenge, focusing either on specific sectors (eg, the power sector in *Better Energy, Greater Prosperity*[1] and the harder-to-abate sectors in *Mission Possible*[2]), or highlighting the regional challenges and opportunities through our Indian and Chinese publications[3].

The overall conclusion from these reports is clear. **It is undoubtedly technically and economically possible to achieve net-zero GHG emissions by around mid-century**, without relying on the permanent and significant use of offsets from afforestation, other forms of land-use change or negative emissions technologies:

- **Technically**: Technologies and business solutions to do so are either already available or close to being brought to market.

- **Economically**: The reduction in conventionally measured living standards in 2050 will be at most 0.5% and is thus trivial compared to the major adverse consequences that unmitigated climate change would trigger by 2050.

Reaching net-zero GHG emissions implies **a profound transformation of our energy system**. Unabated use of fossil fuels – which currently represent more than 80% of primary energy demand – must be phased out, with clean electricity becoming the predominant energy vector, complemented by hydrogen, some limited sustainable biomass and limited use of fossil fuels, combined with carbon capture and storage or use (CCS/U). This will entail a shift to new products, business models and consumption patterns across all sectors of the economy; and will require careful management of the employment and income consequences.

This reconfiguration of the global energy system will generate important benefits. The transition to zero emissions will drive innovation and economic growth, and create new jobs. It will improve living standards – particularly in developing economies – through reduced local air pollution and related health impact; lower energy bills for households, thanks to cheap electricity and more efficient buildings; provide more flexible mobility services; and produce higher-quality, more durable consumer goods.

This report is published in an unprecedented context: the COVID-19 pandemic has brought the world to a standstill, provoking an abrupt fall in GDP and in international trade, and demonstrating the unpreparedness of the global economy to systemic risks, despite early warnings from scientists. While the first priority is to protect populations and urgently reinforce healthcare systems, this crisis also demands an economic recovery response focused on the development of a more resilient economy. In this context, this report provides governments and private sector leaders with a vision of how to invest in the economy of the future and **build a healthier, more resilient, net-zero economy**. In addition, the ETC has published two reports setting out the specific actions which governments can take to drive sustainable recovery from the current crisis[4].

In essence, the ETC is convinced that the developed world should reach net-zero GHG emissions by 2050 and the developing world by 2060 at the latest. **This report explains why we are confident that this is feasible, how to achieve the transition and what steps need to be taken in the 2020s to put the world on the right trajectory** – integrating the findings from our previous publications, and updating our analysis to reflect the latest trends in the readiness and cost of key technologies. It describes in turn:

I

The steps to build a zero-carbon-emissions economy by mid-century

II

The costs, investments and related challenges of the transition towards net-zero emissions

III

Regional differences, challenges and opportunities

IV

The actions required now to put 2050 targets within reach

1. Energy Transitions Commission (2017), *Greater Energy – Better Prosperity*
2. Energy Transitions Commission (2018), *Mission Possible*
3. Energy Transitions Commission and Rocky Mountain Institute (2019), China 2050: *A Fully Developed Rich Zero-Carbon Economy* and Spencer, T. and Awasthy, A. (2019), TERI, *Analysing and Projecting Indian Electricity Demand to 2030*. Pachouri, R., Spencer, T., and Renjith, G., TERI (2019), *Exploring Electricity Supply-Mix Scenarios to 2030*, and Udetanshi, Pierpont, B., Khurana, S. and Nelson, D., TERI (2019), *Developing a roadmap to a flexible, low-carbon Indian electricity system: interim findings*
4. ETC and Rocky Mountain Institute (2020), *Achieving a Green Recovery for China: Putting Zero-Carbon Electrification at the Core; and ETC (2020), 7 Priorities to Help The Global Economy Recover.*

Reaching net-zero emissions is technically and economically feasible

Technologies needed to fully decarbonise each sector with no offsets are known or in development

Full decarbonisation will cost less than 0.5% of global GDP

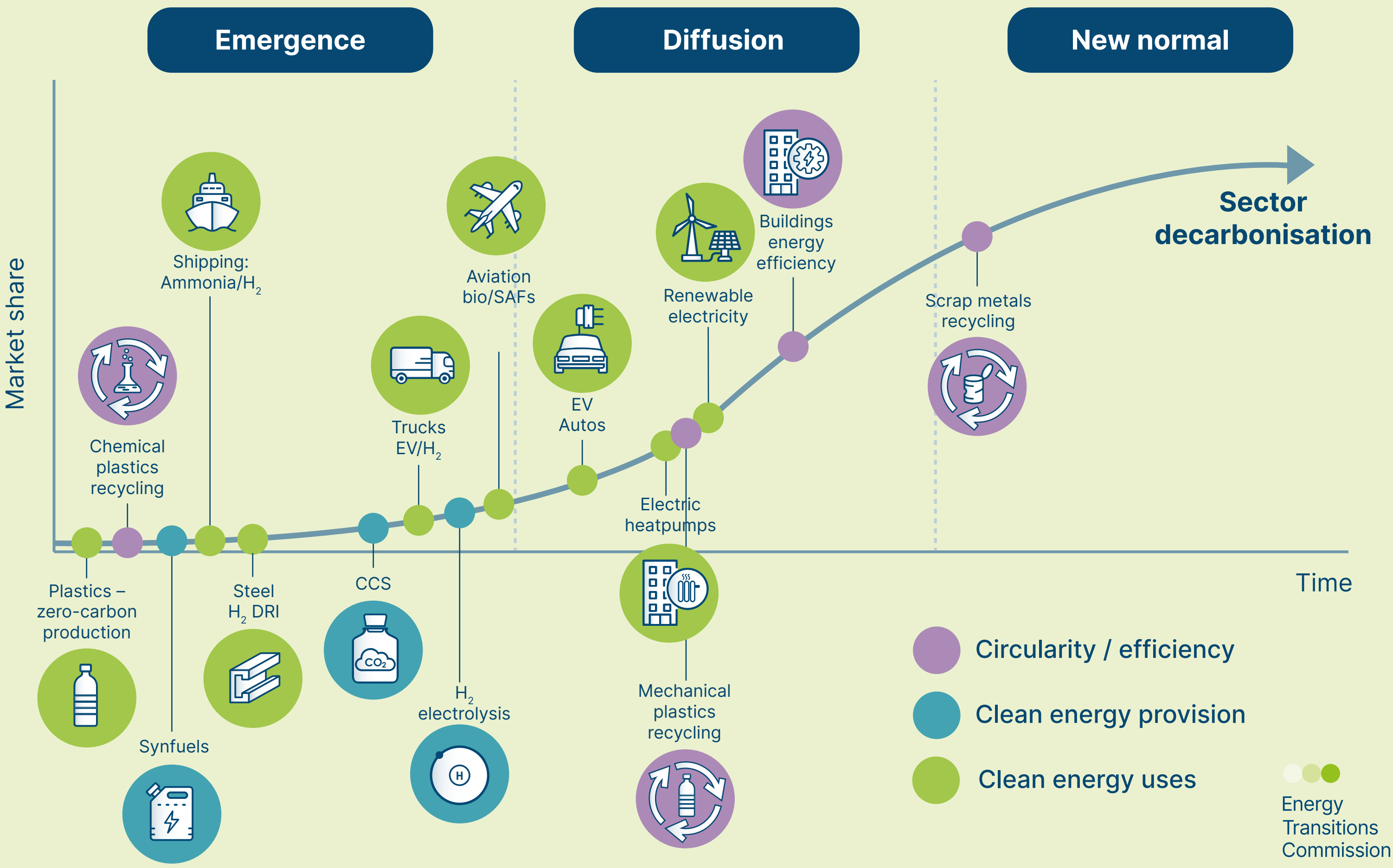
3 steps to a net-zero-emissions economy

3 Use clean energy everywhere
- Drive **massive clean electrification** of buildings, transport and industry
- Use **hydrogen** where you can't electrify
- Decarbonise remaining energy use using **CCS/U and sustainable bioenergy**

2 Scale up clean energy provision
- Multiply by 10-15 **zero-carbon electricity generation**
- Scale up zero-carbon **hydrogen production** to reach 700-1,000 Mt p.a.
- Build **biofuel and synthetic fuel supply chains**

1 Use less energy
- Deploy **more efficient** equipment, transport modes & production processes
- Use **less primary material input** to deliver the same goods
- **Change consumption patterns using fewer products and services** to achieve same living standards

The journey of zero-emissions solutions



Energy Transitions Commission

I. A zero-carbon-emissions economy by mid-century is Mission Possible: three steps to build a net-zero emissions economy

It is technically possible to decarbonise the economy by mid-century, at a total cost of less than 0.5% of global GDP, by taking three steps:

1

Using less energy:

Achieving dramatic improvements in energy productivity.

2

Scaling up clean energy provision:

Building massive generation capacities of cheap clean electricity and zero-carbon energy sources.

3

Using clean energy everywhere:

Decarbonising energy use in all sectors of the economy by shifting to new technologies and processes that use clean energy instead of unabated fossil fuels (clean electricity, zero-carbon hydrogen, sustainable bioenergy, electricity-based fuels and carbon capture).

Using less energy

There are major opportunities to improve the energy productivity by which we turn energy inputs into welfare-enhancing goods and services, reducing energy use while maintaining or even improving living standards. These opportunities lie in three areas [Exhibit A]:

- **Energy efficiency:** Technical energy efficiency can still be improved across multiple applications in, for instance, transport (eg, more efficient aircraft), industry (eg, reduced energy inputs to traditional blast furnace-based steel production) and buildings (eg, better insulation and higher coefficient of performance in air-conditioning systems). Improvements of up 50% are theoretically possible in the transport sectors; while in industry, more modest but still significant improvements of 10% 20% could be achieved.

- **Material efficiency:** There are major opportunities to reduce the primary production of energy-intensive materials, such as steel and cement, through product redesign, more efficient material use and greater materials recycling and reuse. In theory, such measures could reduce global emissions from heavy industrial sectors by 40% below business-as-usual level.

- **Service efficiency:** Finally, it is possible to deliver higher living standards while using less energy-intensive goods and services – for example, via better urban design or shared use models in transport. Here the potential depends on consumer behaviour changes and is therefore more speculative; but in principle, major reductions could be achieved.

Seizing these opportunities will require major changes to business value chains (eg, in product design, distribution and recycling processes), and in consumption and lifestyle choices (eg, in urban design and mobility systems).

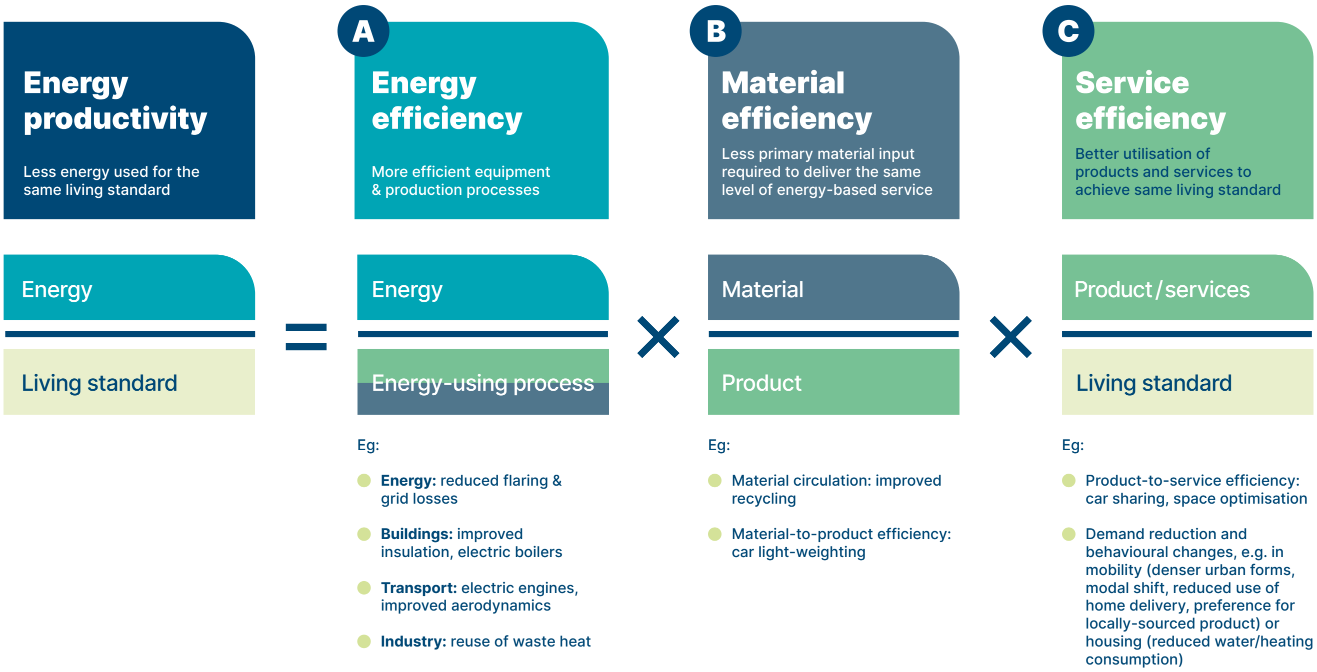
The total amount of final energy needed to support high living standards will also be strongly influenced by **how far we can electrify economic activities** across each sector of the economy. This reflects the inherent efficiency advantage of electricity in several applications – in particular, road transport and building heating.

Finally, **digital technologies** have the potential to significantly contribute to these opportunities by offering both end-use and system efficiency benefits: they can facilitate reductions in energy use in many sectors, from construction to manufacturing (eg, 3D printing, lightweighting); better monitoring of and automated responses to efficiency losses across sectors (eg, industrial energy efficiency monitoring, load management in logistics); and enhanced energy demand monitoring and management at the energy system level (eg, vehicle-to-grid, building heating management).

Taken together, the potential to reduce energy needs, and thus to reduce the costs of the energy transition, is significant: **energy demand could be up to 15% lower by mid-century than it is today** without compromising improvements in living standards in developing economies. If all theoretically available opportunities to improve energy productivity were seized, the investment required to scale up clean energy provision could be greatly reduced. In particular, the investments required in clean power provision could be reduced by 25% compared with a case with limited energy productivity improvement.

Exhibit A

The three dimensions of energy productivity



SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2019), based on Material Economics (2018), *The Circular Economy: a Powerful Force for Climate Change*

Scaling up clean energy provision

Decarbonisation requires a major shift from carbon-intensive fossil fuels to clean energy. **Direct electrification will be the primary route to decarbonisation**, since it is the cheapest and most energy-efficient option in most applications, so **scaling up zero-carbon electricity provision is thus the most important priority**.

However, in some applications, this is not currently feasible; while in others, it is not cost effective. Therefore, total decarbonisation of all sectors of the economy will also require **three additional technologies**:

Hydrogen – an energy carrier whose energy density, storability and suitability for high-heat applications make it superior to electricity in some specific applications. Low or zero-carbon hydrogen can be produced through electrolysis ("green hydrogen") or derived from methane combined with CCS ("blue hydrogen"). Hydrogen can in turn be used to produce hydrogen-based fuels (eg, ammonia and synfuels).

CCS – which, aside from its potential use in making blue hydrogen, can also be applied to multiple industrial processes, and to thermal power plants that continue to provide flexible power supply within primarily renewable power systems. Its cost-effective use will depend on local availability of suitable and safe storage capacity.

Biomass – which in principle can meet a wide variety of applications, including industrial heat, chemical feedstock, flexible thermal power supply and transport fuels; but the total scale of its use across all sectors must reflect the limited potential supply of truly sustainable biomass[5].

It is not possible to forecast precisely what the global energy mix will be in a zero-carbon emissions economy. But all feasible scenarios for a zero-carbon emissions economy involve **a massively expanded role for direct electricity use** (reaching 65% to 70% of final energy demand, versus 19% today), and **a very significant expansion of the role of hydrogen** (accounting for another 15% to 20% of final energy demand, with an increasing proportion produced from electrolysis).

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

As a result, annual global electricity supply will have to grow four to five times to reach ~90-115,000 terawatt-hours (TWh) [Exhibit B], with all of this electricity to be produced in a zero-carbon fashion. Achieving this will require a rapid ramp-up of renewable power investment: over the next 30 years, the average annual pace of wind and solar capacity increases will need to be about five to six times the increase achieved in 2019.

This massive deployment of zero-carbon power will be cost effective: in many countries, **renewable electricity costs are already below total costs of new coal or gas plants and in some cases below the marginal cost of existing thermal plants**; and as renewable costs continue to fall, their cost advantage will become increasingly significant.

The crucial question is thus no longer the cost of generating renewable electricity, but rather the cost of balancing supply and demand in systems with very high levels of variable renewable supply. But here too, technology and cost trends are making solutions increasingly viable:

- Daily flexibility needs can be met by batteries, whose cost has dropped in recent years and is forecast to reach US$100 per kilowatt-hour (kWh) by 2023. But demand management – in particular, via optimal timing of electric vehicle (EV) charging – could provide a still cheaper solution.

- The crucial issue is how to provide weekly or seasonal balancing in countries where there are major seasonal swings in either supply or demand. But here too, there is a wide range of possible solutions, including seasonal energy storage in hydrogen; dispatchable hydro power; a continued role for thermal power plants (running only a small proportion of annual hours and made zero carbon via either the application of CCS/U to gas generation or the use of sustainable biomass); and the potential to shift demand from both households and industry across time or across locations.

Gross electricity generation will need to reach ~90,000 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

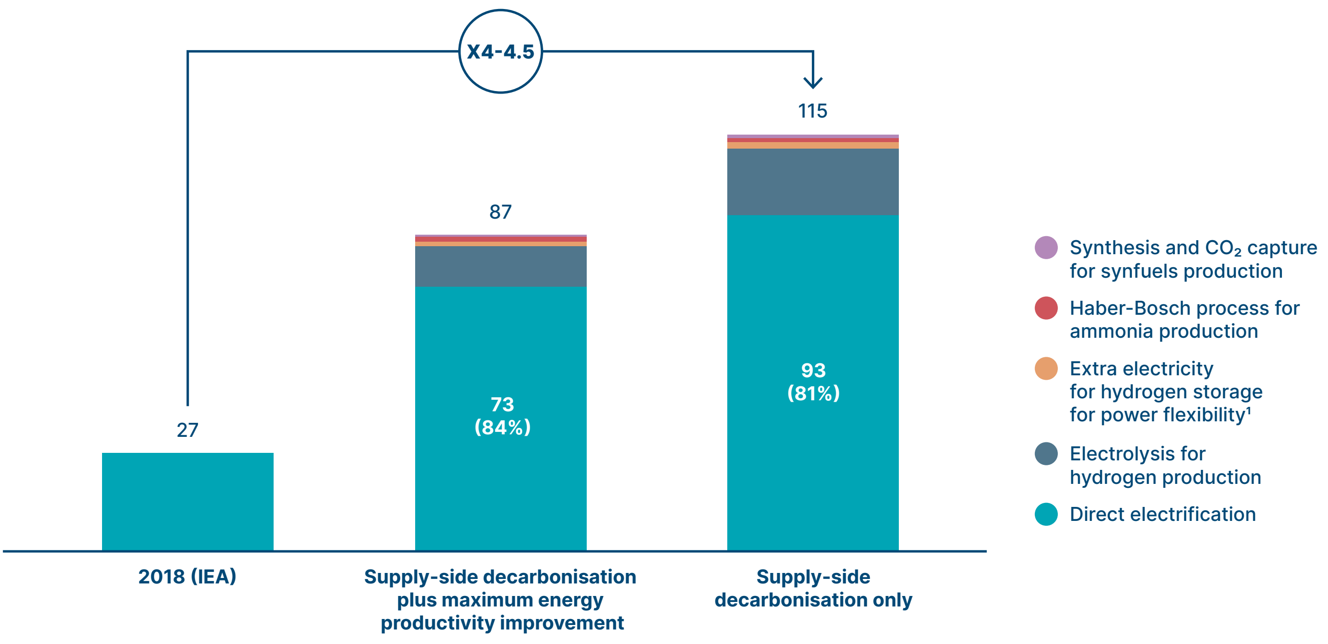


Exhibit B

[1] Extra electricity for hydrogen storage for power flexibility only covers the electricity loss due to the transformation into hydrogen and back to electricity.

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission analysis (2020), IEA (2019), *World Energy Outlook*

As a result, our updated analysis shows that by the mid-2030s at the latest, **it will be possible to run power systems which are as much as 85% dependent on variable renewables at all-in costs (covering all the back-up, storage and flexibility resources required) which will be highly competitive with fossil fuel systems in many locations** and significantly cheaper in some [Exhibit C].

Alongside the dominant role of zero-carbon electricity, however, it is also important to develop the three other technologies on a greatly increased scale. Building a zero-carbon economy by mid-century will require a dramatic acceleration in the pace of investment:

- Total annual **hydrogen production will need to increase from about 60 million tonnes (Mt)** today to 500 to 800 Mt by mid-century to meet the demand for hydrogen, ammonia and synfuels in end-use applications.

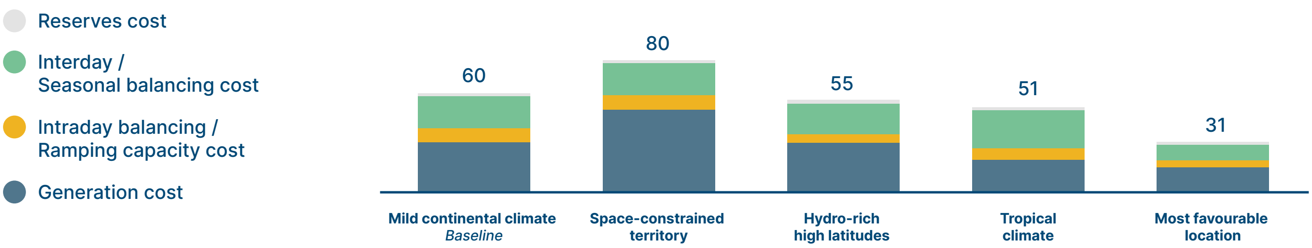
- Around **6 to 9.5 Gt of CO_2 per year of CCS/U** will be needed to make the remaining fossil fuel use near zero carbon, particularly in heavy industry (~40% of total), hydrogen production from methane (~30% or total) and peak power generation (~20% of total).

- **46 to 69 exajoules of energy will need to be derived from bio-feedstocks**, all of which must be delivered in a low-carbon footprint, sustainable fashion, primarily from residual biomass.

Overall, there is no doubt that the world has sufficient natural resources to enable the transition to a zero-carbon economy. There are sufficient land, mineral and water resources to support the massive growth required in green electricity and green hydrogen production. Adequate carbon storage capacity is also likely available globally, though with major differences by region. **The greatest uncertainty relates to the scale of truly sustainable, low-carbon bio-resources**. If use of bio-resources is restricted, this will increase reliance on the electricity, hydrogen and CCS routes, and make it essential to prioritise the use of sustainable biomass in those applications where alternatives are least available.

Local cost of close-to-zero-carbon power will vary depending on climate patterns, natural resources and existing power flexibility infra

Maximum all-in cost of power generation in a near-total-variable-renewable power system by 2035
US$/MWh, breakdown by flexibility services



All archetypes are based on same power demand and have identical reserves costs

	Mild continental climate (Baseline)	Space-constrained territory	Hydro-rich high latitudes	Tropical climate	Most favourable location
Seasonal needs	Strong winter peak Long winter	Identical to baseline	-5% vs. baseline Generation capacity partially covered by existing hydro	-25% vs. baseline Limited seasonality (low latitudes)	-50% vs. baseline Limited seasonality (low latitudes)
Daily needs	Medium: heating needs but complementary wind and sun	Identical to baseline	-41% vs. baseline 80% covered by cheap existing hydro	+20% vs. baseline Long periods with no sun/wind + high air conditioning	-50% vs. baseline Low: mild evenings
Bulk RE generation	Complementary wind and solar	+67% vs. baseline Space availability challenge	Identical to baseline	-33% vs. baseline Abundant wind and solar	-50% vs. baseline Very abundant wind and solar

SOURCE: Adapted from Climate Policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

Exhibit C

Using clean energy everywhere

The four forms of clean energy described above will make it technically possible to reach net-zero emissions by mid-century across all sectors of the economy, with the potential exception of agriculture. In many sectors, direct electrification will dominate, due to its inherent efficiency. In others – in particular, in industry and buildings – a portfolio of solutions exists, and the appropriate decarbonisation route will vary by region depending on local resource availability and prices:

Already electrified sectors – such as household appliances, lighting, cooling, water heating, computing, machinery movement in manufacturing and rail – just have to ensure that the electricity they use is zero carbon.

Surface transport is likely to become electric, in either battery or hydrogen fuel cell electric form, well before 2050 and far faster than many projections suggest, due to the inherent energy efficiency advantage of electric engines. For light-duty vehicles, it is likely that even the upfront capital costs of buying EVs will fall below those for internal combustion engine (ICE) vehicles by the mid-2020s. For medium and heavy-duty vehicles, decarbonisation will likely entail either battery-based electrification or use of hydrogen in fuel cell EVs, with the former dominating for shorter-distance intra-city applications and the latter dominating above some distance.

In the shipping and aviation sectors, battery-based electrification and hydrogen will also play a significant role in short-distance journeys. But the limited energy density of batteries and the low volumetric density of hydrogen may make the use of liquid fuels necessary for long distances for the foreseeable future. These fuels could come from either a low-carbon, sustainable bio-feedstock (eg, alcohols, biofuels) or from a power-to-liquid production route (ammonia in the case of shipping and synfuels in the case of aviation).

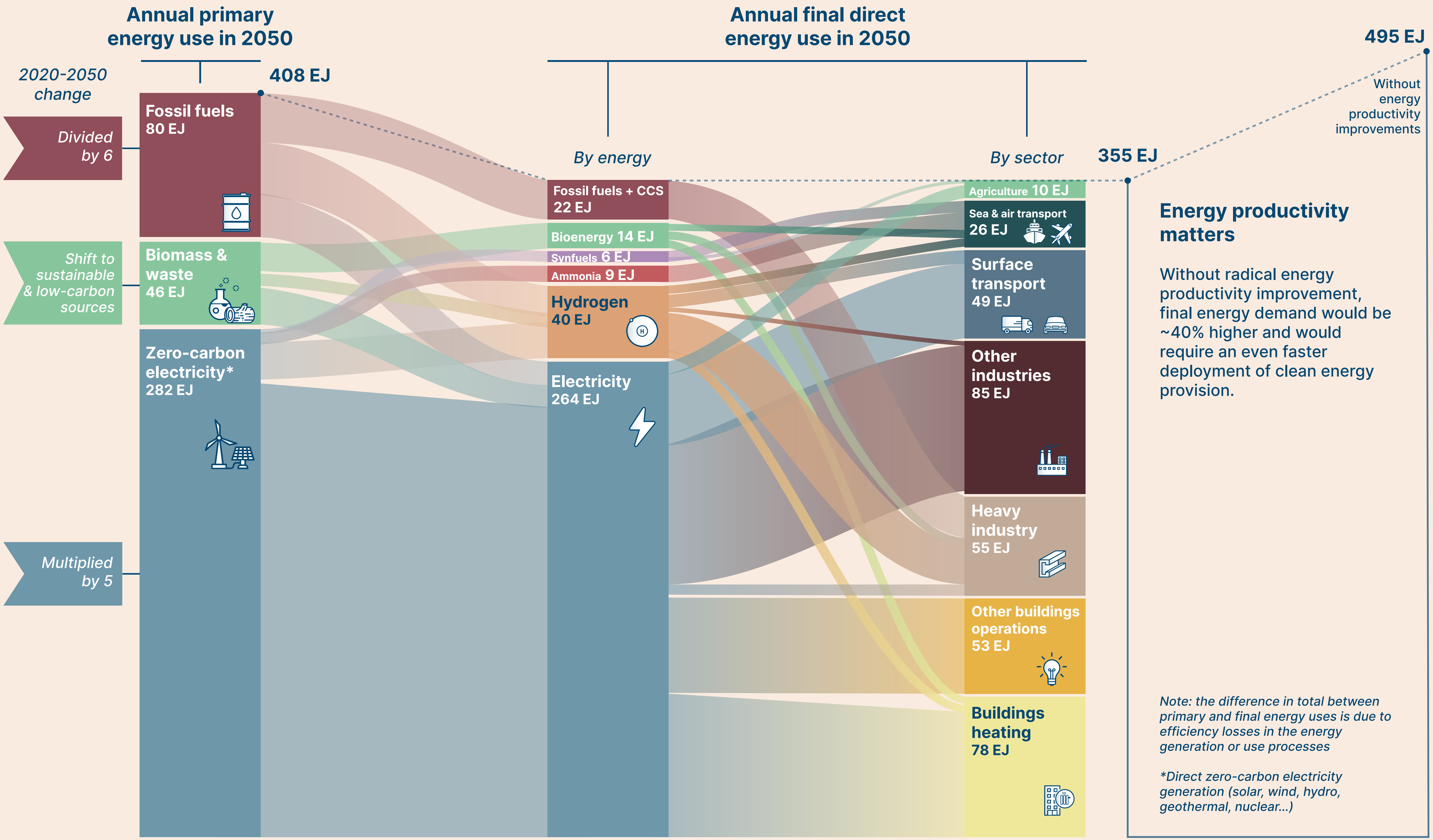
In heavy industry sectors – steel, cement, chemicals and aluminium – a combination of clean energy sources and carbon capture can remove both energy-based emissions and emissions resulting from the chemical processes themselves. The most cost-competitive option is likely to vary by region, and depending on the brownfield or greenfield nature of each site.

Residential and commercial building heating is already electrified in many regions and could be electrified further through the use of electric heat pumps or resistive electric heating. Alternatives include the combustion of hydrogen or bio-methane using existing gas grids and district heating systems. The optimal solution will vary by region, depending on resource availability and existing infrastructure. Better insulation of buildings is particularly important to reduce peak demand and make this fuel switch – in particular, electricity-based options – more manageable from an energy system perspective.

In agriculture, emissions from fossil fuel use can be eliminated by clean electrification or use of e-fuels. However, nitrous oxide and methane emissions from agricultural processes will be more difficult to eliminate. Some supply-side technologies could help to reduce these emissions – in particular, changes in agricultural practices; but major changes in diet will likely also be necessary.

Energy Transitions Commission

A complete transformation of our energy system is required to support a zero-emissions economy



Energy productivity matters

Without radical energy productivity improvement, final energy demand would be ~40% higher and would require an even faster deployment of clean energy provision.

Note: the difference in total between primary and final energy uses is due to efficiency losses in the energy generation or use processes

**Direct zero-carbon electricity generation (solar, wind, hydro, geothermal, nuclear...)*

Implications for fossil fuels use

As a result of these changes, demand for fossil fuels will decline dramatically [Exhibit D]:

Thermal coal use will be almost totally phased out, with the exception of coking coal combined with CCS in steel production and a possible role to produce chemical feedstocks.

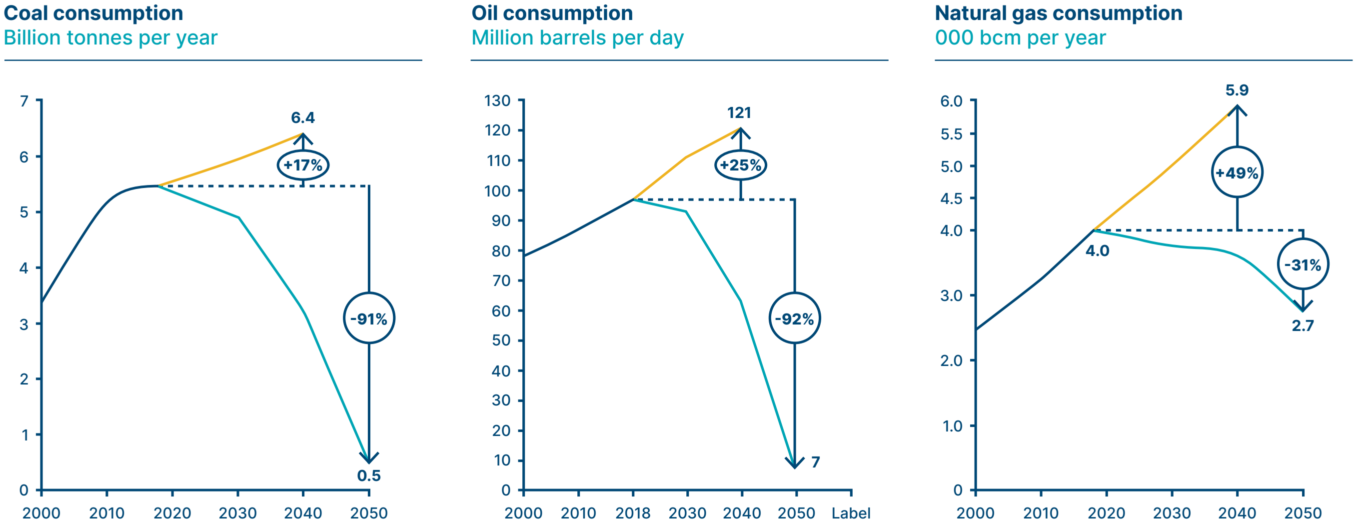
Oil demand could be cut from 100 million barrels per day in 2019 to around 10 million barrels per day by mid-century, with a remaining role as a feedstock for the plastics production process.

Natural gas will have a transitional role in many sectors and locations. However, demand could still decline by ~30% to 57% by mid-century. In transition, its optimal role should reflect the significant warming impact of methane leakage in the natural gas supply chain and the vital need to ensure a subsequent path to decarbonisation through either the retrofitting of CCS/U or a shift to another "green gas", such as biomethane or hydrogen.

Exhibit D

Implications of net-zero decarbonisation for fossil fuel demand

— ETC Scenario – supply side decarbonisation only — IEA Current Policies Scenario



NOTE: ETC scenarios values for 2030 and 2040 are based on the Central Scenario from the Copenhagen Economics paper (reference below)

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2020), IEA (2019), *World Energy Outlook*, Copenhagen Economics (2017), *The future of fossil fuels: How to steer fossil fuel use in a transition to a low-carbon energy system*

Implications for the use of offsets and nature-based solutions

Many models of how to achieve decarbonisation assume some role for "offsets". These could come from three key sources: carbon credits from other carbon-emitting sectors of the economy; negative emissions technologies (bioenergy combined with CCS or direct air capture combined with CCS); and land use changes resulting in reduced emissions (eg, reforestation).

However, the **availability** of offsets is likely to fall in the long run:

- The **potential for carbon credits from other sectors will naturally decrease** as the decarbonisation of the economy accelerates.
- **Nature-based solutions cannot provide a permanent flow of negative emissions**, since all natural ecosystems tend eventually towards a carbon-neutral balance of emissions and absorption after the build-up period (30 to 40 years for reforestation). Furthermore, depending on its form, carbon sequestration can be vulnerable to climatic and natural events.

In this context, the ETC's position is as follows:

- All sectors of the economy (apart from agriculture) can and should achieve "real net-zero emissions" by mid-century, with a role for CCS/U, but **no permanent and major role for the purchase of carbon credits from other sectors or for offsets arising from nature-based solutions.**
- **Nature-based solutions could deliver a very large one-off increase in the carbon stock** held in the terrestrial ecosystem (and a matching reduction in atmospheric GHG concentrations), and the purchase of offsets could play a positive role in financing this effort in the early stages of the transition, provided that:
  - They are **in addition to**, rather than instead of, as rapid as possible progress towards "real net zero" within the sector.
  - Their assumed carbon reduction value takes account of the fact that **the timing of CO_2 emission reductions matters**. In a world where high emissions could take the climate beyond dangerous tipping points, a tonne of carbon dioxide (CO_2) absorbed via many years of forest growth is not as valuable as a tonne of CO_2 saved immediately via within sector actions.
  - Robust systems for certifying the quality of nature-based solutions are adopted.
- A **continued, though relatively small role for nature-based solutions and other carbon removal technologies**, such as direct air capture plus CCS or bioenergy plus CCS, will be required for a number of years beyond 2050. This will be needed to offset **2 to 4 Gt of CO_2 per annum of residual emissions** arising from the agricultural sector (1 to 2 Gt) and from the energy and industrial sectors (1 to 3 Gt, due to the fact that CCS processes do not achieve 100% CO_2 capture).

II. Costs, investments and related challenges of the transition towards a net-zero-emissions economy

Once a zero-carbon-emissions economy has been achieved, the reduction in conventionally measured 2050 living standards in both developed and developing economies will be trivial (less than 0.5%), and the impact on human welfare hugely positive once we allow for the avoided adverse impact of unmitigated climate change. The investment costs involved in transitioning to a zero-carbon economy might amount to about 1.0% to 1.5% of GDP per annum, but are clearly affordable – especially in an era of sustained low interest rates

Sectoral abatement costs per tonne of CO_2 abated

The sectoral costs of abatement per tonne of CO_2 avoided will vary by region and will evolve over time in light of inherently uncertain technological and cost trends:

In the **power sector, already electrified sectors** (eg, building appliances and cooling) and **soon-to-be-electrified sectors** (eg, light-duty vehicles), decarbonisation can be achieved at low, nil or even negative cost. This reflects the low and still falling cost of renewable power and the inherent efficiency of electrified processes.

In **long-distance transport** (shipping and aviation), the shift to “drop-in” fuels will impose significant abatement costs in the long term, compared with fossil-fuel based alternatives (US$100 to US$300 per tonne of CO_2).

In **heavy-industry sectors**, the costs will be moderate to high, depending on the process and fuel change required (ranging from US$25 to more than US$200 per tonne of CO_2). Cement and plastics will be the most expensive materials to decarbonise; however, reducing primary material demand through recycling, material efficiency and use of alternative zero-emissions materials could prove a lower-cost solution.

For **buildings heating**, abatement costs will vary significantly by region and building type, and by the technology used to achieve decarbonisation

In the **agriculture sector**, decarbonising the direct and indirect use of energy should be quite low cost, but improving agricultural practices to reduce nitrates and methane emissions could impose a cost penalty

Impact on living standards and economic growth

The impact on conventionally measured living standards in 2050 can be estimated by considering the additional costs required to run a zero-carbon economy in that year compared with a high carbon economy. The ETC estimates that [Exhibit E]:

- Under a high-cost scenario and with limited energy productivity improvement, the additional costs could amount to **0.49% of projected global GDP (US$1.6 trillion per year)**.
- Under a low-cost scenario and a maximum energy productivity scenario, the cost could be as low as **0.17% of global GDP per annum** (US$600 billion per year).
- In both scenarios, **the costs are dominated by three specific sectors**: cement (and thus building costs), aviation and shipping. The cost of building heating decarbonisation might also be important in some specific countries, but is very small as a percentage of global GDP. Most other sectors of the economy can be decarbonised at very low, nil or even negative cost.

These costs contrast with the potential adverse consequences of unmitigated climate change. Recent research estimates that since 2000, warming has already cost both the US and EU at least US$4 trillion in lost output, and tropical countries are 5% poorer than they would have been without warming. In addition, achieving a zero-carbon economy will dramatically improve local air quality, saving lives and improving health. Estimates suggest that poor air quality currently accounts for 4.2 million premature and preventable deaths worldwide every year[6].

The small impact on living standards reflects the fact that **in many sectors, the impact of decarbonisation of consumer prices will be trivial** [Exhibit F]. Thus, in heavy industry, while decarbonisation could significantly increase the cost of a tonne of steel, the resulting cost increases for consumer prices would be less than 1%. Similarly, while decarbonisation of shipping would likely require large increases in shipping costs, the impact on the cost of imported goods would be minimal.

In some specific sectors, however, the impacts on end consumer costs will be significant; and in a few of these, it is important to recognise **important distribution implications**. In particular, the cost of decarbonising residential heating could have a significant impact on poorer households in insufficiently insulated homes. In aviation also, end consumer prices may need to rise significantly; but the impact on consumer living standards will still be minimal given the small share of air travel within consumer expenditure (around 3% in developed countries), and the distributional effects will be progressive rather than regressive given much higher air travel among higher-income groups.

In addition, it is important to anticipate and manage some **transitional employment effects**. Like any process of technological change, the transition to a zero-emissions economy will eliminate some existing jobs while creating new jobs elsewhere. Overall, its employment disruption effect is likely to be far less significant than other transformations already facing both developed and developing economies, such as the automation of manufacturing, the shift of retailing from traditional to online forms and the continual reorganisation of global supply chains as relative costs change.

But there will be significant **adverse employment impacts in three sectors**, which are often regionally concentrated: the coal mining sector in some developing countries; the auto-manufacturing sector, since EVs are far simpler and easier to manufacture; and livestock farming which could be affected by a major shift away from meat consumption.

Carefully thought-out national and regional **just transition** strategies may be required to ensure offsetting employment creation in affected regions.

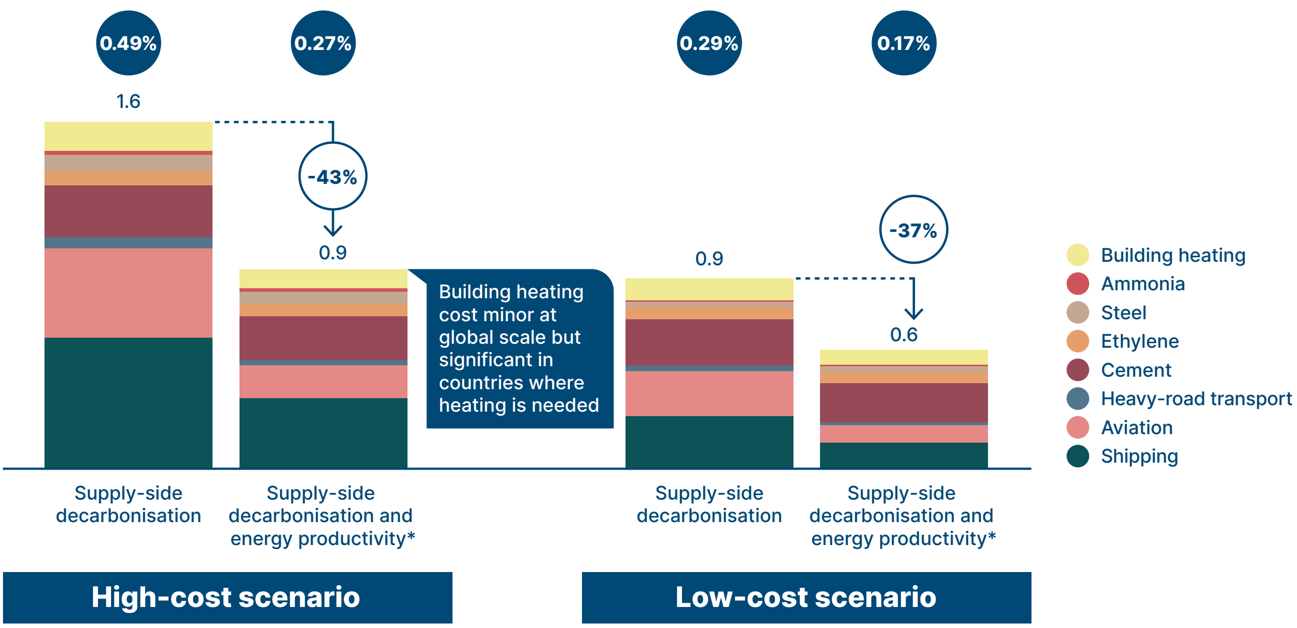
6. World Health Organization (2016), *Mortality and Burden of Disease from Ambient Air Pollution.*

Exhibit E

Decarbonising the economy would cost significantly less if pursuing energy productivity improvements

Total cost of decarbonisation
Trillion US$ per year, 2050

X% Share of global projected GDP, 2050



NOTE: The term "energy productivity" covers energy efficiency, material efficiency and service efficiency.

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2020) based on McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier* and Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit F

Decarbonisation would have a significant impact on the price of intermediate products, but a negligible one on final products prices

		Impact on intermediate product cost US$ / % price increase		Impact on final product cost US$ / % price increase	
Easy-to-electrify sectors		In most sectors of the economy (light-duty road, other industry, rail, building non-heating energy uses), clean electrification is or will soon be cost-competitive			
Industry	Plastics	**+$500** per tonne of ethylene	+50%*	**+$0.01** on a bottle of soda	<1%
Industry	Steel	**+$120** per tonne of steel	+20%	**+$180** on the price of a car	+1%
Industry	Cement	**+$100** per tonne of cement (**+$30** per tonne of concrete)	+100% (+30%)	**+$15,000** on a $500,000 house	+3%
Long-distance transport	Shipping	**+$4 million** on typical bulk carrier voyage call per annum	+110%	**+$0.03** per kilogram of imported sugar	<1%
Long-distance transport	Aviation	**+$0.3-0.6** per liter of jet fuel equivalent	+50-100%	**+$40-80** on a 6,500-km economy class flight	+10-20%
Building heating				**+$650-1000** on a total household utilities budget in a temperate climate country (based on UK case)	+30-45%

*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)

Competitiveness challenges in internationally traded sectors

As Exhibit F shows, even in some sectors where impacts on end consumer prices will be minimal, there will still be very significant increases in **intermediate product costs** – such as for a tonne of steel or cement, or shipping freight rates. This creates a major potential **competitiveness problem** in a world of international trade, multiple independent state governments and imperfect mechanisms for international policy coordination, which is exacerbated by the various forms of support still provided for carbon-intensive activities in many countries.

In heavy industry, international shipping and aviation, optimal public policy would require international coordination; this might be orchestrated through coalitions of countries that play major roles in a given sector rather than through United Nations Framework Convention on Climate Change (UNFCCC)-level agreements. Where such international coordination cannot be achieved, as a second-best policy, **domestic carbon prices combined with border carbon adjustments** will be needed to progress transition fast enough to achieve decarbonisation by mid-century.

Gross and net investments requirements

The impact of achieving a zero-carbon-emissions economy on human welfare in 2050 will thus be hugely positive. But getting there requires us to accept some **transitional costs, stemming from higher investments per annum** during the build-up of this new economy. The ETC estimates that the required additional investments – while significant in absolute dollar terms – will amount to no more than 1% to 1.5% of global GDP (~US$1 trillion to US$2 trillion per year), and are easily affordable given current global savings and investments, particularly in the prevailing macroeconomic context of sustained low interest rates. The scale of required investment is small compared with the massive public spending and fiscal deficits now being dedicated to stimulating the economy after the COVID-19 crisis, providing an opportunity – if well designed – to accelerate the energy transition.

By far the largest elements are the investments required to build a **global power system** that can deliver 100,000 TWh per year, including new renewable electricity capacity, transmission and distribution networks, battery storage for diurnal flexibility, and additional technology deployment to supply interday and seasonal flexibility. This would represent a total additional annual investment of around US$1 to US$1.5 trillion per annum. The ramp-up of **hydrogen production**, transport and storage will also require massive investments either in electrolysis equipment or in the capital equipment for steam methane reforming or autothermal reforming combined with CCS: this investment could amount to around US$3.7 trillion over 30 years, or US$130 billion per annum. Major investments will also be required to construct **buildings in cities** in a low-carbon rather than high-carbon fashion, and to retrofit existing building stocks.

III. Regional differences, challenges and opportunities

Regional differences in resource endowments

Resource endowments vary significantly by region and country. For instance:

- **Renewable power potential varies greatly** depending on climate, latitude and geography, with locations such as western China, the Sahara and Chile well placed to produce abundant cheap power.

- **Total available sustainable biomass supplies also vary greatly:** China has much more limited biomass resource per capita than much of the Americas. The key issue, however, is how much of those resources are available in a truly sustainable way. The distribution of sustainable, low-carbon biomass for use in the energy and industry system might be quite distinct – and indeed concentrated in regions outside of the tropical belt, with less risks of associated deforestation.

As a result, the relative cost of different decarbonisation routes will vary by region, as will the **optimal path** to sectoral decarbonisation in those sectors where multiple solutions are available. The revised nationally determined contributions (NDCs) and long-term low GHG emissions strategies soon to be submitted to the UNFCCC as part of the Paris Agreement should therefore explicitly assess inherent renewable natural resources and the implications for an optimal decarbonisation strategy.

Challenges and opportunities for developing countries

As a general principle, **developed countries should make faster progress**, to reflect both their greater responsibility for past emissions and the fact that higher income makes it easier to absorb the small but still not nil impact on living standards. The ETC therefore believes that the overall objective should be that:

- All rich developed economies reach net-zero emissions by 2050 at the latest.
- All developing countries achieve net-zero emissions by 2060 at the latest.

But **some developing countries may be able to achieve full decarbonisation by 2050 or earlier** at minimal additional cost relative to a 2060 objective. This is because some developing economies are blessed with significant potential solar and wind resources, dramatically reducing decarbonisation costs. Some may also have power systems which are still so underdeveloped that it is possible to "leapfrog" and **build zero-carbon energy systems "right first time",** using the most cost-competitive zero-carbon technologies.

Two countries are particularly significant for the world's emissions trajectory, given their share of total current or future potential global emissions, the pace at which those emissions would grow in the absence of a clean energy transition and the example they set for other developing countries:

China is currently still a developing nation, with a GDP per capita (purchasing power parity basis) about 40% that of Western European levels; but it has a clear national objective to become "a fully developed rich economy" by 2050. Given its high savings and investments, its natural resource endowment and its increasing technological leadership in many important sectors, it could and should achieve this objective while also becoming a zero-carbon economy.

In **India**, a dramatic increase in electricity supply is required to support economic growth, rising living standards and rapid expansion in the use of air conditioning and the electrification of surface transport; but this increase can still happen while also decarbonising electricity supply. ETC India analysis[7] shows that renewable electricity from wind and solar could grow from 8% of India's electricity generation to ~32% by 2030 (with total low- or zero-carbon generation reaching 47%), while doubling total power generation; and that the costs would be no higher than those incurred if growth were supported by continued coal expansion.

Given the fall in the all-in cost of renewable-based power, there is a strong case for ensuring that all expansion of the power system to meet growing electricity demand should be in zero-carbon form. **There is no need for the world to build any new coal-fired power capacity** to support economic growth and rising living standards. But that still leaves the challenge of how to phase out existing coal capacity. Strategies to reduce and eventually eliminate emissions from existing coal will need to entail some mix of adding CCS to coal and gas plants used in a peaking or seasonal backup mode (even if this will inevitably add more cost to total system operation), and closing coal or gas plants before end of useful life.

Finally, neither some aggregate "shortage of capital" nor a high "cost of capital" is likely to constrain progress towards a zero-carbon emissions economy in already developed countries. Nor is this a constraint in China, given its very high savings and investment rates and a state-influenced financial system which ensures low-cost investment finance. In many other developing economies, however, **the cost of capital is significantly higher than in developed economies,** and both the limited availability of capital and its high cost could be a serious impediment to sufficiently rapid investment in new energy systems. It is critical to develop policies specifically focused on **the mobilisation of adequate capital flows at adequately low cost,** including concessional finance flows from developed countries.

7. T. Spencer, N. Rodrigues, R. Pachouri, S. Thakre, G. Renjith, TERI (2020), *Renewable Power Pathways: Modelling The Integration Of Wind And Solar In India By 2030* and R. Pachouri, T. Spencer and G. Renjith, TERI, (2018), *Exploring Electricity Supply-Mix Scenarios to 2030.*

Energy Transitions Commission

Making progress by 2030 to achieve net-zero by 2050

A shared responsibility

Policy-makers	Innovators	Energy producers	Producers of goods and services	Buyers of goods and services	Financial institutions
create conditions for rapid private sector action & build up infrastructure	bring to market and reduce the cost of zero-emissions technologies	produce low-cost and abundant zero-emissions energy	transform deeply processes and business models to embrace efficiency and zero-emissions production	demand and pay for low-emissions and eventuallyzero-emissions goods and services	finance zero-carbon assets and companies in transition

2030 objectives	10 key priorities	Primary accountability
Speed up deployment of proven zero-carbon solutions	1 Build massive capacities of zero-carbon power generation and associated transmission and distribution infrastructure	Energy producers; Financial institutions; Policy-makers
	2 Make the global light-duty vehicle fleet electric and build charging networks required	Producers; Policy-makers; Buyers
	3 Drive ambitious and systematic energy efficiency programmes in the building sector	Policy-makers; Financial institutions; Producers
	4 Improve material efficiency and recycling through greater value chain collaboration	Producers; Buyers; Policy-makers
Create the right policy and investment environment for technology diffusion	5 Remove fossil-fuels subsidies and tax carbon and other GHGs (targeting over $100/tonne CO_2 before 2030)	Policy-makers
	6 Use standards and regulations to accelerate decarbonisation where price signals are insufficient	Policy-makers
	7 Channel investment into the transition of high-emissions activities	Financial institutions; Policy-makers
Enable the emergence of the next wave of zero-carbon technologies	8 Focus public and private R&D support on critical technology targets	Innovators; Producers; Policy-makers
	9 Foster value chain collaboration to coherently develop supply and demand in key emergence sectors	Producers; Energy producers; Buyers
	10 De-risk end-to-end pilots to test new technologies in the context of their value chain	Producers; Buyers; Policy-makers

IV. **Making Mission Possible:** actions required now to put 2050 targets within reach

It is essential to agree the objective of achieving zero emissions by mid-century. But it is also essential to identify and implement the actions and policies needed in the 2020s to make that vision attainable. This will require greatly accelerated progress, for two reasons:

- First, if the world is serious about the 1.5°C objective, it must reduce emissions to 20 Gt CO_2 per annum by around 2030, but we are **far off track to achieve this reduction.** The COVID-19 crisis has produced a significant short-term reduction in global emissions, but they are likely to rebound rapidly as economies recover; and underlying trends plus stated policies and commitments (as expressed in the NDCs which countries have made under the Paris Agreement) leave the world on a path towards 35 Gt CO_2 of emissions in 2030, and towards 3°C of warming or more by the end of the century.

- Second, **it will be impossible to achieve net-zero emissions by 2050 without significant progress along many dimensions by 2030,** but current progress on investments, technologies and policies is far too slow to make a pathway to net zero by 2050 feasible.

Technology transformations of the sort now required can be thought of as involving three phases: the initial emergence of a new technology; its diffusion on a significant scale; and the "new normal" phase when the entire system has adopted the newly mainstream technology. The nature of actions required from industry policy and finance during the 2020s differs by particular technology according to its current stage of development. Three sets of action are required over the next decade to accelerate the transition through these phases.

First, we should speed up the deployment of zero-carbon power and other proven emissions reduction technologies and business models. Where low-carbon solutions exist at similar or lower costs than the high-carbon alternative, focus should be put on unlocking investment at scale to deploy rapidly in the 2020s and achieve major emissions reductions in the short term:

- In the **power sector**, the crucial priority now is not technology development (except in some storage technologies), but to drive the pace of renewables investment fast enough to underpin clean electrification and put the sector on track to net zero. Required policies will entail clear quantitative objectives for the development of zero-carbon power (mainly solar and wind) by 2030 and for a reduction in the carbon intensity of electricity generation (measured in grams per kWh), supported by appropriate power market design and financing mechanisms (including concessionary finance in developing countries).

- In other sectors where there is a clear low-cost path to decarbonisation – such **as surface transport, buildings heating and material circularity** – the crucial priority is to ensure fast deployment of those solutions by reinforcing the economic case for change through clear and compelling regulations (eg, banning new sales of ICE light-duty vehicles in the early 2030s; providing financing solutions to cover the upfront cost of building retrofitting), removing non-economic hurdles (eg, improving waste collection for greater and higher-quality recycling) and mobilising capital at scale.

Second, we should create the right policy and investment environment to enable technology diffusion in all sectors where technologies are market-ready, but still not cost-competitive. The specific mix of technology pathways and climate policies implemented should be tailored to national circumstances and the existing policy landscape, and will thus vary from country to country. Key priorities are threefold:

- First, we should **ensure the appropriate pricing of externalities** by removing all remaining fossil fuel subsidies, using explicit carbon pricing mechanisms and applying the "polluter pays" principle. To avoid inherent competitiveness issues of carbon pricing for globally traded commodities in the absence of international agreements on carbon pricing, these schemes must be combined with carbon border tax adjustments. Well-designed market-based approaches of this sort are potentially very efficient levers, since they allow businesses flexibility in the way they reduce emissions and encourage innovation.

- Second, for sectors where carbon prices are likely to be insufficient to trigger a switch in investment and purchase decisions, governments should **set up standards and regulations** to establish explicit targets, create greater market certainty and thereby facilitate investments. These could take the form of GHG emissions standards, renewable energy or fuel mandates, and eventual bans on the most carbon-intensive products.

- Third, achieving full decarbonisation of the economy will require major investments in clean energy provision and industrial assets (new build and retrofit), starting in the 2020s. **Channelling capital into transitioning activities** will require the right policy environment, a clear investment roadmap to identify investment needs, an assessment of the sectoral transition risks and opportunities for financial institutions, a common definition of what qualifies as transition finance, and the mobilisation of public finance to de-risk first-of-a-kind investments.

Finally, we should ensure that the next wave of zero-carbon technologies is brought to market by the end of the 2020s at the latest.

To achieve this objective, **innovation finance from both the public and private sector** must support the development of technologies which are still at the emergence phase – especially those that are relevant to multiple sectors. These include hydrogen from electrolysis, synthetic hydrocarbon production, CCS/U and biofuels from the most sustainable feedstock sources [Exhibit G].

In addition, the initial deployment at commercial scale of these technologies will require **de-risking mechanisms** to reduce costs (capital costs and operational costs) and lower risks (eg, technology risks, offtake risks) at each step of the value chain. Innovative risk-sharing models and public support mechanisms might include new corporate partnerships (eg, joint ventures or offtake agreements), innovative financing products (eg, new insurance mechanisms) and tailored public support mechanisms (eg, tax incentives, subsidies, blended finance mechanisms, public procurement and public-private partnerships).

Beyond innovation, the crucial challenge for emerging technologies is to overcome the **"chicken and egg" problem** which can slow the pace of development – with early use applications held back by high costs, which in turn makes it difficult for producers to achieve the economies of scale and learning curve effects that can rapidly reduce cost. To solve this challenge, coordinated action must be taken across key value chains to secure demand for new products at a pace coherent with the possible ramp-up of supply.

Key innovation areas to fully decarbonise the economy

Exhibit G

● Incremental innovation ● Breakthrough innovation

Electrification

- Cheaper and more energy-dense batteries
- Cheaper and more efficient heat pumps
- Electric furnaces for cement and chemicals
- Electrochemical reduction of iron for steel production

Hydrogen

- Cheaper electrolysis (targeting $200/kW)
- Cheaper hydrogen fuel cells and tanks
- Long-distance transport of hydrogen via high-capacity piepline
- Large-scale geological storage (in salt or rock caverns)
- Hydrogen / ammonia burning ship engines and turbines

Bio and synthetic chemistry

- Increased efficiency of lignocellulosis/ algal biomass transformation
- Cheaper production of synthetic fuels based on a combination of hydrogen and CO_2
- Electrochemical reduction of iron for steel production
- New chemical products based on bio or synthetic feedstocks

Materials efficiency and circularity

- New designs for consumer products
- Material traceability, collection, sorting and recycling technologies
- New business models: product-as-a-service, sharing

New materials

- Low-carbon cement and concrete chemistries
- Biomaterials for construction
- Cellulose-based fibres as a substitute for plastics

Carbon capture and use

- More efficient carbon capture, especially for cement
- Cheaper direct air capture of CO_2
- Use of carbon in concrete, aggregates and carbon fibre

Food, land and oceans

- Precision/digital agriculture and regenerative agriculture
- Improved supply chain and cold chain storage technologies
- Alternative proteins, including cultured meats
- Large-scale, sustainable ocean macroalgal (seaweed) production

SOURCE: SYSTEMIQ for the Energy Transitions Commission (2020)

Glossary

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

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

BEV: Battery-electric vehicle.

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

Bioenergy: Renewable energy derived from biological sources, in the form of solid biomass, biogas or biofuels.

Carbon capture and storage or use (CCS/U): We use the term "carbon capture" to refer to the process of capturing CO_2 on the back of energy and industrial processes. Unless specified otherwise, we do not include direct air capture (DAC) when using this term. The term "carbon capture and storage" refers to the combination of carbon capture with underground carbon storage; while "carbon capture and use" refers to the use of carbon in carbon-based products in which CO_2 is sequestered over the long term (eg, in concrete, aggregates, carbon fibre). Carbon-based products that only delay emissions in the short term (eg, synfuels) are excluded when using this terminology.

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

Carbon offsets: Reductions in emissions of carbon dioxide (CO_2) or greenhouse gases made by a company, sector or economy to compensate for emissions made elsewhere in the economy.

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

Circular economy models: Economic models that ensure the recirculation of resources and materials in the economy, by recycling a larger share of materials, reducing waste in production, 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 driving electric generators.

Decarbonisation solutions: We use the term "decarbonisation solutions" to describe technologies or business models that reduce anthropogenic carbon emissions by unit of product or service delivered though energy productivity improvement, fuel/feedstock switch, process change or carbon capture. This does not necessarily entail a complete elimination of CO_2 use, since (i) fossil fuels might still be used combined with CCS/U, (ii) the use of biomass or synthetic fuels can result in the release of CO_2, which would have been previously sequestered from the atmosphere though biomass growth or direct air capture, and (iii) CO_2 might still be embedded in the materials (eg, in plastics).

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

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

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

Emissions from the energy and industrial system: All emissions arising either from the use of energy or from chemical reactions in industrial processes across the energy, industry, transport and buildings sectors. It excludes emissions from the agriculture sector and from land use changes.

Emissions from land use: All 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.

Energy productivity: Energy use per unit of GDP.

Final energy consumption: All energy supplied to the final consumer for all energy uses.

Fuel cell electric vehicle (FCEV): Electric vehicle using a fuel cell generating electricity to power the motor, generally using oxygen from the air and compressed hydrogen.

Greenhouse gases (GHGs): Gases that trap heat in the atmosphere – CO_2 (76%), methane (16%), nitrous oxide (6%) and fluorinated gases (2%).

Hydrocarbons: An organic chemical compound composed exclusively of hydrogen and carbon atoms. Hydrocarbons are naturally occurring compounds and form the basis of crude oil, natural gas, coal and other important energy sources.

Internal combustion engine (ICE): A traditional engine, powered by gasoline, diesel, biofuels or natural gas. It is also possible to burn ammonia or hydrogen in an ICE.

Levelised cost of electricity (LCOE): A measure of the average net present cost of electricity generation for a generating plant over its lifetime. The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity-generating plant divided by a discounted sum of the actual energy amounts delivered.

Natural carbon sinks: Natural reservoirs storing more CO_2 than they emit. Forests, plants, soils and oceans are natural carbon sinks.

Nature-based solutions: Actions to protect, sustainably manage and restore natural or modified ecosystems which constitute natural carbon sinks, while simultaneously providing human, societal and biodiversity benefits.

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

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

Steam methane reforming (SMR): A process in which methane from natural gas is heated and reacts with steam to produce hydrogen.

SMR with carbon capture and storage (SMR+CCS): Hydrogen production from SMR, where the carbon emitted from the combustion of natural gas is captured to be stored or used.

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

Synfuels: Hydrocarbon liquid fuels produced synthesising hydrogen from water, carbon dioxide and electricity. They can be zero-carbon if the electricity input is zero-carbon and the CO_2 from direct air capture. Also known as "synthetic fuels", "power-to-fuels" or "electro-fuels".

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

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Making Mission Possible

Executive Summary

Delivering a Net-Zero Economy

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Version 1.0

Energy Transitions Commission