ENERGY TRANSITIONS COMMISSION

Better Energy, Greater Prosperity

Achievable pathways to low-carbon energy systems

www.energy-transitions.org

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April 2017

The Energy Transitions Commission

The Energy Transitions Commission (ETC) brings together a diverse group of individuals from the energy and climate communities: investors, incumbent energy companies, industry disruptors, equipment suppliers, energy-intensive industries, non-profit organizations, advisors, and academics from across 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. The ETC is co-chaired by Lord Adair Turner and Dr. Ajay Mathur. Our Commissioners are listed on the next page.

The *Better Energy, Greater Prosperity* report was developed by the Commissioners with the support of the ETC Secretariat, provided by SYSTEMIQ and McKinsey & Company. It draws upon a set of analyses carried out by Climate Policy Initiative, Copenhagen Economics and Vivid Economics for the ETC, which are available on the ETC's website.

This report constitutes a collective view of the Energy Transitions Commission. Members of the Energy Transitions Commission 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 cutting carbon emissions, but also share a broad vision of how the transition to a low-carbon energy system can be achieved. The fact that this agreement is possible between 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 limit global warming to well below 2˚C, and that many of the key actions to achieve these goals are clear.

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GLOSSARY

A '*' is used in the first instance a term which is defined in the Glossary appears in the report.

2˚C scenario: A scenario for future patterns of activity which is built to limit total greenhouse gas emissions* by 2100 to a level that allow for a probability of two-thirds that warming will not exceed 2˚C above preindustrial levels

Atmospheric CO_2 capture: Extraction of carbon dioxide from atmospheric air

Auction models: The process of buying and selling goods through taking bids and rewarding the bidder with the best offer

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

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

Carbon / CO_2 emissions: We use the terms "carbon emissions" and "CO_2 emissions" interchangeably to describe emissions of carbon dioxide arising from burning of fossil fuels, solid waste, trees and wood products, and also as a result of certain chemical reactions, for instance in cement production. Carbon dioxide represented 76% of greenhouse gas emissions* in 2010, of which 65% from fossil fuels and industrial processes, and 11% from forestry and other land use (IPCC, 2014).

Carbon capture: Unless specified otherwise, we use the term 'carbon capture' to refer to carbon capture on the back of fossil fuels, bioenergy and industrial processes. We exclude atmospheric CO_2 capture* when using this terminology.

Carbon capture and storage (CCS): We use the term "carbon capture and storage" and the abbreviation "CCS" to refer to the combination of capture on the back of fossil fuels, bioenergy and industrial processes, with underground storage*.

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

Carbon productivity: Carbon consumption per unit of GDP

Carbon sequestration (CS): We use "carbon sequestration" or the phrase "all forms of carbon sequestration" to refer to the whole spectrum of carbon capture and sequestration techniques, including natural carbon sinks*, atmospheric CO_2 capture*, carbon capture on fossil fuels, bioenergy and industrial processes*, carbon storage* and CO_2-based products*. In exhibits and graphs, we use the abbreviation "CS" to refer to all forms of carbon sequestration, whereas "CCS" refers to carbon capture and storage* only.

Carbon storage: We use the terms "carbon storage" to refer to underground storage of CO_2, for instance in depleted oil and gas reservoirs, saline formations, or deep coal beds. We exclude natural carbon sinks* and CO_2-based products* when using this terminology.

CCGT: Combined Cycle Gas Turbine, which is an assembly of heat engines that work in tandem from the same source of heat to convert it into mechanical energy so as to drive electric generators

Circular economy models: Circular industrial models aim to redesign the lifecycle of products and services to reduce waste, while minimizing negative environmental impacts. This is an alternative model to the linear economy, which is a 'take, make, dispose' model of extractive production.

CO_2-based products: We use this term to refer to products developed via the conversion of CO_2 in which CO_2 is sequestered over the long term. We exclude CO_2-based products that only delay carbon emissions in the short term when using this terminology.

Concessional finance: Type of financing – which can be either debt or capital – usually offered by a Government agency, allowing for flexible or lenient terms for repayment, usually at lower than market interest rates

Contracts for difference: A financial agreement between a buyer and a seller where the seller agrees to pay the buyer the difference between the current value of an asset and its value at the contract time to compensate for moving prices

Corporate finance: Financing model in which a company procures capital by demonstrating that it has sufficient assets on its own balance sheets to use as collateral in the case of default

DFIs: Development Finance Institutions, which provide concessional finance* to developing countries. DFIs include multilateral, regional and bilateral institutions.

Energy-based goods or services: We use this term to refer to goods or services that require energy input to be produced or delivered, e.g. cement, heating, kilometers travelled.

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

Energy productivity: Energy consumption per unit of GDP

Energy services: We use this term to refer to the delivery of energy to end-users, especially when considering the challenge to ensure access to affordable, reliable, sustainable and modern energy services for all.

EVs: Electric Vehicles

Feed-in tariffs: An economic policy created to promote active investment in and production of renewable energy sources, which uses long-term agreements and pricing tied to costs of production to reduce risks for renewable energy producers

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

Green bonds: Bonds raised to fund projects with a positive environmental impact. Green bonds can be "use of proceeds" bonds (in which proceeds are earmarked for green projects, but backed by the issuer's entire balance sheet), green project bonds (funding a specific underlying green project) or green securitization bonds (which group several underlying green projects).

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

Joules: A joule (J) represents roughly the amount of energy required to lift a small apple 1 meter against the Earth's gravity. / A gigajoule (GJ) equals to one billion joules (109). Historically, 100 GJ per capita per annum has been required to reach a good standard of living. / An exajoule (EJ) equals to one quintillion joules (1018). Today, global final energy demand represents 350 EJ annually.

HDVs: Heavy-Duty Vehicles, which have a gross vehicle weight rating higher than 4,500 kg, such as most trucks

INDCs: Intended Nationally Determined Contributions (INDCs) are national strategies to reduce greenhouse gas emissions* submitted by individual countries prior to the 2015 United Nations international climate change conference in Paris (COP21). These plans will be updated every five years, starting in 2018.

Interday/seasonal shifting: Displacing power generation and/or power demand over the course of several days or months to ensure alignment between electricity supply and demand, and in particular meet peak load demand

Intraday shifting: Displacing power generation and/or power demand over the course of a day to ensure alignment between electricity supply and demand, and in particular meet peak hours demand

LDVs: Light-Duty Vehicles, which have a gross vehicle weight rating of 4,500 kg or less, such as individual passenger vehicles

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

MDBs: Multilateral Development Banks, such as the International Monetary Fund or the World Bank

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

Near-total-variable-renewable power system: We use this term to refer to a power system in which all power supply is provided by variable renewable energies (solar and wind) except for any peak back-up production provided by gas-fired plants.

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 any conversion or transformation process

Project finance: Long-term financing of infrastructure and industrial projects based on the projected cashflow of the project, rather than the balance sheet of its sponsors

Zero-carbon energy sources: This term refers to renewables (including solar, wind and hydro), nuclear, as well as biomass and fossil fuels if and when their use can be fully decarbonized.

Zero-carbon energy/power system: We use this term to refer to an energy or power system that does not produce any carbon emissions or delivers negative carbon emissions. A zero-carbon energy system should be achieved well before the end of the century.

Securitization: Financial practice of pooling various types of contractual debt or other non-debt assets generating revenues, and selling their related cashflows to third-party investors as securities. Securities backed by mortgage receivables are called mortgage-backed securities (MBS), while those backed by other types of receivables are asset-backed securities (ABS).

Sharing economy models: This term describes economic models in which individuals are able to borrow or rent assets owned by someone else, therefore increasing utilization of underutilized assets. Sharing economy models include peer-to-peer services, for instance car sharing or accommodation renting, as well as centralized rental models with business models based on service provision rather than product sales, such as car hire services.

Sunset clause: A provision that sets an end date to specific regulation, unless further legislative action is taken

Tonne of oil equivalent (toe): This is a common unit of energy measurement which enables different fuels to be directly compared and aggregated. One tonne of oil equivalent represents the energy generated by burning one metric tonne of crude oil.

Watt hours: A kilowatt hour (kWh) represents the amount of energy needed by a 1000-watt device, such as an iron or a microwave oven, to operate for one hour. / A megawatt hour (MWh) equals to a thousand kWh. An average European household consumes 3.6 MWh per year. / A gigawatt hour (GWh) equals to a thousand MWh. 1 GWh = 3,600 GJ / A terawatt hour (TWh) equals to a thousand GWh,

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

Executive Summary

Prosperity depends on access to affordable and reliable energy services*. Across the world today huge differences in prosperity are therefore matched by huge differences in energy use per capita, stretching from over 200 GJ per capita in the USA and Australia to only 20 GJ per capita in much of sub-Saharan Africa [Exhibit 1].

It is essential that developing countries are able to attain the standards of living enjoyed today by the developed world, and this will require big increases in their energy use per capita, especially in low-income countries. Even if we achieve radical improvements in energy productivity* – i.e. increasing income attainable per energy input – something like 80-100 GJ per capita will likely be required to support a good standard of living.

But if major improvements in energy productivity are not achieved, and if increasing energy needs are met by an unchanged energy system, severely harmful climate change will result. In a business as usual scenario*, global energy use could grow by 80% to reach 650 EJ by 2050. Today's global energy system relies on fossil fuels to provide 80% of total primary energy consumption, and is responsible for about 75% of total greenhouse gas emissions*. **The expansion of an unchanged energy system, with anything close to current levels of CO_2 intensity, would likely lead to over 4°C global warming by the end of the century.**

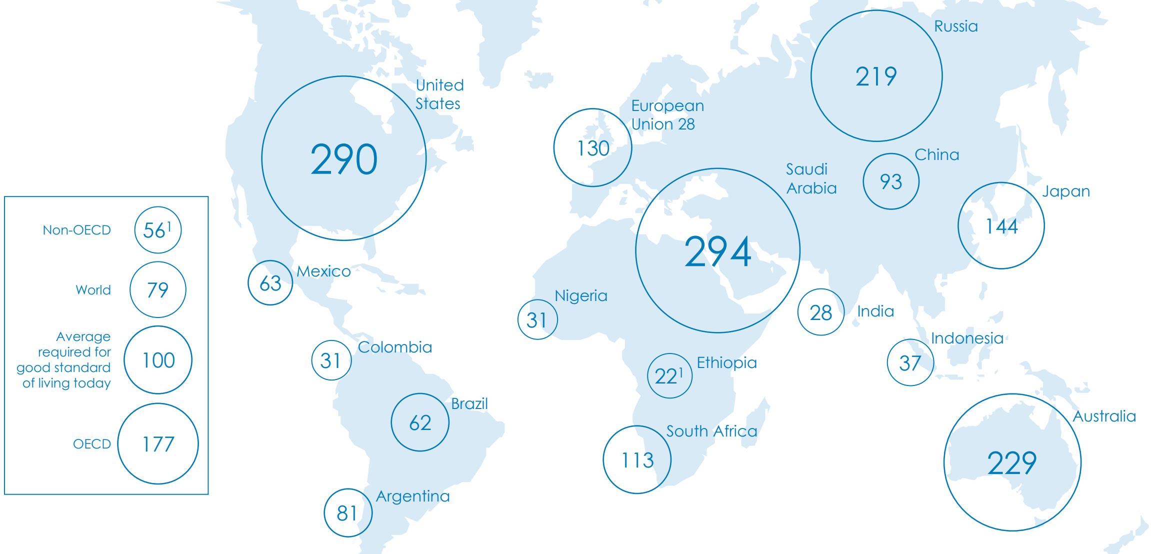
At the 2015 United Nations international climate change conference in Paris (COP21), 195 countries committed to limit global warming to well below 2°C, and national actions to reduce emissions have been ratcheted up. But current plans and pace of progress are still far from sufficient to achieve the well below 2°C objective*. Achieving that objective requires rapid reductions in CO_2 emissions.

We must therefore transition to a global energy system that can both:

- Ensure everyone has access to affordable, reliable, and modern energy services to support a good standard of living – something like **80-100 GJ* per person per annum** is likely to be required, though this threshold may fall over time as energy productivity improvements are achieved;
- Cut annual carbon emissions* from the energy system from **36 Gt of CO_2 today to 20 Gt by 2040 – i.e. less than half the 47 Gt by 2040 expected in a business as usual scenario* –**, with further cuts to a steady-state of net zero emissions in the second half of the century.

Current energy per capita varies significantly across the world

Average per capita primary energy consumption; GJ/capita; 2014

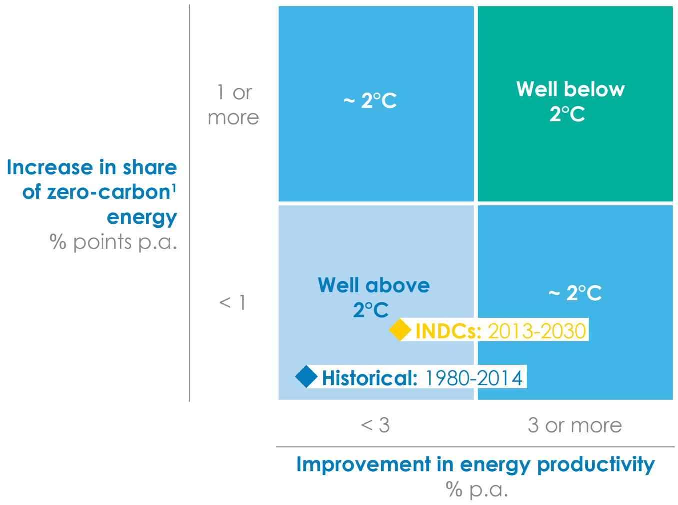


1 2013 due to limited data

SOURCE: Enerdata (2015), Historic actuals; UN Population Division (2015), World Population Prospects: The 2015 Revision

Exhibit 1

Limiting global temperature rise to 2°C whilst extending energy access requires both the decarbonization of energy supply and improvement in energy productivity



1 We include here renewables, nuclear, biomass and fossil fuels if and when their use can be decarbonized through carbon capture and use or storage (CCS). However, if a large share of the increase is from the latter, a higher share is required since this does not reduce emissions to zero completely

SOURCE: Enerdata (2015), Historic actuals

Exhibit 2

Achieving these two goals requires rapid progress on two dimensions [Exhibit 2]:

- Energy productivity*, i.e. GDP per unit of energy, must grow by 3% per annum, compared to a historical rate of 1.7% per annum; and
- The share of energy derived from zero-carbon energy sources* (mainly renewables) must grow by at least one percentage point per annum.

These rates of improvement are far higher than achieved over the last 30 years, and much faster than implementation of the current INDCs* would deliver.

"This transition is technically and economically possible"

Despite the scale of the challenge, the Energy Transitions Commission is confident that **this transition is technically and economically possible**, and that **it would deliver important additional social benefits** – with, for instance, dramatically improved local air quality leading to longer and healthier lives – **and economic opportunities** – related to the development of new industries and business models.

Some vital progress is already being achieved, with dramatic falls in the cost of renewable power and recent gains in the rate of energy productivity improvement, but we **need to accelerate the transition.**

This will require rapid but achievable progress along 4 dimensions [Exhibit 3]:

1. Decarbonization of power combined with extended electrification,
2. Decarbonization of activities which cannot be cost-effectively electrified,
3. Acceleration in the pace of energy productivity improvement,
4. Optimization of fossil fuels use within overall carbon budget constraints.

These 4 transition strategies in turn imply the need for and will crucially depend on:

1. A major shift in the mix and financing of energy system investment,
2. A coherent and predictable policy framework.

Accelerating energy transitions requires to simultaneously implement 4 transition strategies by leveraging two sets of enablers

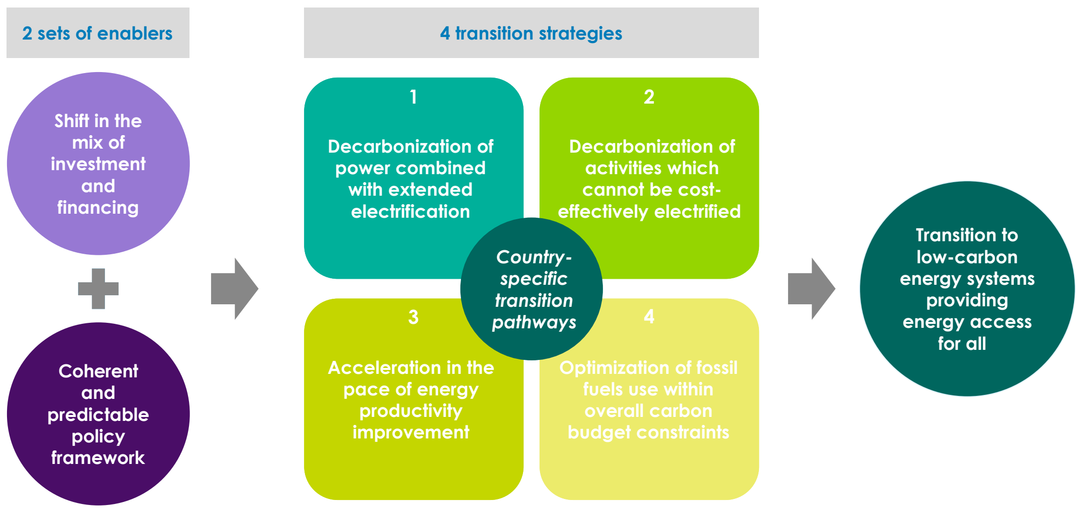


Exhibit 3

4 TRANSITION STRATEGIES

The 4 energy transition strategies are interdependent and we must pursue them all simultaneously. But their likely contribution to emissions reductions differs, as does our degree of confidence that we are on a path to achieve what is required. Exhibit 4, p.16 **presents the ETC's estimate of the feasible contribution of each transition to CO_2 emissions reductions over the next 15-20 years**. If achieved, these reductions would put the world on a path compatible with a well below 2˚C warming pathway. But realizing this potential will require strong action from public and private decision-makers.

- Energy transition 1 – decarbonization of power combined with extended electrification could account for the largest share of emissions reductions between now and 2040. Zero-carbon sources (mainly renewables) could account for up to 80% of the global power mix by 2040, while coal-fired power need to decline steeply as soon as possible.
- Energy transition 2 – decarbonization of activities which cannot be cost-effectively electrified – will probably account for only a small share of emissions reductions over the next 20 years, but will become absolutely vital as the potential for electrification is exhausted. Major work is still required to define the path to success.
- On Energy transition 3 – energy productivity – considerable progress is being achieved, but a further acceleration is required. This is technically and economically feasible, but will required more forceful public policies.
- Energy transition 4 implies falling fossil fuels use, even if carbon capture and sequestration* is developed on a very large scale. However, at the moment, progress on all forms of carbon sequestration (including natural carbon sinks*, underground storage* and CO_2-based products*) is too slow and requires supportive policy frameworks in order to progress.

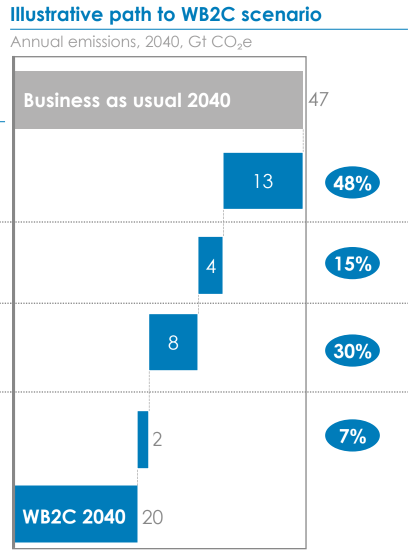
Energy transition 1 – Decarbonization of power combined with extended electrification

By 2040, half of the potential CO_2 emissions reductions compared to a business as usual scenario (48% or 13 Gt per annum) could come from the combined impact of decarbonization of power and extended electrification.

- **By 2035, it will be feasible in many geographies to build a near-total-variable-renewable power system* providing electricity at a maximum all-in cost of $70 per MWh***. This will make renewables fully competitive with fossil fuels, allowing for all necessary flexibility and back-up costs. This estimate

4 transition strategies need to be pursued simultaneously to achieve a well below 2°C scenario

Transition strategy	Major components
1 Decarbonization of power combined with extended electrification	▪ Zero-carbon sources reaching ~80% of power mix ▪ Electrification of transport, buildings, industry: electricity reaching ~30% of final energy mix
2 Decarbonization of activities which cannot be cost-effectively electrified	▪ Fuels substitution (bioenergy, hydrogen...) ▪ CCS and CO_2-based products for industry ▪ District heating and cooling
3 Acceleration in the pace of energy productivity improvement to 3% per annum	▪ Spillovers from extended electrification ▪ End-to-end energy efficiency improvement ▪ Structural shifts (service-based economy, digitization, circular economy, urban infrastructure)
4 Optimization of fossil fuels use within overall carbon budget constraints	▪ Coal to gas transition ▪ Methane leakage management ▪ Phasing out of routine flaring



SOURCE: Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission

Exhibit 4

reflects predictable reductions in the cost of renewables such as wind and solar and rapid cost reductions now being achieved in batteries. This all-in cost could be further reduced if a wider set of flexibility options such as demand management and better grid integration were deployed.

- Renewables deployment will therefore play a key role in decarbonization in all countries, but actual renewables penetration as a percentage of total electricity supply will reflect the feasible and economic pace of investment. **By 2040, intermittent renewables (solar and wind) could reach 45% of the global power mix, with other zero-carbon power sources representing about 35%, and unabated fossil fuels the remaining 20%**. The need for carbon capture in the power sector is likely to be limited to specific countries. A meaningful carbon price* would help drive a faster and more certain transition.

- As power is decarbonized, electricity could then be extended to a wider range of economic activities. The ETC's conservative scenario suggests that around **10-20% of all fossil fuels use could be eliminated through electrification by 2040, delivering CO_2 emissions reductions of at least 2-4 Gt per annum**. Initial opportunities are greatest in light vehicle transport and building heat services. Bigger reductions may well result from faster electric vehicle penetration than our conservative scenario envisages, and in the long-term, innovation will potentially enable significant electrification of industrial processes.

Energy transition 2 – **Decarbonization of activities which cannot be cost-effectively electrified**

While transition 1 will be the most important driver of emissions reductions to 2040, **decarbonization beyond power, e.g. from transport or industrial activities that cannot be electrified at reasonable cost, will be crucial to achieve full decarbonization of the global economy after 2040**. So, while decarbonization beyond power will likely deliver a relatively small share of total emissions reductions over the next 10-20 years (15% or 4 Gt per annum), urgent action, including the introduction of appropriate carbon pricing*, is required to ensure that more extensive decarbonization becomes achievable in subsequent years.

- **Multiple possible decarbonization routes are possible.** On the energy supply side, fossil fuels could be replaced with various forms of bioenergy; hydrogen could be used as an energy carrier; and carbon capture and sequestration (including CO_2 conversion into valuable products that sequester carbon over the long term) could be deployed. On the demand side, circular economy* value chains could reduce the need for virgin energy-intensive products and alternative less energy/carbon-intensive products could be used.

- However, **these supply-side technologies have not experienced the rapid cost reduction and huge scale deployment** seen in renewable power – although (first-generation) biofuels are more advanced than other options. They also face significant barriers to development, such as competition for land use (bioenergy) and large infrastructure requirements (hydrogen, CCS). At present, there is no clarity on which technology will be most appropriate in different industrial and transport applications.

- **This high level of uncertainty generates an unfavorable environment for investment.** Ensuring rapid progress will require substantial R&D expenditures plus large-scale deployment to drive cost reductions. Governments and private industry coalitions should together develop roadmaps to define a clearer way forward; and Governments should adopt infant industry policies similar to those that drove wind and solar industries to self-sustaining scale.

Energy transition 3 – **Acceleration in the pace of energy productivity improvement**

If the world is to enjoy continued economic development while keeping global warming well below 2°C, **a step change in energy productivity, i.e. economic output per unit of energy, must be achieved**. The rate of energy productivity improvement globally must rise from 1.7% to close to 3% per annum to deliver the 8 Gt per annum of CO_2 emissions reduction required from these levers by 2040. For this energy productivity revolution to happen, rapid progress on two dimensions is essential:

- **Improvements in the efficiency with which energy-based goods and services* are delivered** (e.g., reduced kWh* per lumen of light or per kilometer travelled), which would deliver two-thirds of the prize if historic trends continue. Electrification will itself deliver large benefits, and there are multiple opportunities to continue the efficiency improvements already observed in building insulation, household appliances, transport equipment and industrial processes. Performance standards, procurement process principles and appropriate regulation are the key policy tools to drive further improvement.

- **Increased GDP productivity of energy-based services** (e.g., reduced kilometer travelled per unit of GDP). Structural shift towards more service-based and information-intensive economies could itself drive significant improvement, but to achieve the full potential requires: (i) increased progress towards more efficient and dense urban design than is currently being achieved – without this, rapid urbanization in developing economies could lock the world into unsustainable emission pathways; and (ii) the development of economies which are both "circular"* (closed loop supply chains with near total recycling) and based on "sharing"* (more efficient ownership models of assets such as vehicles).

Energy transition 4 – **Optimization of fossil fuels use within overall carbon budget constraints**

To achieve a cost-effective transition to a carbon-constrained economy, the use of fossil fuels needs to be optimized and fossil fuels treated like a scarce resource, even if there is an abundant supply. **Efficient management of fossil fuels use optimizing carbon productivity* could contribute 7% of required CO_2 emissions reduction up to 2040** (or 2 Gt per annum).

- To put the world on a pathway to a 2°C rise in global temperature, **total CO_2 emissions from the energy system between now and 2100 must be at most 900 Gt**.

- Even if different forms of carbon sequestration (CCS, CO_2-based products and natural carbon sinks) were able to remove up to 8 Gt of CO_2 emissions per annum by 2040 (versus less than 50 MT today), fossil fuels use would still need to fall by around one third by that date to make it possible to stay within the carbon budget. This carries different implications for the three main fossil fuels:
  - **Unabated coal use must begin immediate decline** and be eliminated as rapidly as possible from developed country power systems to make space for unavoidable use in some developing countries. Total coal consumption (including both thermal and metallurgical coal) would need to decline by 70% from today's level by 2040. Thermal coal consumption would need to decline even faster, leaving space for continued use of metallurgical coal.

- A limited increase in gas production is possible, but with a flat profile beyond the 2020s, and with a total volume in 2040 only 2% higher than today – provided methane leakages are drastically reduced;
- **Oil must peak in the 2020s**, falling about 30% below today's volumes by 2040.

- **These trajectories can be achieved** through the combination of clean electrification, energy productivity improvements and decarbonization beyond power, as illustrated by Exhibit 4, p. 16.

- The amount of CO_2 that must be sequestered (in products, storage or natural sinks) to ensure that the world is on a well below 2˚C trajectory will depend on the pace at which we decarbonize power, expand electrification and improve energy productivity, as well as on the uptake of alternative solutions for industrial decarbonization. The distribution between different forms of capture and sequestration* can also vary. **The ETC illustrative pathway shown on Exhibit 4, p. 16 assumes only 3-4 Gt of carbon capture on fossil fuels* per annum, primarily in industry**.
  - Even to achieve 3-4 Gt of carbon capture on fossil fuels would require **a step-change in the development of CCS***, with major public and private investment. This should include greater focus on **CO_2 conversion into products** with an estimated potential of 1-6 Gt of carbon sequestered per annum by 2040.
  - **Greater focus on natural carbon sequestration is also needed**. Up to 11 Gt per annum could potentially be sequestered in natural carbon sinks, including 7 Gt through natural forest management, reforestation and avoided reforestation. In some cases, this sequestration could enhance agricultural productivity through boosting soil health, but competing demands for land between food/feed, fiber production, bioenergy, renewable energy and carbon sequestration will require careful management.

- **Increased renewables penetration, greater energy productivity and declining fossil fuels use means that fossil fuels prices could fall (relative to a business as usual scenario)**. Overall, this combination could lower energy costs as a share of household budgets, creating a net welfare gain for society. However, it could also undermine the energy transition by slowing renewables investment and generating demand rebound effects. **A carbon tax wedge is therefore essential**.

2 SETS OF ENABLERS

The 4 energy transition strategies described above require a major shift in the pattern of investment and types of finance needed. They must also be supported by a range of public policies.

Enabler 1 – **Investment shift**

The transition to a low-carbon global economy* will require significant additional energy system investments – around $300-$600 billion per annum – compared with a business as usual scenario. In the context of global GDP running at around $80 trillion in 2017, and global annual investment at $20 trillion, additional investments of around $300-$600 billion per annum **do not pose a major macroeconomic challenge**. Clean energy investments with predictable long-term returns could be attractive to a range of institutional investors in the current low interest rate environment.

> ***"A well below 2°C pathway requires a major change in the mix of investment"***

However, a well below 2˚C pathway requires a major change in the mix of investment. Total fossil fuels investment between now and 2030 could be some $3.7 trillion ($175 billion per year) lower than in a business as usual scenario; investment in renewables and other low-carbon technologies some $6 trillion higher ($300 billion per year); while the largest required increases – of almost $9 trillion ($450 billion per year) – will be in more efficient energy saving equipment and buildings.

These shifts raise important financing issues:

- **The cost structure of low-carbon power**, with high upfront capital and low operating cost, makes the cost of capital, and therefore the perception of risks, particularly important. If required returns can be reduced by 100-300 basis points, the levelized cost of renewable energy would fall by 10-20%. Policies which increase the predictability of long-term cashflows (e.g. delinking low-carbon energy prices from volatile fossil fuels markets) will spur more rapid deployment and reduce prices for energy consumers.

- **"Atomized" energy efficiency* investments**, involving decisions by multiple individual households and companies, make appropriate regulation and, in some cases, temporary fiscal investment incentives vitally important.

- **High investment needs in developing economies** imply a major role for multilateral and national development banks and for global concessional financial flows.
- Fossil fuels companies and investors face complex challenges arising from the fact that **although total fossil fuels investment must decrease, large investments in some fossil fuels are still required** over the next 15 years to meet global/regional energy needs.

Enabler 2 – **Integrated public policy framework**

Public policy must ensure that private stakeholders face credible and reliable market signals and incentives. This requires the following:

- **Carbon pricing*** – an explicit, predictably rising, forward price curve for carbon, resulting from policy, reaching approximately $50 per tonne in the 2020s and rising to around $100 per tonne in the 2030s – is essential to drive decarbonization beyond power, to reinforce regulatory-driven improvements in energy productivity and to prevent falling fossil fuels prices from undermining the pace of the energy transition. Extensive fossil fuels subsidies, which create powerful incentives for wasteful consumption and often primarily favor middle and high income groups, should be phased out.
- While carbon pricing levers are important, they are not sufficient by themselves. Other crucial public policy levers include:
  - **R&D and focused deployment support** for a range of low-carbon technologies, in particular those which will enable decarbonization beyond power;
  - **Market redesign and pricing mechanisms, especially in the power market** to encourage the most efficient integration of large-scale renewables coupled with stronger flexibility management and phase-out of old coal plants;
  - Continued implementation of **performance standards and other regulations** to drive energy efficiency improvement;
  - **Transport systems and urban planning** which make it possible to grow GDP rapidly while limiting the growth of energy-based services;
  - **Integrated energy system planning** to ensure adequate coordination across a diversity of sectors (e.g. enabling much greater use of electricity across multiple sectors).
- In addition, **policy needs to entail a strong focus on the distributional implications of specific national energy transitions**, especially the implications for jobs and end-user consumer energy costs. If potential downsides for specific groups are not recognized and addressed, political resistance will make progress slower and increase the eventual costs.

COUNTRY-SPECIFIC TRANSITION PATHWAYS

All four energy transitions will be important in every country, and **INDCs should identify how to secure progress along each dimension. Action over next 15 years is critical**. But important differences between countries must also be recognized:

- **Some developing countries, especially low-income countries, face a significant energy access challenge**, which they may have an opportunity to meet by leapfrogging to new and better technologies, avoiding unnecessary investments in fossil fuels and centralized power systems, although progress to date is insufficient.
- **Some densely populated and low-income countries, such as India, might find it more difficult to meet electricity energy needs with zero-carbon power in the short term**; while rich and lightly populated countries such as the US or Australia face far easier challenges in this respect.
- **Conversely, many developing economies have an opportunity to get energy productivity "right first time"** avoiding the lock-in effects that have made it more challenging for some high-income countries to reduce energy use per capita to the 80-100 GJ "benchmark".
- **Fossil fuels exporters, meanwhile, face major adjustment challenges and economic diversification**, which will be most urgent for countries with large and rapidly growing populations.

Introduction

Energy is fundamental to a modern economy and to growth in income per capita. But across the world today there are huge variations in energy use per capita, stretching from over 200 GJ per capita in the US and Australia to only 20 GJ per capita in much of Sub-Saharan Africa[1] **[Exhibit 1, p. 13]****. Expanding access to an affordable, reliable, sustainable and modern energy system for all is critical, but this challenge is far from being met. Today, over 1 billion people do not have access to electricity and over 3 billion people do not have access to clean cooking[2].**

Our challenge is to build an energy system that can expand access to affordable, reliable, sustainable and modern energy services, while allowing the global economy to flourish. This requires a transformation of the global energy system, since, if we meet growing needs for energy-based services* with an unchanged fossil fuels dependent system, harmful climate change is inevitable.

- **In a business as usual scenario, total global energy use would grow from 350 EJ today to 650 EJ by 2050,** but, at that date, many low-income countries will still be far below today's developed country standards of living. If all of the world's projected 11 billion people[3] eventually reached these standards of living by 2100 and required the 177 GJ per capita consumed today across the developed world, total global energy needs would grow more than five times.
- Even if we achieve radical improvements in energy productivity, so that a good standard of living can be enjoyed using just 80 GJ per capita, **total global energy needs will still more than double by the end of the century.**
- But to limit global warming to 2°C, **we need to cut annual emissions from the global energy system from 36 Gt of CO_2 today to 20 Gt by 2040 – i.e. less than half the 47 Gt by 2040 expected in a business as usual scenario – and to reach net zero emissions by the end of the century.**

Within a generation, we must therefore break the historic link between growth in prosperity and growth in energy-related carbon emissions, and instead head towards a zero-carbon economy*. Today's global economy is powered by an energy system that relies on fossil fuels to provide 80% of total primary energy consumption[4], and is responsible for 75% of total greenhouse gas emissions[5]. If we meet growing energy needs with an unchanged energy system, the world could be 4˚C warmer than pre-industrial levels by the end of the century.

"The energy transition represents a huge opportunity for economic and social progress"

Achieving the massive transformation in energy systems required, and doing so rapidly, poses huge challenges both on the demand side and the supply side of the energy system, but it also represents a huge opportunity for economic and social progress.

Without an energy transition, local air quality would deteriorate, especially in cities where pollution from transport and power is already posing a serious health hazard. The World Health Organization estimates that 3 million people die prematurely each year due to poor outdoor air quality, nearly 90% of those in low- and middle-income countries[6]. The economic cost of local air pollution is also high – estimated at a minimum of 2% and a maximum of 10% of GDP across G20 economies[7]. The IMF fiscal affairs team estimates an economic burden of well over $5 trillion associated with fossil fuels burning[8]. Irrespective of climate factors, there is a strong public health and local environmental case for addressing these costs.

1) UNDP (2015), Human Development Index / World Bank (2016), Databank.
2) Sustainable Energy For All (forthcoming), 2017 Global Tracking Framework.
3) United Nations, Department of Economic and Social Affairs, Population Division (2015), World Population Prospect: The 2015 Revision.
4) IEA (2016), Energy Technology Perspectives. Data from 2013.
5) IPCC (2014)
6) World Health Organization (2016), Ambient (outdoor) air quality and health, Press Release, September 2016, available here: http://www.who.int/mediacentre/factsheets/fs313/en/
7) The New Climate Economy (2014), Better Growth, Better Climate
8) Clements, B.J., Coady, D., Fabrizio, S., Gupta, S., and Serge, T. (2013), Energy Subsidy Reform: Lessons and Implications. International Monetary Fund, Washington, DC.

The transition to low-carbon energy systems is also likely to drive improved energy access, accelerating the provision of low-cost, decentralized clean energy services, and hence directly contributing to poverty reduction. Sustainable Development Goal 7 is devoted to access to affordable, reliable, sustainable and modern energy for all. In addition, innovations directly linked to energy transitions have the potential to create positive technological spillovers, generate new jobs and improve energy security. **To limit the rise in global temperatures to well below 2˚C while expanding energy access, future energy systems require rapid progress on two dimensions** [Exhibit 2, p. 14].

- Energy productivity – i.e. GDP per unit of energy – needs to grow by close to 3% per annum, allowing developing economies to grow rapidly, but in an increasingly energy-efficient fashion, and enabling developed economies to reduce total energy demand, while maintaining steady economic growth.
- Simultaneously, the share of energy demand delivered by zero-carbon sources has to grow by at least one percentage point per annum.

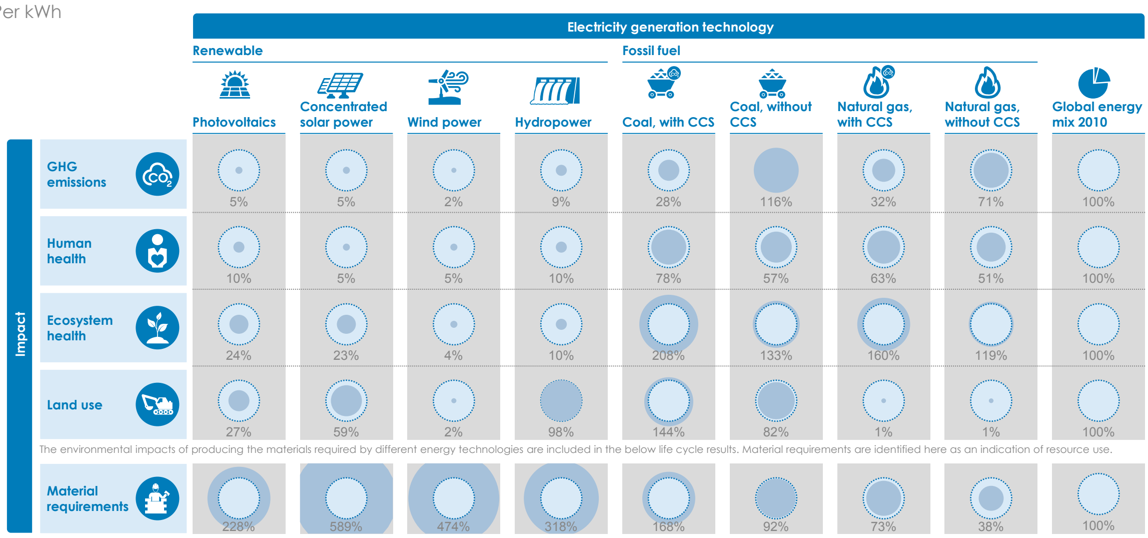
As [Exhibit 2, p. 14] shows, **this pace of improvement would need to be far higher than the global economy has achieved over the last 30 years**, and while implementation of the current INDCs* would deliver significant improvement on both dimensions, this would still be far from sufficient to limit global warming well below 2°C. The ETC's own review of the INDCs[9] confirmed the findings of UNEP (and many others) that the current INDCs are more in the range of 3˚C pathway and, in addition, that, beyond a relatively clear agenda in the power sector, there is very little clarity about how to drive decarbonization across the economy as a whole [Illustration 1, p. 24]. The huge scale of the challenge must therefore be recognized. There are many potential barriers to success – in particular if inappropriate policies and investments over the next 15 years leave economies locked in to high-carbon, energy-intensive systems.

"Implementation of the INDCs would still be far from sufficient to limit global warming well below 2°C"

In addition, **this energy system transformation needs to be managed in the context of wider economic and environmental challenges**, such as those relating to the lifecycle of raw materials used to manufacture renewable technologies

Beyond greenhouse gas emissions, the environmental impact of power generation varies significantly for different technologies

Per kWh



SOURCE: UNEP (2015), How energy choices influence the human future, Infographics, International Resource Panel

Exhibit 5

9) Energy Transitions Commission (2016), Pathways from Paris: Assessing the INDC opportunity.

or to land use. Exhibit 5 describes how different power generation technologies score in terms of different environmental impacts, with the impact of the global energy mix in 2010 defining the index of 100[10]. While in general the renewable power technologies have less impact than fossil fuels, some of them, for instance concentrated solar power and hydropower, have important material requirements and land use implications. Meanwhile, bioenergy – which may be required to decarbonize activities which cannot be electrified – imposes major land use impacts.

Overall, current models of land use result in significant greenhouse gas emissions (up to 25% of the total); conversely, however, effective land use management could sequester up to an additional 7 Gt per annum[11]. **Over the next 25 years, we will therefore see increased competition for land and water**, given growing demand for food, animal feed, bioenergy, forest products, and renewable energy, as well as for carbon sequestering forest or other land management approaches. Individual countries will need to develop explicit strategies to resolve these competing demands. It is clear that there are very few choices around the energy system that do not involve some tradeoffs or have indirect, unintended consequences.

Despite these complications, the ETC is confident that the required energy systems transition is technically and economically possible. **Fueling our future prosperity with a low-carbon energy system* will depend on simultaneously achieving four crucial transition strategies** [Exhibit 3, p. 15]:

1. Decarbonization of power combined with extended electrification;
2. Decarbonization of activities which cannot be cost-effectively electrified;
3. Acceleration in the pace of energy productivity improvement;
4. Optimization of fossil fuels use within overall carbon budget constraints.

We describe each of these transitions in turn below and Exhibit 4, p. 16, illustrates how much each transition might contribute to progress towards a low-carbon economy between now and 2040[12]. If achieved, these reductions would put the world on a growth path compatible with the well below 2˚C warming objective, but realizing this potential will require strong action from public and private decision-makers.

Until 2040, decarbonization of power combined with extended electrification (1) and energy productivity improvements (3) represent the biggest prizes, accounting for 78% of the potential emissions reduction. Beyond 2040, achieving the further emissions reduction required to reach a well below 2˚C pathway will only be possible through far greater progress on decarbonization beyond power (2).

In Sections 5 and 6, we then describe **the major shift in the mix of investment** that this implies and **the policies required** to make these transitions possible. We conclude in Section 7 by considering ways in which **the specific nature of the transition might need to vary between countries**.

10) For instance, 1 kWh generated by a coal-fired plant has twice the impact on ecosystems than 1 kWh produced with the average global power mix today, whereas the same kWh produced with wind turbines generates only 4% of the impact of the average global power mix today. Conversely, 1 kWh generated by a non-abated gas plant requires less than half the amount of materials needed to produce 1 kWh with the average global power mix today, whereas concentrated solar power has 6 times higher material requirements.
11) Adams, J. (2016): This Decade's Most Important Climate Solution, The Nature Conservancy, available here: https://global.nature.org/content/this-decades-most-important-climate-solution
12) Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission.

Illustration 1

Analyzing the INDCs[13]

Current INDCs will not limit global warming to well below 2°C. If fully implemented, they will set the average global temperature on a path to rise between 2.2°C and 3.4°C by 2100. The INDCs are due to be revised and strengthened every 5 years following the Paris Agreement, with the first revision due in 2018. Our analysis of the current INDCs reveals five overall trends:

- A massive expansion in renewable electrical energy. Worldwide, the planned aggregate increase in power generation from renewable energy by 2030 (4,400 TWh) is more than double the planned increase from fossil fuels (1,800 TWh). This will give renewables roughly one third of the combined power supply mix in 2030, up from 20% today.

- Limited growth in natural gas-fired power generation and significant growth in coal-fired power in developing countries. Natural gas-fired power generation will see a net increase of almost 1,600 TWh, but only about 480 TWh of this will be in industrialized nations. Currently planned growth in coal-fired power generation in China and India of more than 1,800 TWh will exceed the expected reduction in developed countries of about 1,400 TWh. A continuing expansion in coal-fired capacity would risk locking energy systems into rising emissions from coal-fired power, especially as there are no compensating large commitments to CCS in most INDCs.

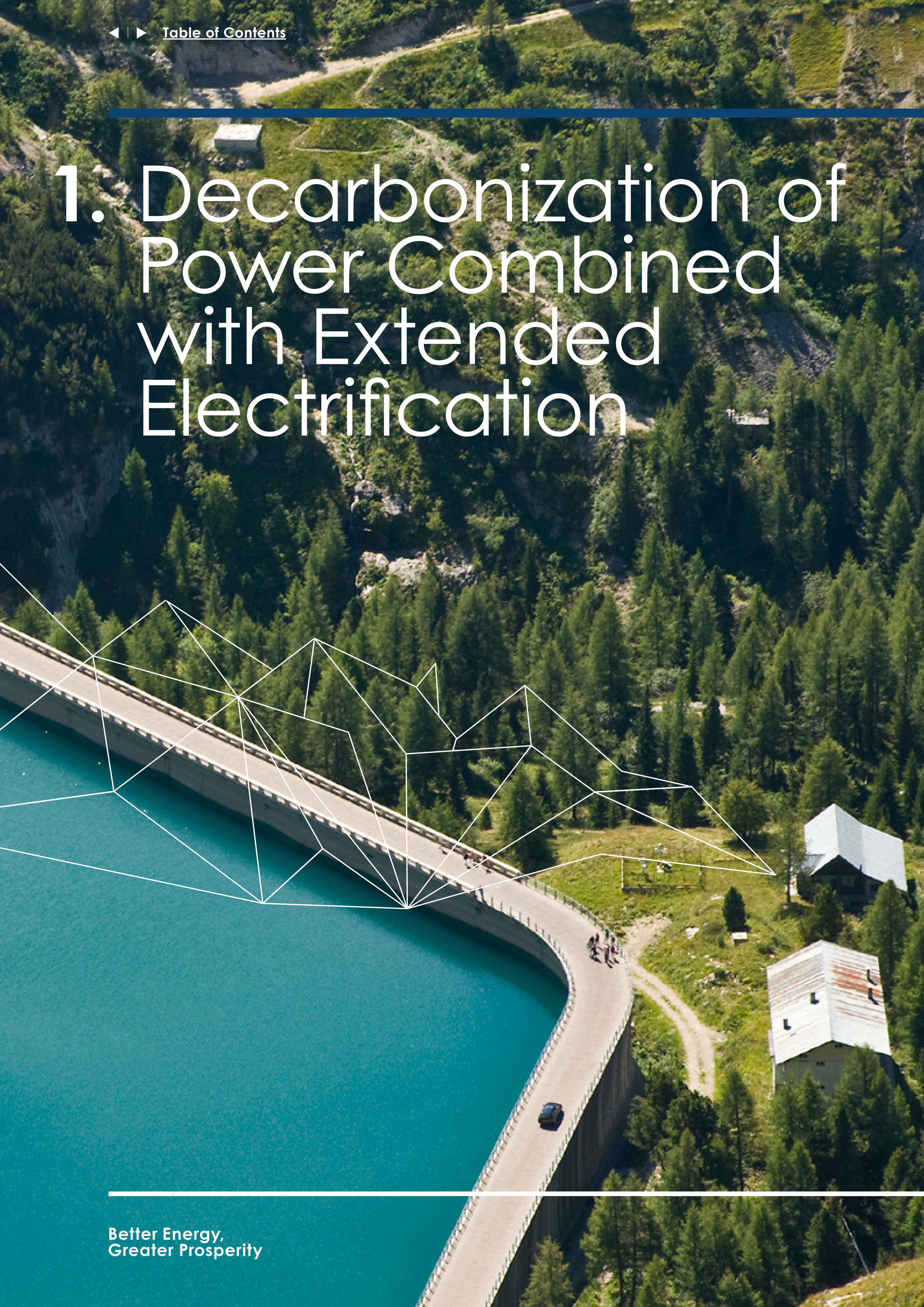
- Very limited measures to decarbonize energy supply beyond the power sector. Few INDCs specify details about how to decarbonize energy supply to the transport, building or industry sectors, either directly or through increased electrification.

- Average energy productivity to improve by 1.8% a year, but with large variations. This estimated improvement will mainly result from China and India's better performance achieved through greater energy efficiency and a structural shift from industry to less energy-intensive sectors. However, INDCs rarely specify how different sectors are likely to achieve these efficiencies.

- One fifth of the total emissions reductions depends on international financial support and technology transfer to developing countries. 100% of the planned emissions reductions of Ethiopia and India are described as being contingent on some degree of international financial support, as are about 70% of Vietnam, 60% of Nigeria, and 30 to 50% of Argentina, Indonesia, and Mexico. This points to the critical importance of strengthening mechanisms for international capital mobilization, such as the multilateral development banks and specialized 'climate finance' vehicles.

13) Energy Transitions Commission (2016), Pathways from Paris: Assessing the INDC opportunity.

1. Decarbonization of Power Combined with Extended Electrification



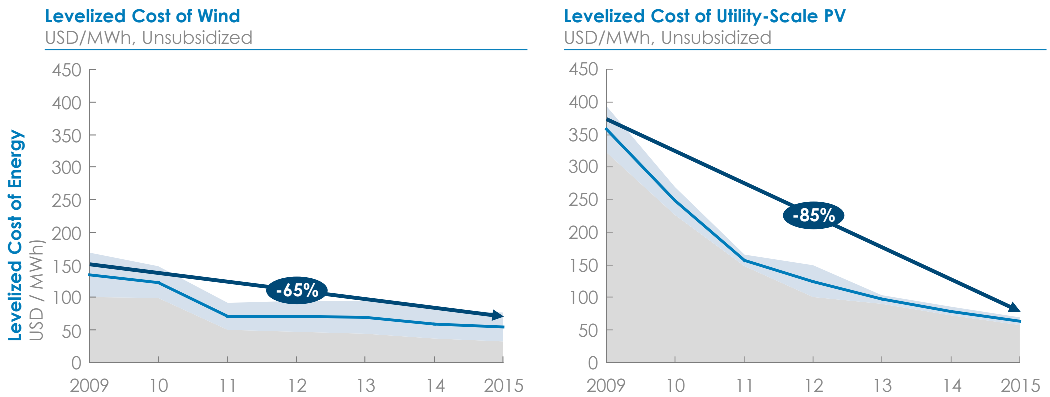
Today, electric power accounts for 17% of total final energy demand, 37% of total energy consumption and 40% of CO_2 emissions[14]. Decarbonizing power generation would therefore be essential, even if the only emissions eliminated as a result were those currently produced within power generation. But the prize from decarbonization of power is far more important than these figures suggest since, once power generation is clean, the electrification of a far wider set of economic activities across the transport, buildings and industry sectors can further displace fossil fuels use. Overall we estimate that power decarbonization combined with extended electrification could reduce emissions by up to 13 Gt of CO_2 per annum in 2040 versus business as usual, achieving almost 50% of the reductions required to keep global warming below 2°C (see Exhibit 4 in the Executive Summary).

There is already great momentum behind the cost-competitive deployment of renewables, and progress is building also in the electrification of key applications, especially in transport. The ETC is therefore confident that a low-cost, low-carbon power system is achievable in most geographies, provided an adequate policy framework continues to drive down the cost of renewable power generation and flexibility.

A. DECARBONIZATION OF POWER SUPPLY

The ETC is confident that power supply can be decarbonized at an affordable cost, because of dramatic cost reductions in renewable power generation and storage technologies such as batteries, as well as the potential to use a wide range of other technologies and techniques (e.g. demand management) which can reduce the cost of providing flexibility in renewable-based power systems. In this section, we describe (i) our estimate of the likely future cost of a new near-total-variable-renewable power system, and how this could be further reduced, and then (ii) the implications of these cost estimates for power system evolution.

Wind and solar costs have declined significantly in recent years



Recent Bid Prices (wind)
- 30 USD/MWh Onshore – Morrocco, Jan. '16
- 35 USD/MWh Onshore – USA, '15
- 50 EUR/MWh Offshore – Denmark, Nov. '16
- 55 EUR/MWh Offshore – Netherlands, Dec. '16

Recent Bid Prices (PV)
- 24 USD/MWh – Abu Dhabi, September '16
- 27 USD/MWh – Mexico, February '17
- 29 USD/MWh – Chile, August '16
- 30 USD/MWh – Dubai, May '16

NOTE: USA 2015 wind bid price adjusted for Production Tax Credit. According to LBNL's 2015 Wind Technologies Market Report, 2015 USA PPA prices are as low as ~20 USD/MWh after PTC, plus an adjustment of 15 USD/MWh levelizedvalue of the PTC.
SOURCE: Lazard Levelized Cost of Energy 9.0 (2015), Greentech Media, Lawrence Berkeley National Lab

Exhibit 6

14) IEA World Energy Outlook (2015). Data from 2013. / IPCC (2014).

Over the last five years, solar power costs have come down by 80%, and the cost of wind power by 60%, and in some favorable locations auctions* for power are now being won by renewable generators at prices as low as $25/MWh (excluding any subsidy), which is below the cost of fossil fuels competitors [Exhibit 6, p.27].

"We observe dramatic cost reductions in renewable power generation and storage technologies"

Looking forward to 2035, it is likely that renewable energy will be available at similar costs across much of the world – with still lower costs very likely to be achieved in future in favorable locations. Predictable technological progress provides the momentum behind this cost pathway. It needs to be combined with the right policies, institutions, market design and financing arrangements.

Generation and flexibility costs within a near-total-variable-renewable power system*

The analysis carried out by Climate Policy Initiative (CPI) for the ETC[15] suggests moreover that the challenges created by the intermittent nature of renewables can be overcome at a reasonable cost given already available and rapidly evolving technologies. There is no technical barrier to the deployment of variable renewables in the power sector and flexibility options will become available at increasingly lower cost in most geographies. By 2035 at the latest, a near-total-variable-renewable power system could be competitive with a system based on gas-fired power generation in many geographies, provided an adequate policy framework drives the development and use of low-cost flexibility solutions.

Annual shifting needs in a near-total-variable-renewable power system could represent about 25% of total load, half of that requiring intraday shifting* and the other half interday/seasonal shifting* [Exhibit 7]. In countries with large hydro resources (whether already existing or still to be developed), hydropower will often provide the most cost-effective flexibility option. In other countries, there are two basic technologies to provide storage and backup: these are lithium ion batteries (for intraday load shifting) and gas turbines (to deal with imbalances between supply and demand over several days or longer).

We have modelled what the maximum cost to provide flexibility and backup would be even if these were the only two technologies available. Given the rapidly falling costs of the former [Exhibit 8] and the already relatively low capital cost of the latter, we believe that **close to zero-carbon power systems with very high levels of intermittent renewable penetration** (up to 98% in countries like Germany) **could deliver reliable power in many countries at a maximum of $70 per MWh by 2035**. This $70 would cover $40 per MWh of levelized renewable power generation cost – which is likely to be a very conservative assumption given the observed prices of the most recent bids –, and $30 per MWh to cover all necessary system balancing and backup costs [Exhibit 9, Exhibit 10 and Exhibit 11].

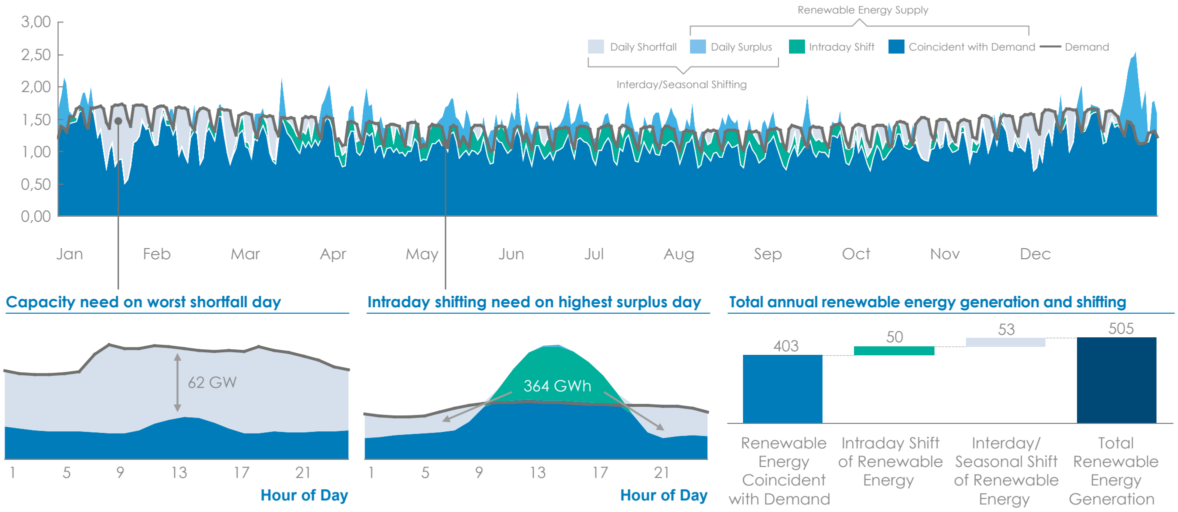
In reality, these forecasts for the costs of integrating intermittent renewables in the grid are likely to be conservative. **The flexibility cost of $30 per MWh could be significantly reduced** if, rather than simply relying on lithium ion batteries and gas turbines, we used the full range of potential flexibility resources outlined on Exhibit 12, p. 32 and 13, p. 32. For instance, enhanced inter-regional transmission capacity could cut the cost of interday/seasonal shifting by a further 60%, especially if better operations management facilitates the wider utilization of existing infrastructure. Automated load shifting, incentivized by appropriate tariffs, could halve the cost of intraday shifting. In addition to the options explicitly modelled on Exhibit 13, p. 32, multiple other means exist to store energy: for instance, large-scale heat storage or distributed thermal storage in the built environment may be an important option in some countries, and compressed air is an alternative technological approach.

Demand management could play a major role in providing low-cost flexibility. In principle, at least 25-40% of all electricity use is not extremely time-critical and could be shifted away from peak

15) Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility. Research paper for the Energy Transitions Commission.

In a near-total-variable-renewable power system, annual shifting needs could represent about 25% of total load in a country like Germany

Example: Germany, Variable Renewable Energy System
Variable Renewable Energy Generation: 64% Wind, 34% Solar, 2% Run of River Hydro, Daily TWh



SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 7

demand periods, without adversely affecting customers. EV* charging could rapidly become a significant source of flexibility, provided adequate incentives are in place. Power-intensive industries might also offer one of the cheapest source of load shifting provided a reliable, long-term planning horizon is secured [Exhibit 14, p. 33]. But the large potential to reduce costs by deploying demand management will not be achieved unless electricity market design and customer pricing policies create the right incentives for demand shifts, and unless smart metering and related control and forecasting systems are deployed at scalescale [Exhibit 15, p. 35].

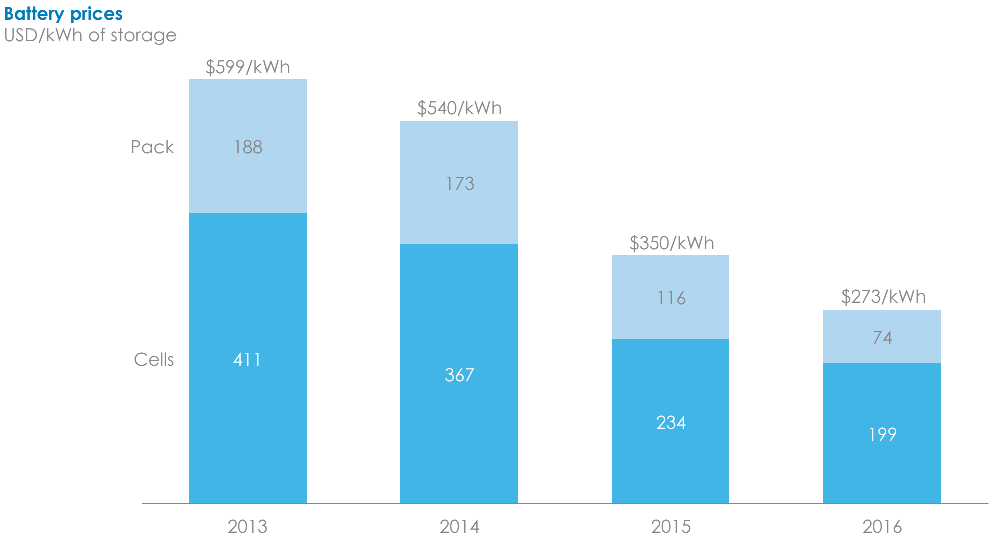
"Demand management could play a major role in providing low-cost flexibility"

It is therefore vital to seek lowest cost flexibility provision. This will vary by geography and the challenges may be greatest in some developing countries; but the multiple options available make it likely that in many countries the cost of electricity in a close to zero-carbon power system could be significantly lower than $70/MWh by 2035, with the $70/MWh achieved much earlier. Moreover, case studies carried out on four different regions – California, Germany, Maharashtra, and the Nordic region – show that, in most cases, **flexibility resources already available today are sufficient to cope with renewables deployment by 2025**, by which date some regions plan to reach 40% of variable renewables penetration [Illustration 2, p. 33].

The example of Maharashtra shows, however, the challenges created in developing countries by rapid power demand growth. To deal with rapidly increasing daily ramp-up needs (due to growing consumer use in the evenings combined with higher solar penetration) and high seasonal variations in renewable power generation, India will have to invest significantly in expanded inter-regional connections, better leakage control, development of storage capacity and increased forecasting capacity. Constraints on capital and technology availability could make such investments costlier in developing countries than in developed countries if appropriate policies are not put in place[16].

16) Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility. Research paper for the Energy Transitions Commission.

Cost of batteries has declined significantly in recent years



SOURCE: Bloomberg New Energy Finance 2017

Exhibit 8

A mixed flexibility system of gas and storage matches the cost of a pure CCGT based system – i.e. at about 22 USD/MWh – even without a carbon price

Intraday Balancing provided by:	Gas Only (with no Carbon price)	A mix of Gas and Storage (with no Carbon Price)
CCGT		
Capacity	62 GW	50 GW
Energy Generated	50 TWh	17 TWh
Capacity Cost per Year	140 USD/kW-yr	140 USD/kW-yr
Variable Cost	50 USD/MWh	50 USD/MWh
Total Cost	**11.2B USD**	**7.8B USD**
Lithium Ion Battery		
Capacity		21 GW x 136 GWh
Energy Shifted	-	33 TWh
Capacity Cost per Year	-	160 USD/kW-yr
Variable Cost (Losses)	-	3.2 USD/MWh
Total Cost	-	3.5B USD
Total	**11.2B USD**	**11.3B USD**
Cost Per MWh Shifted (50 TWh)	225 USD/MWh	229 USD/MWh
Cost Per MWh of Total Load (505 TWh)	**22.1 USD/MWh**	**22.5 USD/MWh**

- Costs are similar for a gas only and mixed system without a carbon price.
- With a carbon price the mixed system will be a significantly less expensive option and would further reduce carbon emissions by 13 MT per year.

NOTE: Excludes cost of curtailment to avoid double-counting with energy generation cost
SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 9

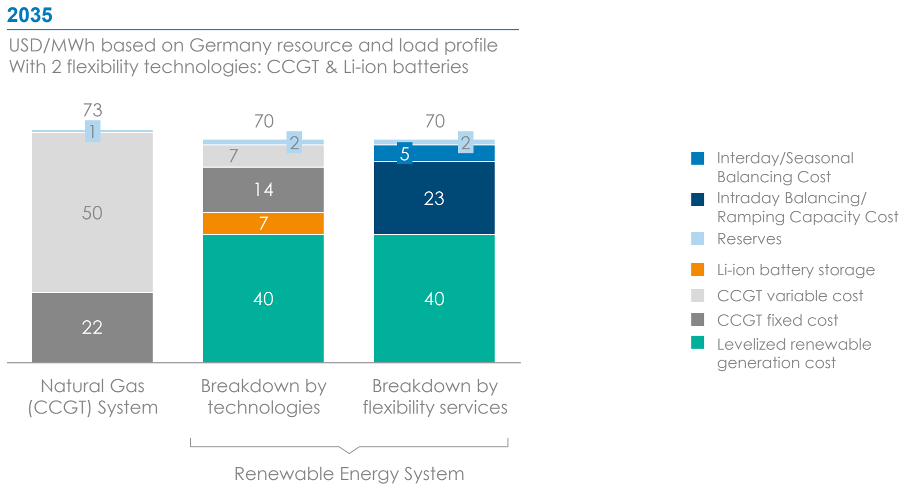
The additional cost of interday/seasonal balancing in a near-total-variable-renewable power system could be as low as 5 USD/MWh using existing CCGT capacity

CCGT	CCGT to provide Interday/Seasonal balancing (with no carbon price)
Capacity	62 GW
Energy Generated	53 TWh
Capacity Cost per Year	Counted under Intraday Balancing
Variable Cost	50 USD/MWh
Total Cost	**2.6B USD**
Cost Per MWh Shifted (53 TWh)	50 USD/MWh
Cost Per MWh of Total Load (505 TWh)	**5.2 USD/MWh**

NOTE: Excludes cost of curtailment of renewable energy to avoid double-counting with energy generation cost
SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 10

By 2035, a fully loaded near-total-variable-renewable power system using CCGT and batteries to provide flexibility could be competitive with a natural gas power system



NOTES: "Intraday Balancing Cost" includes fixed cost of CCGT, "Interday/Seasonal Balancing Cost" only includes incremental generation cost from same CCGT. Levelized renewable energy generation cost includes all energy potentially produced, including amount curtailed or stored/shifted.
SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 11

A variety of flexibility solutions are available to meet load shifting needs in a near-total-variable-renewable power system, in addition to CCGT and batteries

Flexibility Option		Existing	New Build	Description
Supply Side	Gas Turbine		✓	▪ Open cycle combustion turbine running on natural gas
	Gas CCGT	✓	✓	▪ Combined cycle generator running on natural gas
	Coal	✓		▪ Pulverized coal-fired power plant with capital costs fully depreciated
	Reservoir Hydro	✓		▪ Existing dispatchable hydro generation with capital costs fully depreciated
Demand Side	EV Charging		✓	▪ Shiftable electric vehicle charging ▪ Typical shiftable throughout the day if sufficient infrastructure exists to ensure vehicle is connected to the grid ▪ Costs are based on the cost of an additional level-2 vehicle charger to enable flexible charging
	Residential/Commercial Automated Load Shifting		✓	▪ Automation of lighting, heating and cooling loads in residential and commercial buildings ▪ Cost includes automation (e.g. auto DR, smart thermostat, or direct load control) and telemetry equipment needed for
	Industrial Load Curtailment		✓	▪ Manual or automated load shedding from industrial loads ▪ Cost includes switches and automated controls, as well as opportunity cost of load-shedding (e.g. lost production)
	Industrial Load Shifting		✓	▪ Running industrial process (e.g. electric arc furnace or aluminum smelter) below capacity to allow seasonal shifting
Energy Conversion	Hydrogen Electrolysis		✓	▪ Hydrogen electrolysis (costs based on cost targets for polymer electrolyte membrane electrolyzers) ▪ Hydrogen storage in pressurized tanks (short-term storage) or geologic storage (long-term storage) ▪ Open cycle combustion turbine to generate power from hydrogen
Energy Storage	Lithium Ion Battery		✓	▪ Grid-scale lithium ion battery installation ▪ Costs include battery cells, inverters, controllers and balance of plant
	Pumped Hydro		✓	▪ New build pumped hydro facility
Infrastructure	Transmission Interconnection		✓	▪ Transmission infrastructure to connect regions to capture benefits of complementary load and resource profiles, as well as to connect markets with low-cost flexibility resources (e.g. existing hydro) with markets that face flexibility needs

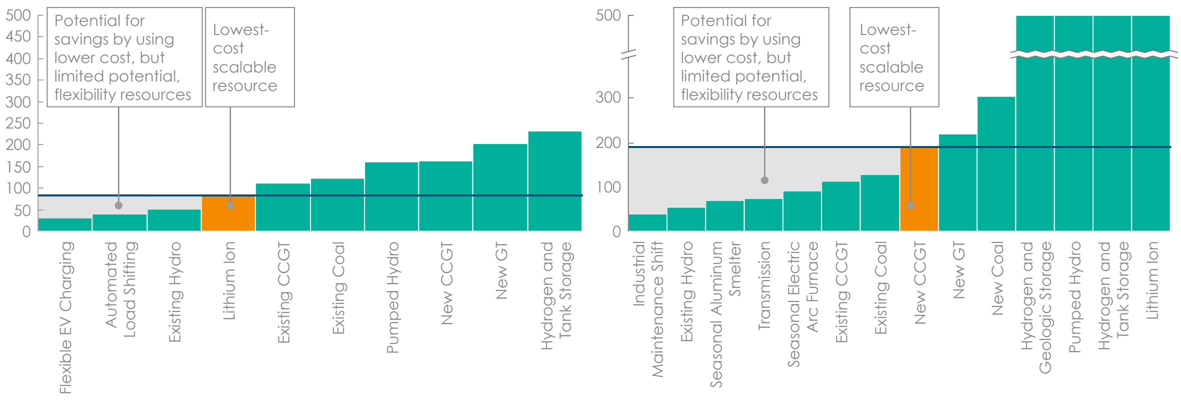
SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 12

Many flexibility resources have lower costs than the default technology and represent a potential for additional savings

Cost of Intraday Shifting Resources at 30% load factor – Post-2030 Costs
USD/MWh shifted

Cost of Interday/Seasonal Shifting Resources – Post-2030 Costs
USD/MWh shifted



NOTES: 30% load factor is roughly equivalent to storage operating 8 hours per day. Seasonal shifting assumes that new capacity is required to meet this load and includes fixed costs. Often, seasonal shifting can share capacity that is developed to meet intraday balancing needs. Includes $50/tonne carbon price.

SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 13

Illustration 2

California: low-cost flexibility resources in an existing power system

Climate Policy Initiative modelled a power system based on near-total-variable-renewable power generation (e.g. 90% or more), assuming that only two flexibility resources are available (lithium ion batteries and gas turbines). This model estimates the maximum cost of integrating intermittent renewables in the grid at $30/MWh. In real power systems, we expect this cost to be up to 50% lower. Real costs will vary greatly by region, depending on existing flexibility resources.

For California, we estimate that the 2040 flexibility cost could be 30-50% lower given the various low-cost flexibility resources likely to be available by then.

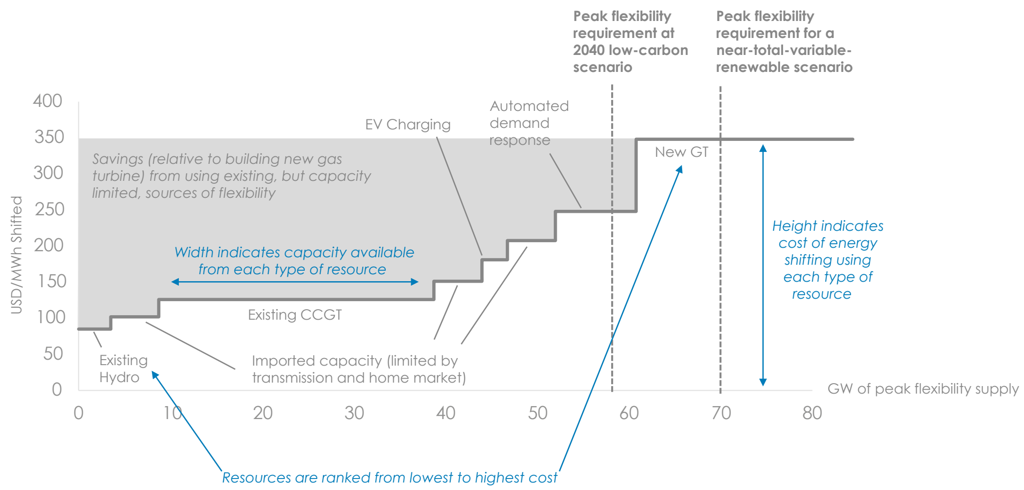
Today, almost one-quarter of California's electricity comes from intermittent renewables, with a nearly even split between solar and wind. By 2040, residential and utility scale solar are expected to supply 36% of the State's electricity production, with wind generating an additional 30%. Given the expected load profile, peak intraday flexibility needs could reach 70 GW.

If no existing or demand-side flexibility was available, these peak flexibility needs would be met by building new gas turbines. However, as Exhibit 14 shows, there will be approximately 60 GW of lower cost flexibility options available in the Californian power system. This would include existing hydro – as the State imports 25% of its electricity, including significant quantities of hydroelectric power generation from the northwest – and existing CCGTs*, as well as demand response, especially related to electric vehicle charging. The estimate also takes into account interconnections to Nevada and Arizona. Using the lower-cost options first, rather than relying solely on new gas turbine plants, would reduce intraday flexibility costs by almost 50% if California had then reached a near-total-variable-renewable power system, and by almost 60% under the more likely 65%-70% variable renewable penetration scenario.

As for the next 10 years, California already has sufficient flexibility resources to meet flexibility needs. Ramping due to the increase in rooftop solar is the most pressing concern, by contrast seasonal storage will only become a priority at much higher levels of variable renewables than currently planned for 2025.

Developing and increasing the role of demand response and flexibility requires further development of forecasting, business models and technology – especially automation

Cost and supply of California peak intraday shifting using the lowest-cost available options
USD/MWh shifted, 2040



SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 14

The way forward

Power market design

Electricity systems must now strike the right balance between encouraging capital intensive variable renewable power generation and incentivizing a diverse range of measures to supply flexibility to the system. In this context, key principles for developing and reforming electricity markets include:

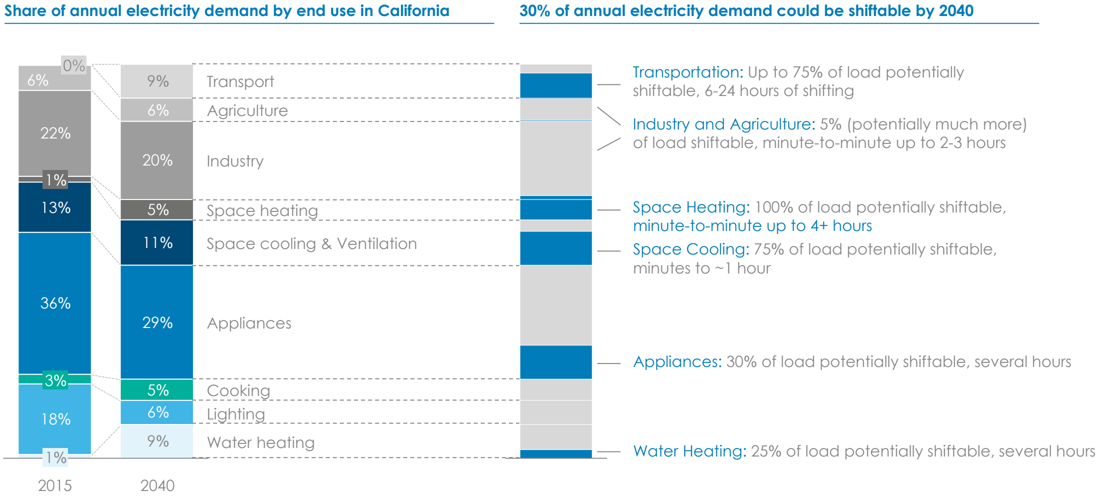
- Real-time and locational price signals that incentivize the provision of flexibility when and where it is most valuable;
- Price signals to electricity consumers or aggregators to encourage energy shifting and other flexibility services from the demand side;
- Market mechanisms that drive efficient investment in new power generation, flexibility and infrastructure;
- Allocation of risks, such as fuel price volatility or resource variability, to those actors best suited to manage or control them;
- Harmonization of market design across neighboring jurisdictions to smooth regional variations in demand and energy resources and utilize existing resources most efficiently;
- Incorporation of external environmental costs, such as carbon emissions and local air pollution, into operational and investment decisions;
- Targeted policies and market mechanisms to support emerging technologies that may not be competitive today but hold great promise for reduced future costs.

The specific application of these principles will vary across regions. In many developing economies, expanding access to electricity is paramount. This requires a stable environment for investment and careful planning to ensure system reliability. In some cases, new models such as off-grid systems and micro-grids may be the most cost-effective option, and regulatory and market approaches designed for centralized grids may not be suitable. In some developed economies, electricity demand may not grow significantly, but markets must support significant investment in low-carbon power generation while providing clear signals for the value of flexibility.

Regional differences notwithstanding, the energy transition puts renewed focus on the role of electricity markets, which will have significant consequences for whether a low-carbon electricity grid can be achieved at low cost.

In this context, appropriate power market design will be crucial to incentivize the development of low-cost flexibility solutions, drive down the cost of renewables investments, and therefore accelerate the decarbonization of power. While all power market structures are based on some common objectives – such as affordability and reliability of supply – they differ greatly in how they seek to achieve them. In regulated markets, electricity pricing and new investments are controlled. In 'deregulated' markets, such as those in parts of the US and Europe, operational and investment decisions of the power sector are determined by price dynamics in wholesale electricity markets. Most of the prevailing market structures were designed for circumstances that no longer pertain. Hourly pricing models, for instance, were largely designed to optimize the dispatch

Electric vehicles, heating, cooling and buildings appliances are easily shiftable loads and, with the right incentives, can increasingly contribute to system flexibility



Source: CPI analysis, based on E3 Pathways study

Source: CPI analysis; Shiftable shares based on Birrer et. al. (2015), Oak Ridge National Lab (2013) and interviews with industry experts.

Exhibit 15

Developing and increasing the role of demand response and flexibility requires further development of forecasting, business models and technology – especially automation

	Supply and demand forecasting	Market design and flexibility service pricing	Consumer aggregators	Response and control technology	Metering data and analysis	Consumer infrastructure
Role	▪ Provide advance information to flexibility suppliers and operators	▪ Provide short term incentives to respond to flexibility needs and long term incentives to develop new response capacity	▪ Aggregate market to consumers to reduce transaction costs and improve reach and scope	▪ Enable aggregators to access flexibility potential of consumers and respond to market signals	▪ Consumer end use metering to enable control, measurement and payment	▪ Infrastructure that will allow consumers energy demand to be more flexible
Examples	▪ Renewable energy supply forecast ▪ Weather and demand forecast	▪ 5 minute energy markets ▪ Capacity markets ▪ LT contracts for reserve ▪ LT contracts for flexible supply ▪ Annual flexibility auctions ▪ Transmission rights	▪ Energy service companies ▪ Utilities and municipalities ▪ Consumer aggregators	▪ Automated control systems ▪ Internet and broadband based communications ▪ Integration and trading platforms and software	▪ Smart meters ▪ End use meters ▪ End use analysis software ▪ Integration software	▪ Fast electric vehicle chargers to increase EV response ▪ Building insulation to increase heat demand shifting ▪ Appliance control systems for remote response
Current Status	▪ Accuracy and advance timing steadily improving, substantially reducing short term reserve costs	▪ Many examples in place, but most do not yet provide optimum allocation of incentives	▪ Many examples in development, but much greater potential once market design and price signals become more focused	▪ Technology is available, but great potential to refine and expand as incentives and systems improve	▪ Smart meter/end use meter roll out is underway in many geographies, room for improvement in the adoption and cost performance of end use metering	▪ Build out is ongoing, but lack of incentives means development is slow

SOURCE: Climate Policy Initiative (2017), Low-cost, low-carbon power systems: How to develop competitive renewable-based power systems through flexibility.

Exhibit 16

Illustration 3

Pathway to decarbonize power in India

India, like many other developing countries, faces the challenge of balancing several objectives – growing the economy, ensuring access to affordable and reliable energy for all, reducing dangerous levels of local air pollution, and reducing carbon emissions. Getting decarbonization of power right in India would create a compelling roadmap for other countries; it would also make a major contribution to the CO_2 emissions reductions necessary for a below 2°C pathway.

In February 2017, TERI released a report titled "Transitions in the Indian Energy Sector - Macro Level Analysis of Demand and Supply Side Options"[17], which builds on the research commissioned by the ETC. This report comes at a crucial moment for the Indian electricity sector, which must deliver an estimated three-fold increase in power supply from 1,115 TWh today to around 3,200 TWh by 2030.

Key conclusions from this analysis are that, provided the all-in cost of renewable power generation can come down to 5 rupees per kWh (i.e. $7 cents per kWh):

- Current installed capacity, together with the 50 GW of coal plant already under construction or planned, would be sufficient to meet India's growing power demand till about 2026.
- Beyond 2023-24, new power generation capacity could be met entirely with renewables, which would be more cost-competitive than coal-fired power generation.

These findings challenge the conventional wisdom that new coal must continue to play a central role in the Indian power sector for several decades. They reflect (i) power demand assumptions that allow for recent technology and market trends, rather than simple extrapolation from past trends, and (ii) the rapidly falling cost of renewables deployment in India as across the world.

India thus faces a window of opportunity over the next 10 years – potentially switching all new power investment after the early 2020s to renewables and limiting total peak coal use to around 900 Mt per annum (versus the 1.5 Gt currently assumed). To achieve this would require massive investments not only in renewable power generation, but also in the transmission grid and in battery-based balancing power.

of fossil fuels based power (or hydropower in specific geographies like the Nordic Region), and to incentivize investment in plants to meet peak demand. However, they become decreasingly relevant in systems with growing shares of renewable or nuclear power generation. Indeed, as these shares rise, hourly pricing models become ultimately unworkable, since hourly competition between generators with close to zero marginal cost will result in such low average wholesale prices that no new investment will be forthcoming. Most market structures have also been almost entirely supply-focused, with only limited attention to demand-management levers. New power market designs are therefore needed to achieve low-cost delivery of variable renewable power generation, while providing incentives for a diverse range of demand- and supply-side measures to provide flexibility to the system.

17) The Energy and Resources Institute (2017), Transitions in Indian electricity sector, 2017-2030.

Implications of cost scenarios for power system evolution

Our estimated cost for a near-total-variable-renewable power system – at most $70/MWh by 2035 – implies that, **in the long term, many power systems across the world will become almost entirely renewables-based**, and that, from the 2030s onwards (and in many countries earlier), all new power capacity will likely be provided by renewables rather than fossil fuels power plants. **The actual and optimal pace of renewables deployment between now and then, and the resulting share of renewables in the total global power mix, will reflect a number of additional factors**, in particular:

- While it could take 15 to 20 years for the cost of flexibility to fall sufficiently to make a 80-90%-variable-renewable power system cost-competitive, **the costs of providing flexible backup are much lower when renewables penetration is lower**, and large-scale renewables investment is therefore already cost-effective in many regions. In some countries, penetration may well rise to very high levels by the 2030s, by which time the flexibility costs will have fallen sufficiently to make this high penetration economic.
- However, in some countries, **land availability constraints may limit the deployment of renewables**.
- **In some developing economies**, which must increase electricity supply rapidly to support economic growth and social inclusion of a growing population, **there may be limits to the maximum feasible and cost-effective pace of renewables investment**. Several countries are therefore already committed to large-scale coal-fired power generation investments, which can only be compatible with a low-carbon pathway if the plants are later retrofitted with CCS or closed before their technical end of life. India's INDC, for instance, envisages 160 GW of additional coal capacity between 2013 and 2030. However, a recent study by TERI suggests that, with rapidly falling renewables costs, much lower coal investment may be optimal and all electricity demand growth after the 2020s could be met by renewables. Even in this scenario, however, 55% of India's electricity would still come from coal-fired power generation in 2030 (compared to roughly 80% today)[18] [Illustration 3].
- Finally, **existing fossil fuels power plants could have a cost advantage, versus new renewables investments, since able to compete on the basis of marginal cost alone.** A carbon price resulting from public policy between $50-$100 would therefore be required to accelerate the decarbonization of power systems through lower utilization or early retirement of fossil fuels plants, as well as, in some cases, the development of CCS facilities.

Balancing these considerations, **the illustrative low-carbon pathway presented in the Executive Summary assumes that variable renewables could reach roughly 45% of the global power mix by 2040**, with other zero-carbon power sources (most importantly hydro and nuclear) representing about 35%, and non-abated fossil fuels (mostly gas) the remaining 20%[19].

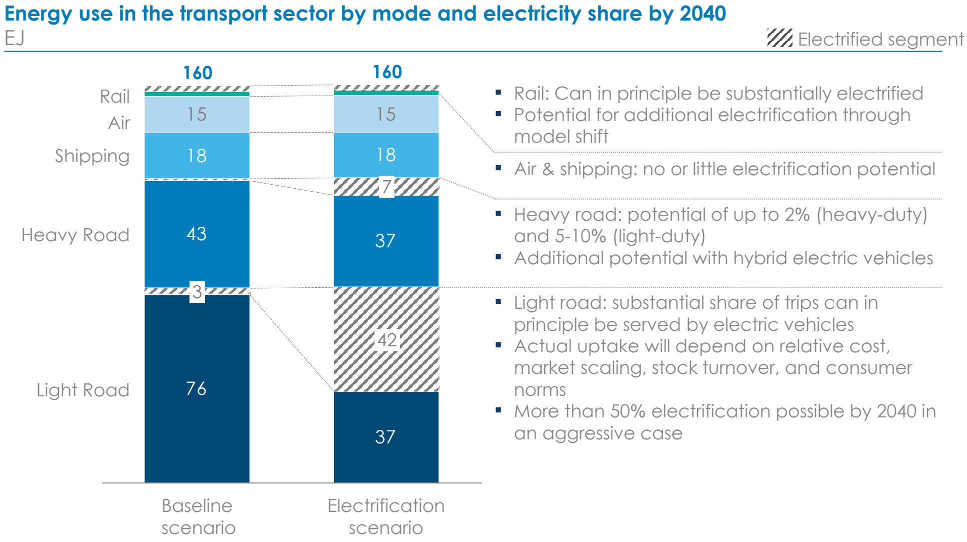
Whatever the precise 2040 situation, it is clear that renewables will be a vital driver of power decarbonization in all countries, and, in many countries, be by far the most important one, with nuclear and carbon capture likely only to be cost-effective in specific contexts.

Nuclear power may find it difficult to compete with a fully loaded cost of renewables of $70/MWh unless significant cost reductions can be achieved. The pace of nuclear investment lost momentum in recent years, due partly to safety considerations following the Fukushima incident, but also to less favorable economics. While the cost of renewables has fallen dramatically, and gas-fired power generation costs have also fallen significantly in some countries such as the US, estimated nuclear power costs have failed to fall or have actually increased. As a result, new plant construction numbers decreased between 2015 and 2016, and several nuclear plants have been stopped in the US. Nuclear will continue to play an important role in some G20 countries, especially those with geographical constraints on the deployment of renewables and limited hydro resources. However, absent a transformation in technology (e.g. small modular reactors) and significant shifts in public acceptance for security- and safety-related risks, the ETC does not see nuclear growing its overall share of total power generation.

18) The Energy and Resources Institute (2017), Transitions in Indian electricity sector, 2017-2030.

19) The ETC illustrative low-carbon pathway assumes roughly 27% wind, 18% solar, 18% hydro, 10% nuclear, 5% bioenergy and other renewables, 2-5% abated coal, 1% abated gas, 9-15% unabated gas, 2-6% unabated coal, 1% oil.

In the transport sector, at least 10-30% of fossil fuel use can be replaced through electrification by 2040



NOTE: Non-electrified segments include, in addition to fossil fuels, hydrogen and biogas.
SOURCE: Copenhagen Economics analysis based on data from IEA, ETP (2016) and the Global Calculator.

Exhibit 17

Similarly, in many countries, carbon capture and sequestration (in CO_2-based products or underground storage) seems likely to play only a minimal role in power systems (while remaining important in the industrial applications discussed in Section 2). Estimated CCS costs have not fallen at anything like the pace achieved in renewables and, even if CCS could be delivered at an average future cost of $50-100 per tonne, it would add up to $2-4 cents per kWh to gas-fired power generation costs and $5-10 cents per kWh to coal-fired power generation costs, making it highly unlikely that new abated coal or gas capacity could provide a cheaper low-carbon solution than renewables. Nevertheless, in developing economies that are already committed to further significant coal-fired power generation investment over the next 10 years – and even if the planned capacity is in the most modern (and hence fuel-efficient) plants – CCS retrofit is likely to be required before end of useful life. However, it may turn out that these investments are lower than predicted even 1-2 years ago and that, as a result, CCS retrofit requirements in the power sector are correspondingly lower.

B. EXTENDED ELECTRIFICATION

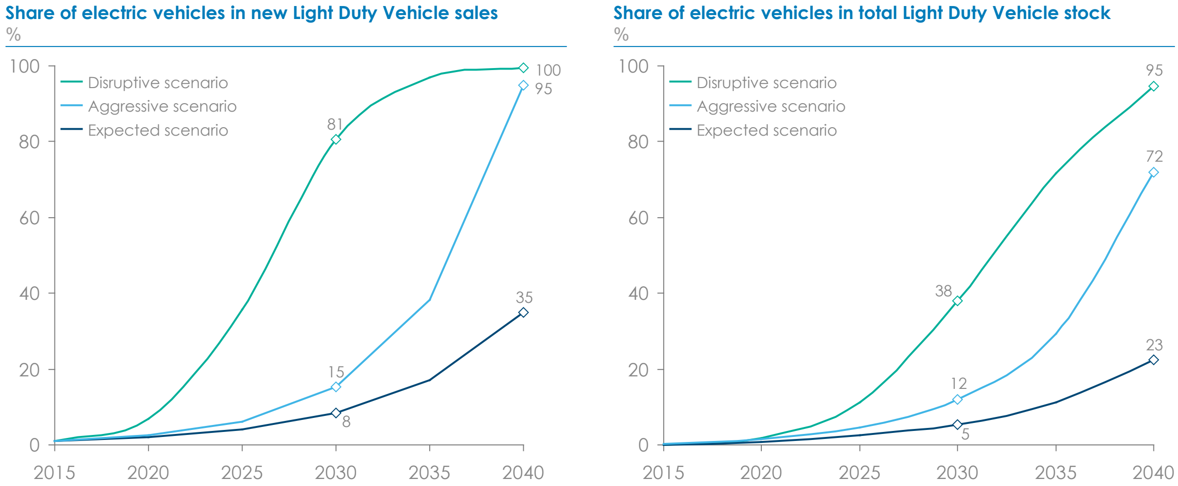
In all countries, rapid decarbonization of the power sector should be a key priority. **Decarbonized power can and should then be applied to a wider range of economic activities.** A conservative scenario suggests that **at least 10-20% of total fossil fuels use could be eliminated by electrification by 2040**[20], with higher percentages in particular in buildings and transport, and with longer term potential to extend electrification to an increasing range of industrial processes.

"At least 10-20% of total fossil fuels use could be eliminated by clean electrification by 2040"

In the transport sector at least 10-30% of business as usual fossil fuels use could be eliminated via electrification by 2040 – and a rapid deployment of electric vehicles (EV) could lead to an even higher percentage [Exhibit 17]. The electrification

20) Climate Policy Initiative and Copenhagen Economics (2017), A New Electricity Era: How to decarbonize energy systems through electrification. Research paper for the Energy Transitions Commission.

An acceleration of the penetration of electric vehicles in the early 2030s would lead to a more disruptive transport electrification scenario



NOTE: Key assumptions on stock turnover: 12-year lifetime for vehicles / 2.9% growth in passenger kilometres
SOURCE: Copenhagen Economics analysis based on data from IEA, ETP (2016) and the Global Calculator.

Exhibit 18

of light vehicle road transport is now underway, potentially delivering major air quality benefits in many cities. As the fleet is electrified, the resulting distributed battery storage capacity could make it easier to manage renewables intermittency, provided appropriate pricing incentives and demand management systems are put in place. Other transport activities such as aviation and heavy goods, which account for some 50% of current energy use in the transport sector, are however unlikely to be extensively electrified in the next few decades.

The higher end of the ETC scenario assumes that electric vehicles could represent up to 95% of new car sales by 2040, which, combined with accelerated turnover due to increased utilization (which would result from car sharing practices), could push the share of electric vehicles in the Light Duty Vehicles (LDV)* stock to 70%. But a very wide range of EV penetration scenarios is possible, implying either significantly slower shifts in energy mix or more rapid change, depending to some extent on future end-user gasoline and diesel prices. A plausible scenario for an accelerated penetration of electric vehicles in the early 2030s rather than the late 2030s could lead to a 90%+ share of electric vehicles in the LDV fleet by 2040, displacing more than 40% of business as usual fossil fuels use in transport[21] [Exhibit 18].

Similarly, in the residential and commercial building sector, at least 35% of the energy needs not currently met by electricity could be electrified by 2040 – and there are reasons to believe that the percentage could be significantly higher. [Exhibit 19, p.40] In principle, all building energy applications can be electrified, and indeed every one of them is already electrified on a significant scale in some countries. There is thus no absolute need to use fossil fuels in any building application. In particular, one-third of space heating could be provided by electricity by 2040 [Exhibit 20, p. 41]. In many locations, the use of heat pump technology will significantly favor electrification. In some newly developing cities, which have more limited space heating needs and have not yet installed gas distribution systems, even induction-based electrification may be a favored least-cost option. However, the appropriate pace of electrification in buildings should reflect its cost-effectiveness relative to other decarbonization options, such

21) Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission.

as district heating and cooling systems, or non-electric solar and thermal energy sources, as described in Section 2b.

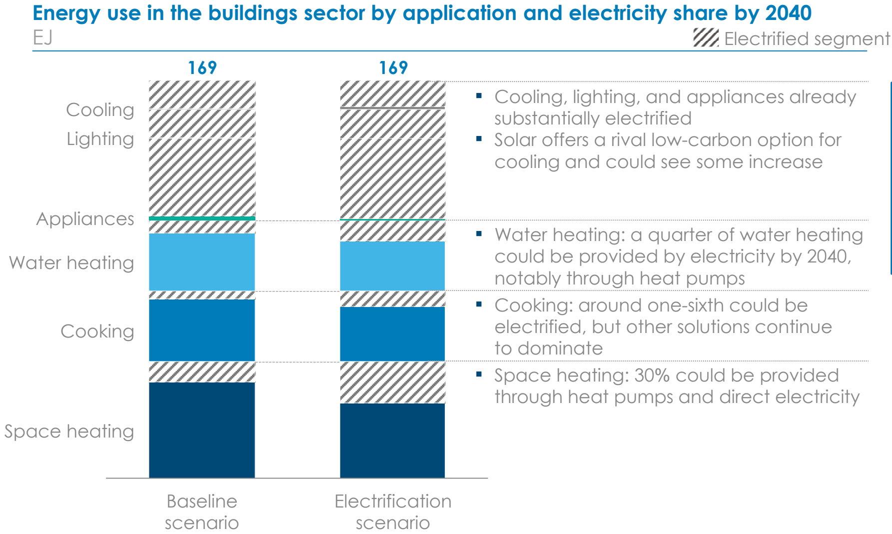
In the industry sector, electrification could play a significant role in the long term, but short-term opportunities for cost-effective electrification – while still important to pursue – are likely to replace only a small proportion of existing non-electricity energy use over the next 25 years [Exhibit 21, p. 42]. Many intense heat-based processes will continue to depend on fossil fuels for some time, making it essential to increase the efficiency with which heat gets used across industrial processes. Better process design, more attention to optimization opportunities across different plants within industrial complexes, and the introduction of advanced control systems can all make a significant difference, as will other decarbonization routes, such as the use of biofuels or carbon capture and sequestration, described in Section 2a.

Overall we estimate that **more widespread clean electrification could replace at least 10-20% of current fossil fuels energy use by 2040** [Exhibit 22, p. 42], eliminating about 2-4 Gt of CO_2 emissions per annum[22] [Exhibit 23, p. 43]. **This would imply expanding power generation to meet an energy demand from transport, buildings and industry rising from 19,000 TWh today to 33,000 TWh by 2040** [Exhibit 24, p. 43]. Significant investments in transmission and distribution grids would also be required, especially in developing countries. The scale of the required investment should not be underestimated. Section 5 describes in more details how the financing implications of this challenge can be met.

This significant expansion in power generation could help to drive further cost reductions in renewables and perhaps also nuclear power. Rapid progress on decarbonization of power would moreover be essential, since wider electrification could otherwise generate an initial

In the buildings sector, at least 35% of fossil fuel use can be replaced through electrification by 2040

Energy use in the buildings sector by application and electricity share by 2040



- Electrification of an additional 10% of buildings energy use is feasible by 2040.
- This can displace 35% of baseline fossil fuel use.

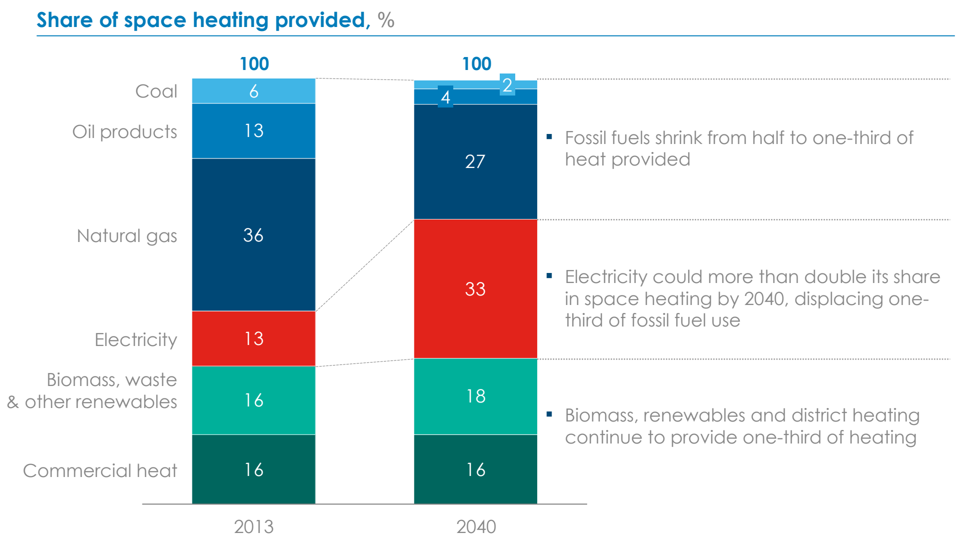
NOTE: Non-electrified segments include, in addition to fossil fuels, hydrogen and biogas.
SOURCE: Copenhagen Economics analysis based on data from IEA, ETP (2016) and the Global Calculator.

Exhibit 19

22) This estimate does include additional benefits of electrification in terms of increased energy efficiency, which are discussed – and accounted for – in Section 3.

increase rather than decrease in carbon emissions. The carbon intensity of power generation needs to be below 600g/kWh to make a shift from gas heating to electric heat pumps carbon efficient, 600g/kWh to ensure that switching from gasoline to electric vehicles reduces emissions, and 200g/kWh before a shift from gas heating to electrical induction heating would be beneficial. However, achieving high penetration of, for instance, electric vehicles or heat pumps by 2040, is likely to require significant early penetration of these technologies, even if adequate decarbonization to assure immediate emission reductions has not yet been achieved. Countries should explicitly describe how they will manage this complex trade-off within their INDCs.

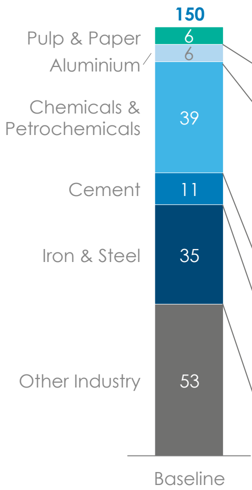
One-third of space heating could be provided by electricity by 2040



NOTE: Calculation of implied shares assumes doubling of average electrical space heating efficiency from 2013 to 2040, from 100-200% heat output per energy input.
SOURCE: Copenhagen Economics analysis based on data from IEA, ETP (2016).

Exhibit 20

The technical potential for electrification in industry could be high, but significant innovation and deployment is required to decrease cost of alternative technologies

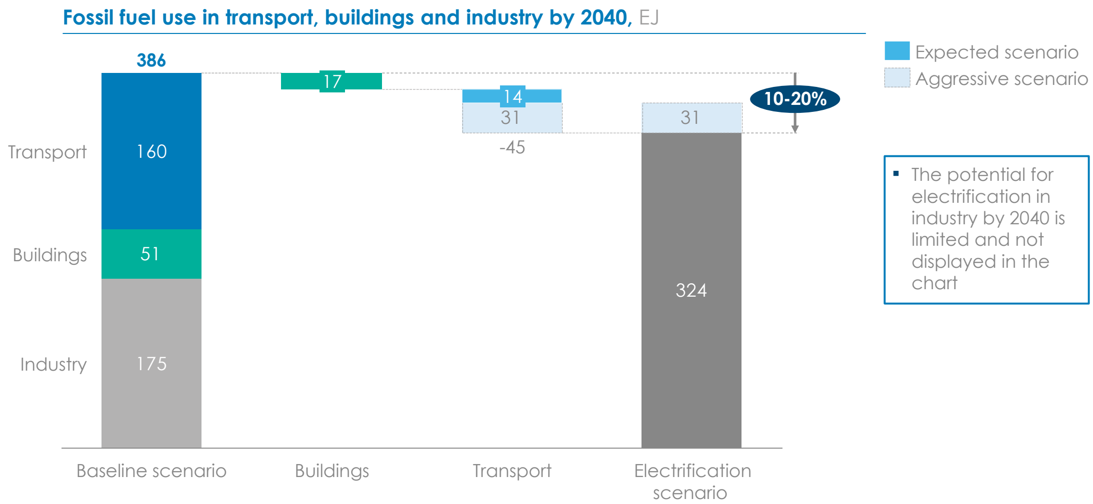


Electrification Options: Industry/Process	Electrification Options: Alternative technology	Technical opportunity (% of final process energy)	Technology availability
Pulp & Paper drying	Electro-thermal technologies (induction, electric arc, etc.)	85%	Moderate
Alumina production *(bauxite reduction)*	Electro-thermal dryers or syngas firing (grid electrolysis)	25%	Low
Chemicals & Petrochemicals cracking	Electro-thermal furnaces	65%	Low
Olefin production *(ethylene, propylene)*	Methane-to-olefins (MTO) from syngas and oxidative coupling of methane (OCM)	n/a	Moderate
Ammonia production	Grid electrolysis	n/a	Moderate
Cement production *(clinker calcination)*	Electro-thermal dryers or syngas firing (grid electrolysis)	80%	Low
Recycled steel production	Electric arc furnace (EAF)	25%	High
Iron ore reduction	DRI (hydrogen or gas) or electro-winning	70%	Moderate/High

SOURCE: CPI analysis based on IEA, ETP (2016); ETP 2016, DOE, LBNL, Energy Star, Heyl & Patterson, ICIS, KEMA, U.S. Steel, Lechtenbohmer et al. (2015).

Exhibit 21

Broader clean electrification has the potential to reduce fossil fuel use by 10-20%



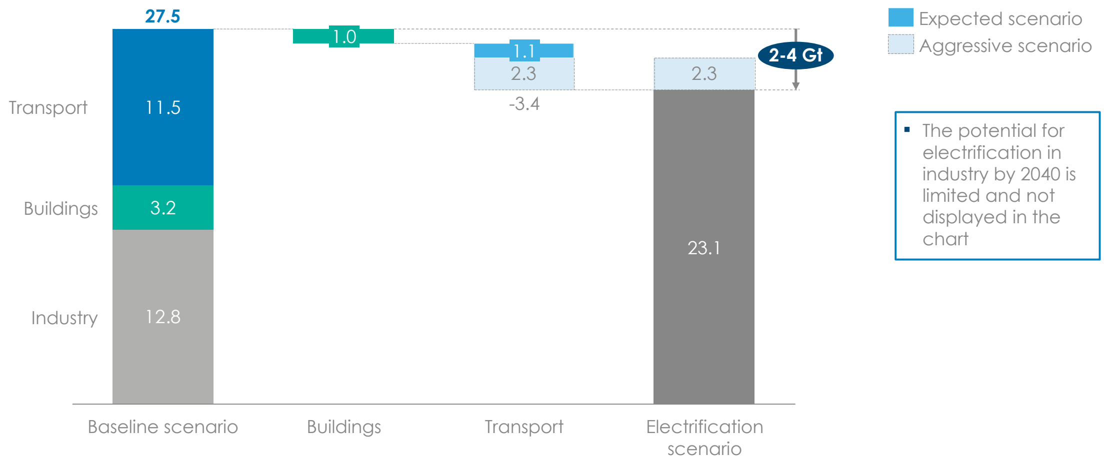
NOTE: Potential for electrification in industry is limited and has not been analyzed in detail. The total potential for reduced fossil fuel use through electrification is therefore somewhat larger than what is shown in the above chart. The scenario only includes fossil fuel savings from increased electrification. Other potential for fossil fuel savings, such as energy productivity improvements, are not included.

SOURCE: Copenhagen Economics analysis based on data from IEA, ETP (2016) and the Global Calculator.

Exhibit 22

Broader clean electrification has the potential to reduce CO_2 emissions by 2-4 Gt by 2040

Emissions from fossil fuel use from transport, buildings and industry by 2040, Gt CO_2

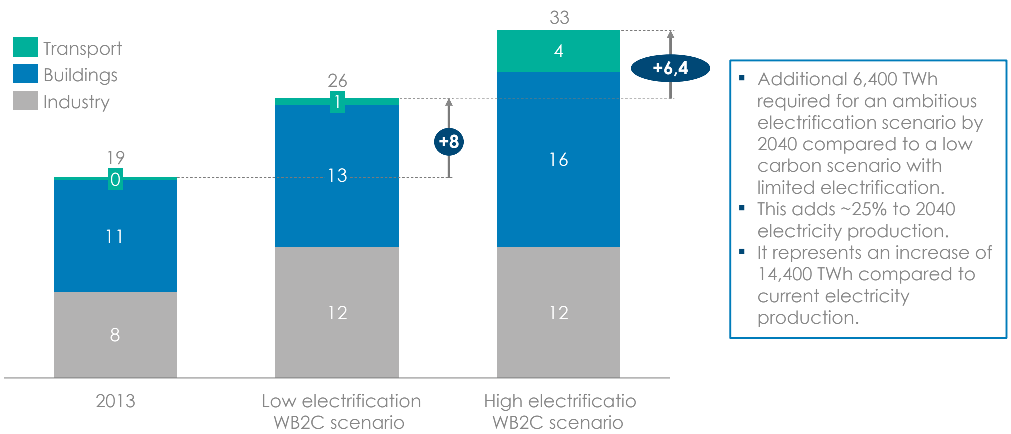


NOTE: Potential for electrification in industry is limited and has not been analyzed in detail. The total potential for reduced fossil fuel use through electrification is therefore somewhat larger than what is shown in the above chart. The scenario only includes fossil fuel savings from increased electrification. Other potential for fossil fuel savings, such as energy productivity improvements, are not included.
SOURCE: Copenhagen Economics analysis based on data from IEA, ETP (2016) and the Global Calculator.

Exhibit 23

Broader clean electrification could increase electricity requirements by over 25% in 2040

Electricity demand from transport, buildings and industry, 1000 TWh



NOTE: *Low electrification WB2C scenario* shows the expected electricity use in a WB2C scenario, including all efficiency and productivity gains, but assuming no further electrification compared to current levels. *High electrification WB2C scenario* shows the expected electricity use in a WB2C scenario with further electrification in transport and buildings, assuming an average of the expected and aggressive electrification cases in the transport sector. Potential for electrification in industry is limited and has not been analyzed in detail. The total potential increase in electricity demand is therefore somewhat larger than what is shown in the above chart.
SOURCE: Copenhagen Economics analysis based on data from IEA, ETP (2016) and the Global Calculator.

Exhibit 24

The way forward

Decarbonization of power and wider electrification

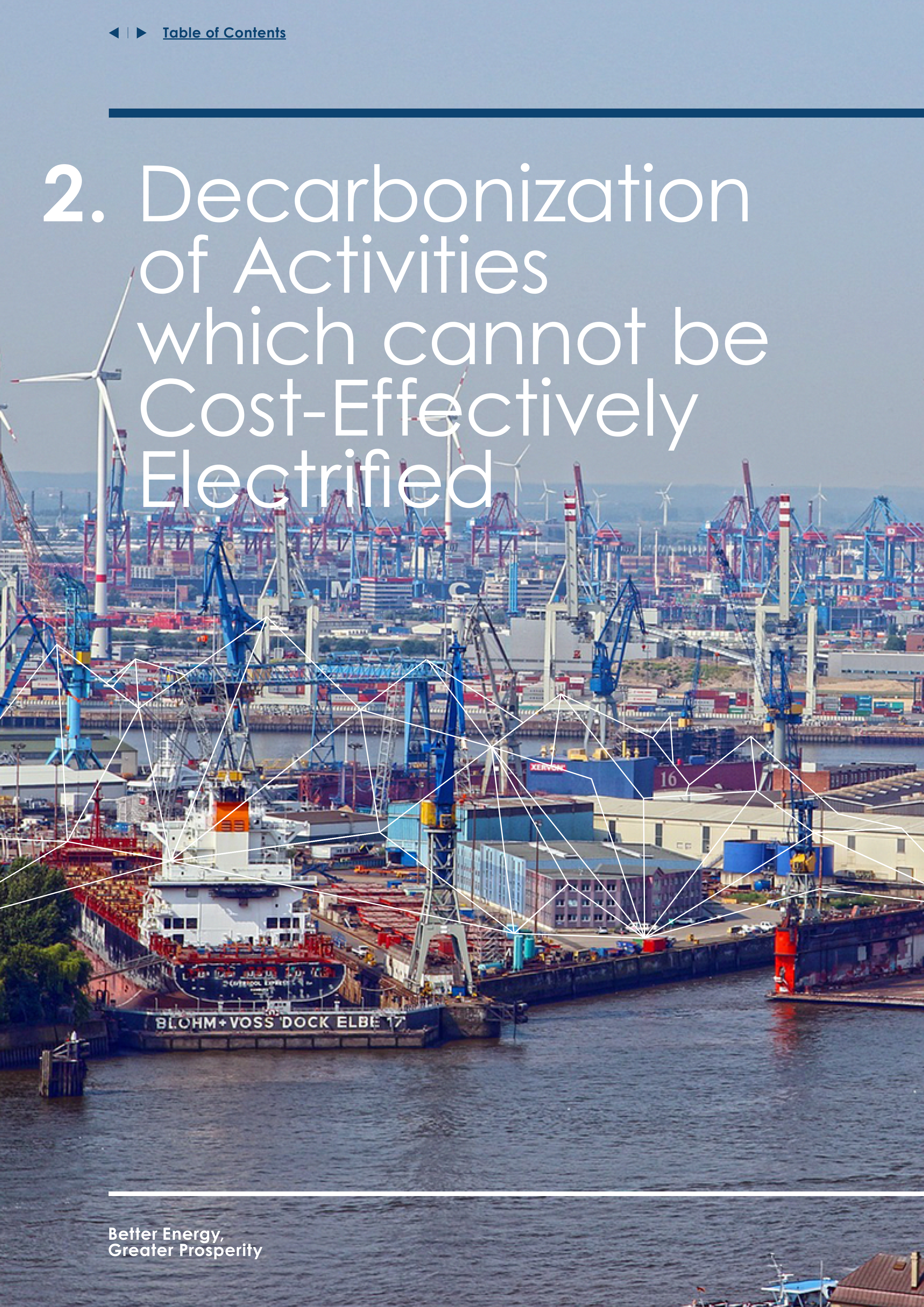
Decarbonization of power and wider electrification should be a cornerstone of INDCs for all countries. INDCs should:

- Set-out specific targets to achieve a declining path of average and marginal carbon intensity of electricity supply, and take this into account in electrification plans, recognizing that early penetration of electrified technologies might be required even before power generation has been significantly decarbonized;
- Specify priority areas for wider electrification, supported by specific high impact policy interventions, e.g. to encourage EV take-up via charging infrastructure investment or subsidy, or to encourage heat pump take-up by subsidy, tax incentive or building regulation.

The feasibility of power decarbonization and wider electrification does not depend on uncertain future technological breakthroughs. But ensuring rapid enough progress will still require large mobilization of private capital, supported by well-designed public policies. In particular, it is essential that:

- Policies directly support the initial deployment of the low-carbon power generation technologies most appropriate to each country's geographic and natural resources, to help drive initial scale and cost reductions based on learning curves, and to establish supply chains capable of supporting large capacity investment. As discussed in Section 6, appropriate policies to support these "infant industries" cannot rely solely on either R&D expenditure or publicly mandated carbon prices to ensure sufficiently rapid progress.
- The cost of capital for investment in renewables is reduced, thanks to appropriate market design and financing models reducing risks, as described in Section 5. For many developing countries, this is likely to require access to large-scale supplies of concessional international finance, given domestic capital constraints.
- Governments, regulators and grid operators work together to design or encourage technology deployment (including the rollout of smart meters and other control technologies), market structures and pricing regimes to enable the optimal use of demand management, energy storage and other flexibility mechanisms, so as to minimize the cost of electricity in a low-carbon power system.

2. Decarbonization of Activities which cannot be Cost-Effectively Electrified



Decarbonizing power and electrifying a wider range of economic activities has potential to significantly reduce the CO_2 intensity of our energy system. However, it cannot be sufficient to build a low-carbon economy because many economic functions cannot be electrified either at all or, at least in the short to medium term, at any reasonable cost.

There are multiple technologies which could play a role in decarbonizing these activities, but none of them currently displays the dramatic cost reductions and rapidly increasing scale of deployment seen in renewable power. Moreover, the mix of technologies and business solutions likely to secure decarbonization at least cost is much less clear than it is in the power sector. It is therefore crucial to put in place the public policies and private actions which will ensure that some or all of these solutions are developed and deployed at large scale in the near future.

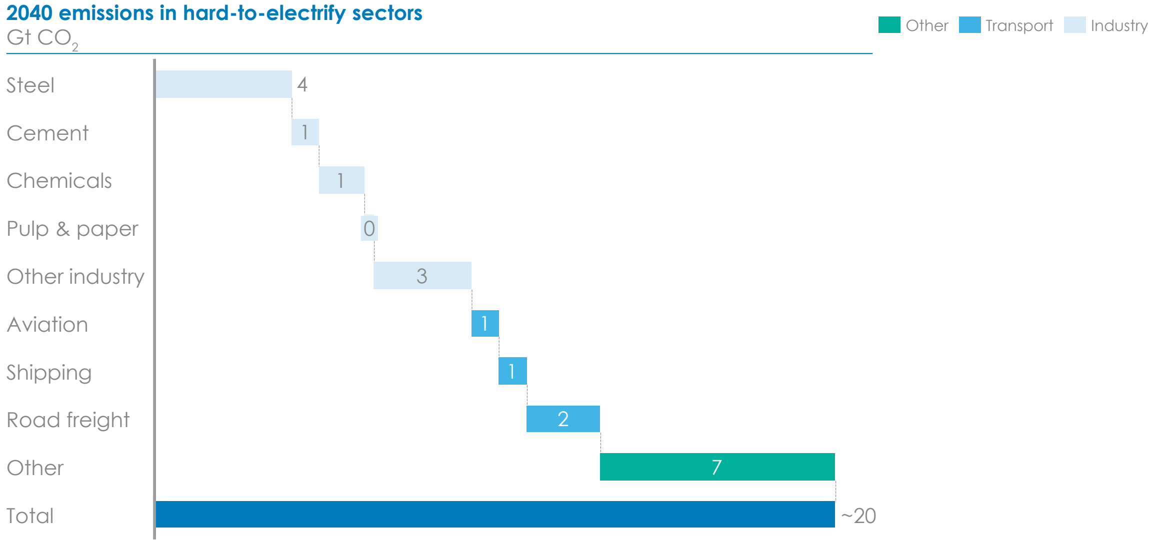
In this section, we consider in turn the options available (a) in transport and industry, and (b) in heating, cooling and cooking.

A. HARD-TO-ELECTRIFY SECTORS IN TRANSPORT AND INDUSTRY

Key hard-to-electrify sectors include some parts of transport (aviation, heavy duty freight, shipping) and a significant number of industrial processes. In total, these activities account for about 13 Gt per annum and 36% of CO_2 emissions today. Underlying growth in demand means moreover that, even with greater technical energy efficiency*, industry would still account for about the same 13 Gt by 2040 unless the rapid development of circular economy models* reduces the demand for industrial output and supply-side measures are implemented to change energy input or capture CO_2 emissions [Exhibit 25]. In Section 3, we describe in further details how circular economy models could reduce greenhouse gas emissions from food and industrial goods by 30-50%.

On the supply side, while several different technologies exist which might achieve this decarbonization, the way forward is far less clear than it is for the decarbonization of power. The technology options are not yet cost-effective

Decarbonization beyond the power sector is required to mitigate impact of non-electrifiable applications, especially in the industry sector



SOURCE: Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission.

Exhibit 25

Pathways for decarbonizing beyond power are unclear: a range of alternative technologies are available, but they have not matured and face significant barriers

Land use/feedstock supply · Energy density · Infrastructure requirements · Cost/willingness to pay

Industry · Transport

Key barriers / Application	Liquid biofuels	Other bioenergy	Hydrogen	CCS
	Land use/feedstock supply; Cost/willingness to pay	Land use/feedstock supply; Cost/willingness to pay; Energy density	Infrastructure requirements; Cost/willingness to pay	Infrastructure requirements; Cost/willingness to pay
High temperature processes	✓	✓	✓	✓
Steelmaking		✓	✓	✓
Chemicals feedstock		✓		✓
Aviation	✓		✓	
Shipping (ocean freight)	✓		✓	
Heavy road freight	✓		✓	

SOURCE: Ad hoc analysis developed by McKinsey & Company for the Energy Transitions Commission.

Exhibit 26

and face significant barriers. In some cases, these technologies are not yet even tested in pilot plants. Obstacles include competition for land use or water resources (in the case of bioenergy) and the scale of infrastructure and value chain development required (for hydrogen, CCS and CO_2-based products). Options to decarbonize these “hard-to-electrify” sectors fall into two categories: fuels substitution, and carbon capture and sequestration through conversion into products (which has the benefit of creating some economic value) or storage. [Exhibit 26]

Fuels substitution

Biofuels may play a major role in enabling the decarbonization of transport activities where electrification may be either a sub-optimal solution (in the case of long-distance heavy duty freight) or unfeasible in the foreseeable future (in the case of passenger aviation[23]). **But there are major issues about the extent to which current bioenergy technologies will compete for land with food production, other agricultural products (e.g. timber) or with terrestrial-based carbon sequestration**. New bioenergy technologies, based on advanced crop genetics, more effective forms of bio-waste conversion or new strains of algae may be able to avoid such competition. However, their economic viability remains unproven, with further technological progress required to enable cost-effective and large-scale deployment [Exhibit 27].

Other forms of bioenergy are likely to be used in multiple industrial applications – where the need for intense heat makes it difficult to decarbonize via electrification – **or for use in district heating systems**. But while both uses are clearly possible and potentially cost-effective, here too, there are open issues relating to competition for land, the complexities of scaling up large scale bioenergy supply chains and uncertainties about future technological progress.

Hydrogen could be produced by electrolysis from renewable electricity during periods of otherwise excess supply, thus also playing a role in the management of intermittency. **But while the technical potential is clear, the cost-effectiveness of hydrogen-based solutions (for both industrial and transport application) is still uncertain**. In particular, a large-scale role for hydrogen could

23) Even in aviation, however, options for battery-powered short-haul flights are being considered by a number of companies.

Biofuels constitute the most advanced alternative technology to date to decarbonize beyond power, but land use efficiency constitutes a major barrier to deployment

Generation	Feedstock type	Commercialization Production in billion liters[1]	Land use efficiency (yield) Liters[1] per hectare	Land required to meet 50% current transport needs[4] Million hectares
1st	**Starch crops** corn, barley, wheat	**High – 134** 3% of global transport	~2,400	1,100
	Sugar crops cane, beet, sorghum		3,700-4,800	550-700
	Oil crops palm, soybean, rapeseed		900-4,800	340-1,800
2nd	**Lignocellulosic crops** switchgrass, miscanthus, jatropha	**Low – 0.6** 0.01% of global transport	3,700-5,200	500-700
	Lignocellulosic waste forestry, agricultural, municipal		N/A (high[2])	N/A[2]
3rd	**Algae**	**Not commercialized** Early demonstrations	20,000-50,000[3]	~30-80
	GMOs		TBD	TBD

vs. ~3,000 million hectares total arable land (global)

1 In liters of gasoline or diesel equivalent
2 Incremental land not required for waste feedstocks
3 Conservative range of potential yield estimates
4 Assumes full availability of land to deliver average yield

SOURCE: IEA, Tracking Clean Energy Progress (2016); IRENA, Production of Liquid Biofuels (2013), Ad hoc McKinsey & Company analysis (2016)

Exhibit 27

require the creation of an extensive storage and distribution infrastructure, which would in some ways duplicate the existing gas system.

Hydrogen might in some cases be combined with carbon capture and sequestration, which would entail either (i) the production of hydrogen from methane, for use as a liquid biofuel in transport, which could be made carbon neutral if carbon capture were cost-effectively applied or (ii) the production of methane from hydrogen (produced by electrolysis) plus CO_2, using the Sabatier process, for use in back-up power generation, which could also be made a zero-carbon system if carbon capture were available at reasonable cost. But the first of these combined technology routes depends on the still uncertain cost-effectiveness of carbon capture and sequestration, while the latter depends on the economics of both carbon capture and electrolysis.

Carbon capture and sequestration through conversion into products or storage

Debates about carbon capture and sequestration* must recognize that carbon capture may be essential to achieve three objectives: (i) to decarbonize specific industrial activities – especially chemicals, steel, and cement –, (ii) to retrofit coal-fired power plants in those countries where significant new coal investment will likely occur in the near future, and (iii) to achieve negative emissions when combined with bioenergy production in the second half of the century. It also needs to reflect the difficulties involved in large-scale deployment.

Section 4 describes these considerations in more details and Exhibit 55, p. 83, in that section presents a comprehensive overview of the different routes to carbon capture and sequestration, including atmospheric capture and natural sinks. In this section, we focus on the capture of CO_2 emissions from industrial processes (whether arising from fossil fuels input or as a result of required chemical reactions), and on the subsequent storage or conversion into products. We use the word "sequestration" to cover both options for conversion of CO_2 into products that sequester CO_2 in the long term and subsurface storage in reservoirs[24]. **Existing projects to capture and use or store CO_2** have been implemented where CO_2 has an inherent commercial value, i.e. injected to enhance oil recovery (EOR). Successful projects have also, to a large extent, relied on existing CO_2 storage and transport infrastructure undertaken by large energy companies with subsurface competence.

"Multiple opportunities to transform and use, rather than simply store captured CO_2 must be exploited"

However, **multiple potential opportunities to transform and use, rather than simply store, captured CO_2 must be exploited to the maximum extent possible**. These applications cover a range of industries including cement, concrete and aggregates, liquid fuels and some polymers. Compared with carbon storage, CO_2 conversion into products has the advantage of avoiding storage costs. It may also generate revenue streams which can offset the cost of capture. The applications differ however in their precise impact on CO_2 emissions, in some cases raising complex issues about appropriate public policy support.

Carbon capture and sequestration value chains comprise several different possible elements – including capture, transport, conversion into products, and storage. Current cost estimates for combinations of capture and storage lie in the range of about $40-$110 per tonne, depending on specific applications, but over the last 10 years both median estimates and the ranges have tended to increase [Exhibit 28]. Such costs would significantly increase the cost of production in heavy industry – for example by around a third in steel and over 50% in cement [Exhibit 29].

Future costs are uncertain, with the impact of large-scale deployment offering both potential cost savings (through standard learning curve effects) and cost increases (as the best storage sites get used first). Different elements of the value chain present different challenges, and have different opportunities for cost reduction.

Carbon capture* costs accounts for a significant proportion of the total costs of CCS projects, often representing 70% of the total[25]. Several capture solutions are now proven in large-scale capture projects, for instance in hydrogen production, oil refineries and natural gas processing. But in industrial sectors such as iron and steel, cement, and pulp and paper, the lower concentration of CO_2 in gas streams makes capture more challenging, and necessitates more expensive approaches. Scaling investment in carbon capture technologies will be demanding for low-margin industries and probably dependent on effective policy measures and certainty of CO_2 off-take infrastructure. We estimate that up to a half of industrial emissions in 2040 could be amenable to carbon capture, making CCS and the expansion of CO_2-based products essential but insufficient to decarbonize industry [Exhibit 30, p.52].

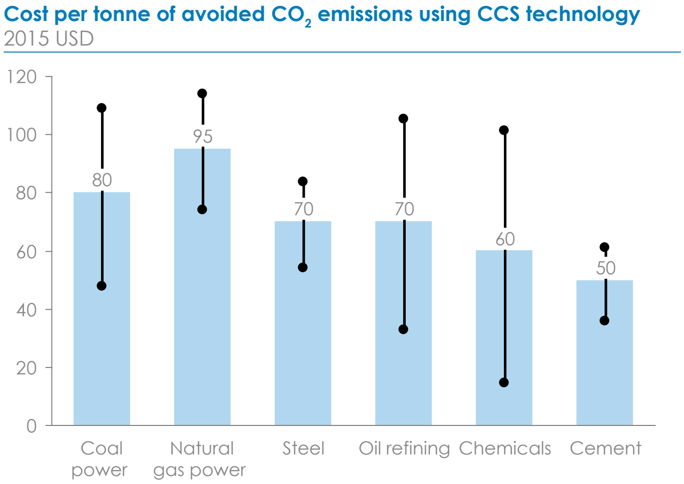
CO_2 transport is required to link capture facilities to sequestration options. It is a mature technology, but a coordinated approach to infrastructure development will be essential to ensure cost effectiveness. Transport to link stand-alone industrial emission sources to sequestration options is likely to be high-cost as individual emission sources may be low-volume. Coordinated industrial planning, including the development of industrial hubs, could enable development of more cost-efficient shared transport and sequestration options.

CO_2 conversion into products* which sequester CO_2 in the long term could help drive the development of carbon capture. These CO_2 utilization options need to be assessed on both environmental and economic criteria, including the CO_2 capture potential, the permanence of sequestration, the cost/price point at which a product is competitive, and the ease of implementation.

The Global CO_2 Initiative indicates that commercialization of CO_2-based products represents an annual revenue opportunity of up to $800 billion by 2030[26].

24) Natural carbon sinks are considered separately in Section 4.
25) The Global CCS Institute (2016), The Global Status of CCS 2016.
26) Ibid.

The cost of CCS to date ranges from $50-100 per tonne depending on application; the potential cost of carbon capture at scale is very uncertain

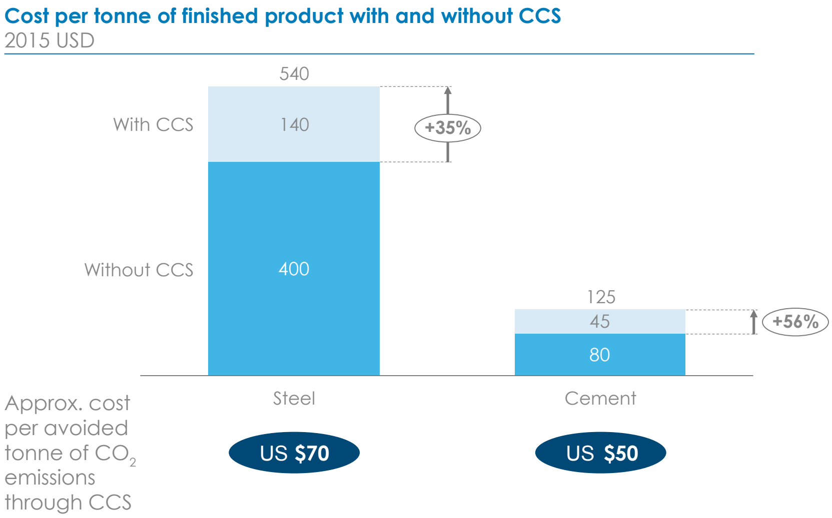


NOTE: Figures show avoided cost of emissions. The central values show average values of ranges given in sources below. The error bars show full range of estimates. Costs vary by process in individual sectors; the values shown are averages for applications

SOURCE: Copenhagen Economics analysis based on IEA (2013), Element Energy (2010), Global CCS Institute (2015), IPCC (2005)

Exhibit 28

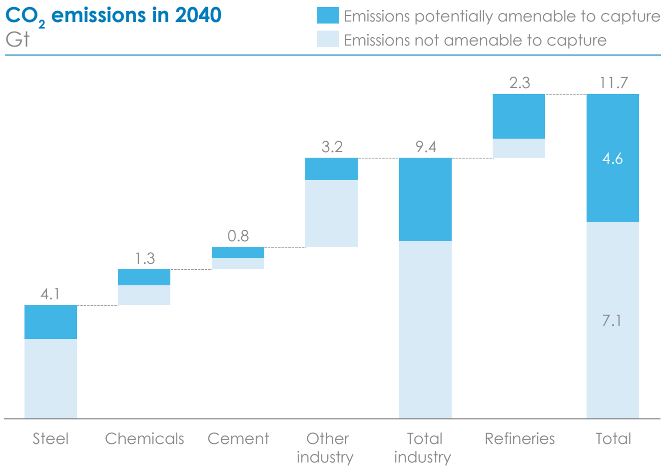
Estimated CCS costs would significantly increase the cost of production in heavy industry



SOURCE: Copenhagen Economics analysis based on Ecofys (2009); IEA (2013); Global CCS Institute (2015); Global Calculator (2014)

Exhibit 29

Up to half of industrial emissions in 2040 could be amenable to carbon capture: CCS is therefore essential, but insufficient to decarbonize the industry sector



- Industry and refining account for 28% of emissions today, but may be as much as 60% of remaining emissions in 2040 in a 2°C scenario.
- This reflects the relative difficulty of reducing emissions in industry; CCS therefore may be a prerequisite.
- The figure shows a stretch scenario for CCS in industry, but costs may increase rapidly if many small installations need to use carbon capture.
- Bioenergy, process changes, and hydrogen may offer alternative long-term options to address these emissions.

NOTE: Estimated potential share of CO_2 captured with industrial CCS technology varies between sources. Typical ranges for plants are: steel 40-80%; chemicals 50-95%; cement 60-90%; refineries ~80%; other 30-100%. Conservative point estimates have been chosen where available.

SOURCE: Copenhagen Economics analysis based on IEA (2013) – Technology Roadmap Carbon capture and storage; Global CCS Institute (2016) – Introduction to industrial carbon capture and storage; [GC sources]

Exhibit 30

Estimates of the potential for cost-effective use of CO_2 continue to vary substantially, but it is possible that 1-6 Gt of CO_2 per annum could be transformed by 2030[27]. Five categories of CO_2 conversion have the most promise:

- Mineralization in construction materials such as concrete and carbon aggregates could in principle achieve sequestration of up to a few billion tonnes of CO_2 per year, and may be the most promising product category.
- Enhanced oil recovery (EOR) is a proven form of CO_2 utilization at scale, supported by the value of additional oil production. However, its contribution to carbon emissions reductions is offset by the emissions arising from the additional oil produced and used.
- Options to produce chemicals such as methanol, syngas and formic acid are becoming more feasible as research projects improve conversion efficiency. However, the permanence of the achieved CO_2 sequestration need to be considered when deciding on the relative value of the different conversion options.
- CO_2 conversion to synthetic fuels could provide an alternative to petroleum-derived feedstock or biofuels. Fuel conversion is energy-intensive, and would probably require excess energy to be produced at scale. The net CO_2 mitigation potential through fuel conversion is yet unknown and will depend on a full lifecycle analysis.
- Polymers have been commercialized for high-value products in niche markets. The cost level of the technology is still high. Improvement depends on R&D investment to find an effective catalyst, and on scaled operations.

Carbon storage* has significant technical potential, but well designed and implemented public policies will be required to prevent it becoming a bottleneck in the overall carbon sequestration innovation system. Regional storage potential is assessed at present in most key regions of the world[28]. Much experience has been gained by CO_2 EOR and storage projects associated with oil and gas production, providing increased confidence in the technical do-ability of storage as a permanent sequestration option for significant volumes.

It is not certain, however, that financing for storage investments will be forthcoming, since there is no intrinsic commercial value for a potential storage service provider. Long lead time and significant investment cost for greenfield storage is

27) The Global CCS Institute (2016), The Global Status of CCS 2016.
28) The Global CO_2 Initiative (2016), Roadmap for the Global Implementation of Carbon Dioxide Utilization Technologies.

a barrier to value chain development, increasing execution risk and ability to secure financing. One option could be to separate carbon storage development as a distinct business and investment opportunity for entities with subsurface expertise, and partially insulate it from the different operational and risk profiles of carbon capture and transport. A significant hurdle will also be public acceptance and concerns driven by a fear of CO_2 leakage, especially for onshore solutions.

The mix of decarbonization options

The combination of available technologies – from fuels substitution to carbon capture and different forms of sequestration – provides reasonable assurance that the decarbonization of non-power sectors is possible and that some progress will be made prior to 2040. However, the respective contribution of different technologies is difficult to assess at this stage. **Realistic estimates suggest that it would be possible to reduce emissions by 4 Gt by 2040** against potential 2040 emissions of 20 Gt per annum for these "hard-to-electrify" activities. Rapid and significant further reductions after 2040 will therefore be essential (see Exhibit 4, p.16 in the Executive Summary).

"Without greater clarity on the way forward, private investment will likely be insufficient"

Lack of clarity around the multiple options, each facing unresolved issues relating to cost evolution, competitiveness, and public acceptability, may delay the implementation of this necessary transition. This leaves us less certain that this vital element of the energy transition will be achieved rapidly enough. Without greater clarity on at least some aspects of the way forward, private investment will likely be insufficient to ensure that economies of scale and learning curve effects produce dramatic cost reductions. It is noticeable that many of the INDCs are relatively silent on how countries plan to achieve decarbonization of non-power energy use. Without strong policy signals, private investment will likely be insufficient to ensure that economies of scale and learning curve effects produce dramatic cost reductions.

B. COST-EFFECTIVE ALTERNATIVES TO ELECTRICITY IN HEATING, COOLING AND COOKING

As described in Section 1, in principle, all buildings energy applications can be electrified, and indeed every one of them is already electrified on a significant scale in some countries. However, the appropriate pace of electrification in buildings should reflect its cost-effectiveness relative to other decarbonization options, such as district heating and cooling systems, non-electric solar and thermal energy sources, or more efficient use of biomass for cooking.

"District systems can deliver cost-effective, low-carbon heating and cooling"

Decarbonization of heating, cooling and cooking represents one of the largest prizes in the energy transition. Production of heat accounts for around one-third of global energy-related CO_2 emissions. The rapid deployment of cooling in developing countries also creates a pressing decarbonization challenge. Finally, developing countries face a specific set of environmental issues, related to the inefficient and unsustainable use of biomass, especially charcoal, in cooking. The scenario presented on Exhibit 20, p. 41, in Section 1 shows electricity-based space heating doubling as a percentage of the total energy use for space heating globally, while fossil fuels-based heating falls from 55% to 33%. But it is possible that a combination of electrification and other decarbonization options will replace fossil fuels more rapidly and more completely in the buildings sector.

Technologies, applications, resources and demand vary so significantly that **the challenge for local policymakers is to coordinate the right combination of incentives that fit the regional context.**

- There are a number of countries, especially in Northern and Eastern Europe, which already have extensive **district heating systems** with potential to deliver cost-effective, low-carbon heating and cooling. Sweden has the highest share of final energy demand in buildings supplied through district heat (65%) followed by Denmark (more than 50%). There is also a good case for incorporating these systems into the design of new cities, especially when these are planned and built on a more compact basis. The third of all space heating which is currently provided by biomass, waste and district heating systems and alternative low-carbon energy sources might therefore grow at the expense of fossil fuels, through a diversity of solutions tailored to local contexts, including biomass CHP[29], waste to energy and heat from in-life thermal power sources.
- **Non-electric solar and thermal energy can provide a cost-competitive alternative for heating**. In recent years, solar hot water installations have become cost-competitive with fossil fuels and electricity in China, Israel, Morocco and several other countries including Denmark where the world's largest solar thermal district heating plant opened in 2014.
- In developing countries, rapidly **replacing the inefficient and unsustainable use of biomass, especially charcoal, in cooking** might require a shift to gas or to more efficient use of biomass, although non-electric solar can also constitute a cost-competitive option.

29) A combined wood-fueled heating and power system for decentralized renewable energy.

The way forward

Hard-to-electrify sectors

There are a range of technologies which could decarbonize these sectors. The challenge is to ensure that they are now developed and deployed at large scale, achieving self-reinforcing learning curve effects equivalent to those already evident in renewables and batteries.

- **Greater clarity on the way forward is essential to reduce uncertainty and facilitate decision-making by policymakers and private investors.** Governments and private industry groups should develop roadmaps for alternative decarbonization solutions, setting out the combination of technological improvements/breakthroughs, infrastructure investments, and scale of deployment required to make different technologies (or combinations thereof) feasible solutions to various specific decarbonization challenges.
  - These technology roadmaps – for bioenergy/biofuels, hydrogen, and carbon capture, conversion and storage – should build on existing IEA roadmaps and be designed to achieve large-scale decarbonization, consistent with a well below 2˚C pathway.
  - They should avoid the risk of a technology-centric perspective and be informed by an integrated vision of the likely roles and combinations of different technologies for different applications.
  - They should aim at reducing costs to significantly less than $100 per tonne of CO_2 by 2040.
- **The same infant industry policies used to drive wind and solar industries to self-sustaining scale should be used to support alternative decarbonization technology solutions**, starting with feed-in tariffs*, evolving into auctions* and contracts for difference* pricing regimes, with the ultimate goal of making these options cost-competitive with a publicly mandated carbon price of at least $50-$100 per tonne of CO_2. Public funding in combination with private capital will be essential to support investment in new major projects and in infrastructure development.
- **Scaling carbon capture and sequestration solutions** – including both conversion into products and storage – must be a high priority. This requires public policy focus on each of the steps in the value chain – capture, transport, sequestration in products and storage.
- **Encouraging the deployment of a portfolio of low-carbon solutions for heating, cooling and cooking** adapted to each regional context will require that local policymakers develop a tailored set of incentives and regulations.
- **The introduction of a comprehensive carbon price** resulting from public policy (discussed further in Section 6) is essential to drive the search for multiple cost-effective solutions by energy-intensive sectors.

3. Acceleration in the Pace of Energy Productivity Improvement

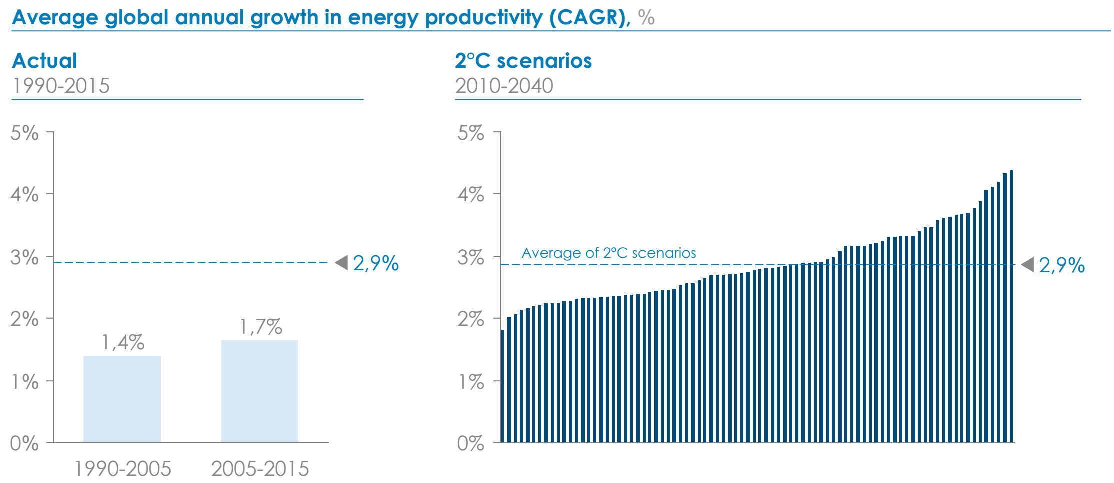
Decarbonization of electricity, wider electrification and decarbonization of energy supply beyond the power sector are vital but, as Exhibit 4 in the Executive Summary illustrates, would not be sufficient to achieve the emissions reductions required to make possible a well below 2°C scenario. All models suggest that in addition the world needs to achieve a dramatic increase in the pace of energy productivity* improvement, with the global average required to rise from around 1.7% per annum between 2005 and 2015 to close to 3% per annum[30] [Exhibit 31].

For many countries, this will still imply growth in total energy consumption. Historically about 100 GJ per capita has been required to achieve a good standard of living. Even though it may be possible in future to lower the threshold to 80 GJ, significant energy consumption increases would be required in many countries to meet the needs of a growing population, while those countries currently consuming well above the 100 GJ per capita level would have to actually reduce their energy consumption [Exhibit 32, p.58].

"Energy productivity improvement needs to rise from 1.7% to 3% per annum globally"

In all countries, this would entail breaking the historic link between per capita energy consumption and per capita GDP, achieving a productivity revolution. On average, in low-carbon scenarios, **the OECD must roughly halve per capita energy consumption versus today**, while GDP per capita keeps increasing by about 1% per year. **Non-OECD countries will overall need to keep per capita consumption broadly flat, even while GDP grows at 2.5-3.5% per annum, though with wide variations between low- and middle-income countries**. [Exhibit 33, p. 59]. Non-OECD countries would account for two thirds of the reduction in global energy demand in a low-carbon scenario versus a business as usual scenario, while OECD countries would account for the remaining third[31].

In a well below 2°C pathway, energy productivity needs to improve at twice historical rates



NOTE: Selection of WB2D scenarios that limit the risk of a global temperature rise of more than 2 degrees to less than one third, with 2020 emissions of at least 30 $GtCO_2$, and with no more than 40 $GtCO_2$ removal from CCS in any given year. Historical energy productivity based on GDP in terms of PPP (constant 2011 international $). WB2D energy productivity based on GDP at market exchange rate (constant 2005 US$). Missing GDP values (13 scenarios) have been replaced with median GDP

SOURCE: World Development Indicators, BP Statistical Energy Review 2016, AR5 Database.

Exhibit 31

30) Latest numbers from IEA suggest that energy productivity improvement reached 1.8% globally in 2015. Source: IEA & IRENA (2017). Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System.

31) Vivid Economics (2017). Economic growth in a low carbon world: How to reconcile growth and climate through energy productivity. Research paper for the Energy Transitions Commission.

Increasing energy productivity – i.e. rising GDP per unit of energy consumed – can occur either [Exhibit 34]:

- Because energy-based services* (e.g. lumens of light, degrees of ambient space heat, or kilometers travelled) can be produced with less primary energy input – this has historically accounted for two-thirds of the improvements in energy productivity; or
- Because GDP is able to grow faster than energy-based services due to shifts in the structure of the economy (e.g. because of a shift away from industrial activities towards services or because kilometers travelled grow less rapidly than GDP thanks to smart urban design).

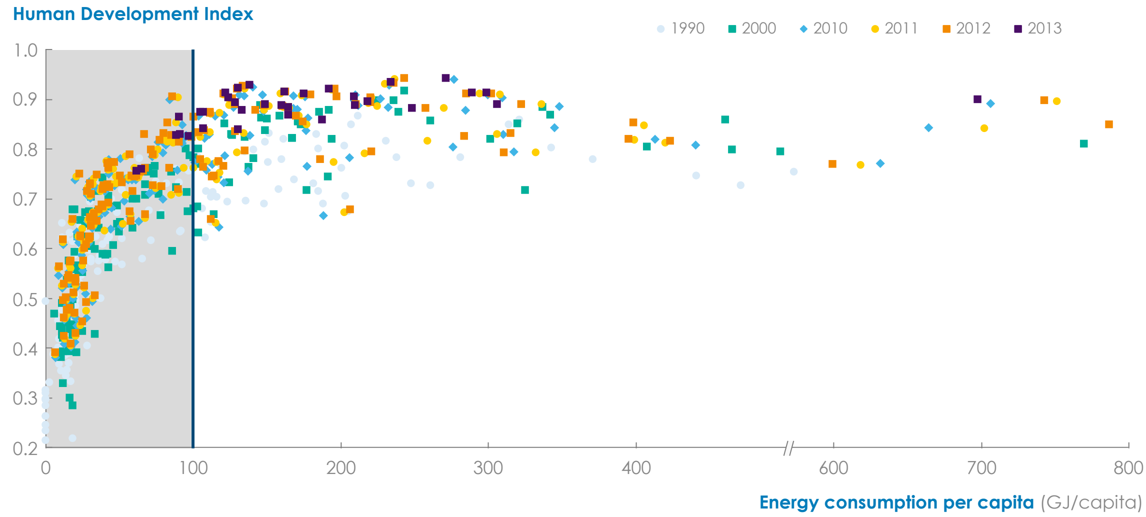
The increasingly intensive application of information and communications technology, in what some people label the "digital economy", may trigger a structural break in both energy efficiency* and GDP productivity of energy-based services. For instance, end-to-end energy losses can be reduced thanks to better performing infrastructure and flows management systems (such as smart grids), energy efficiency can be improved by the automated control of energy-using equipment, and GDP will tend to grow faster than energy-based services as economies become more service-intensive. But more rapid progress than will naturally occur will be essential if the world is to achieve the overall productivity improvement required.

A. INCREASING THE ENERGY EFFICIENCY OF ENERGY-BASED SERVICES

An increase in energy efficiency of energy-based services can result from three effects [Exhibit 34]:

- Increased energy efficiency in upstream generation;
- Electrification of downstream activities (such as surface transport);
- Other improvements in the efficiency by which either electrical or non-electrical power sources are converted into useful energy-based goods and services such as light or usable heat. This could happen either because of new technologies, such as LEDs for lighting or better insulation materials, or through new digital control technologies, which substitute better information for resource use.

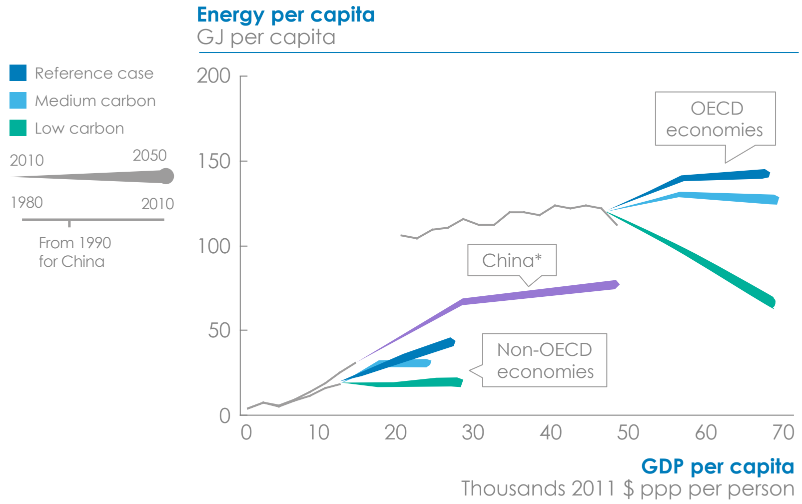
Historically, about 100 GJ per capita were required for a decent standard of living



SOURCE: UNDP (2015), Human Development Index; World Bank (2016), Databank

Exhibit 32

A structural break in energy productivity is required: Developed and developing countries need to decouple energy consumption and economic growth per capita



- GDP per capita reaches similar levels in low, medium and high carbon scenarios in OECD and non-OECD economies.
- In low carbon scenarios, energy per capita:
  - Decreases in OECD countries;
  - Stabilizes in non-OECD countries.

NOTE: GDP per capita is lower in medium carbon scenarios due to inclusion of scenarios with a radical shift from a high carbon path to a low carbon path post-2030. Average of reference, medium and low carbon scenarios is presented for China as fewer scenarios explicitly represent China.

SOURCE: Vivid Economics (2017), Economic growth in a low carbon world: How to reconcile growth and climate through energy productivity.

Exhibit 33

Accelerating energy productivity improvements requires leveraging several sources of energy productivity simultaneously

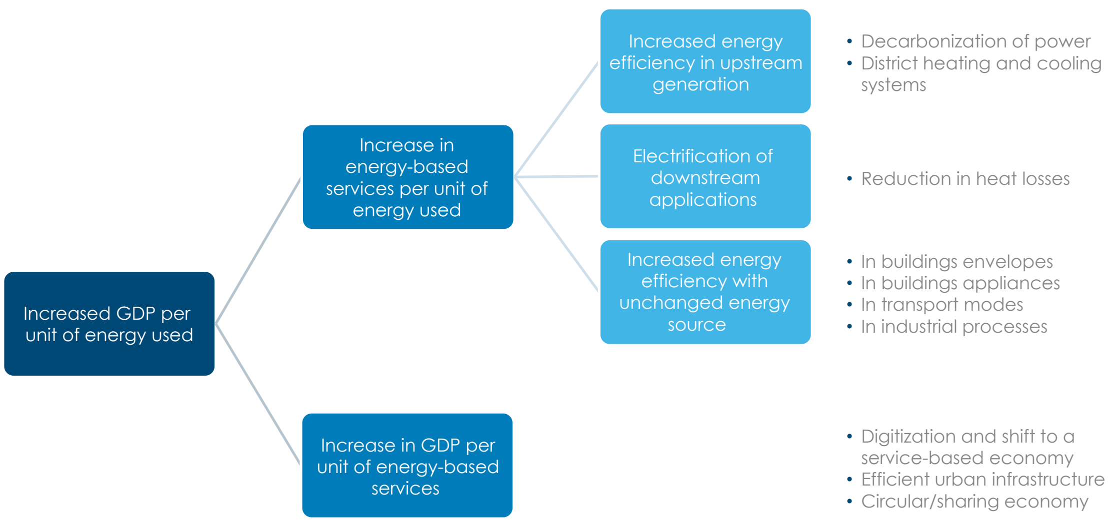


Exhibit 34

Decarbonization of energy supply and electrification

The decarbonization of energy supply and electrification of an increased proportion of economic activities will themselves significantly improve energy productivity. This is because:

- **In upstream generation, a shift from fossil fuels to renewables in power eliminates large waste heat losses**. Reduced heat losses in power generation can also arise from the development of CHP and retirement of older inefficient plants. Outside the power sector, district heating and cooling can also constitute a cost-effective solution to increase upstream energy efficiency. This results in a fall in primary energy demand, but not in final energy demand.
- **In downstream applications, electrification can reduce the final energy demand needed to deliver a given quantity of energy-based services**. Since electric vehicles convert around 90% of battery stored energy into kinetic energy, while internal combustion engines can achieve only about 20% efficiency, electrification could reduce automobile transport final energy demand by over 70%. Similarly, electric heat pumps can produce the same level of usable energy-based services (i.e. home or office heated to any given temperature) with less than a third of the energy consumed by an efficient gas boiler [Exhibit 35].

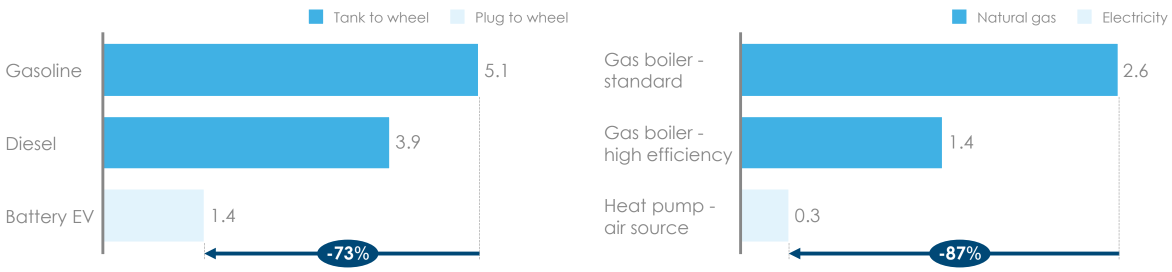
Section 1 described achievable scenarios for wider electrification, with at least 15-30% of fossil fuels use in buildings and transport eliminated via electrification by 2040. This would in itself reduce primary energy use in 2040 by 15-40 EJ – adjusting for additional electricity demand from increased electrification –, while the shift to low-carbon power sources could save another 60 EJ. **Together, this would increase the rate of energy productivity improvement over 25 years by about 0.5-0.7 percentage point per annum**[32]. In addition, wider electrification is likely to enhance the potential for digitization of many economic processes, generating further productivity gains through improved control and automation. These improvements in energy productivity are clearly technically feasible, and highly likely to be achieved provided countries put in place the appropriate supporting policies.

> ***"Electrification can increase energy efficiency by eliminating energy losses"***

Electrification constitutes a major opportunity for additional energy efficiency gains

Transport example: BEVs consume one fourth the energy of gasoline cars
Liters of gasoline equivalent per 100 km

Buildings example: Electric heat pumps are ~90% more efficient than gas boilers
kWh final energy per kWh heat delivered



Assumptions
- All vehicle efficiencies based on 200 km driven through New European Drive Cycle
- BEV assumes Li-ion battery with 95% roundtrip efficiency

Assumptions
- Standard gas boiler is 70% combustion efficient and 55% system efficient
- High-efficiency boiler is 90% combustion efficient and 80% system efficient
- Heat pumps have a coefficient of performance (COP) of 2.0-4.0 with average of 3.0 shown here

SOURCE: Energy & Environmental Science, "Well to wheel analysis of low carbon alternatives for road traffic" (2015); EnergyStar Portfolio Manager

Exhibit 35

32) Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission.

Increased energy efficiency in buildings, transport and industry

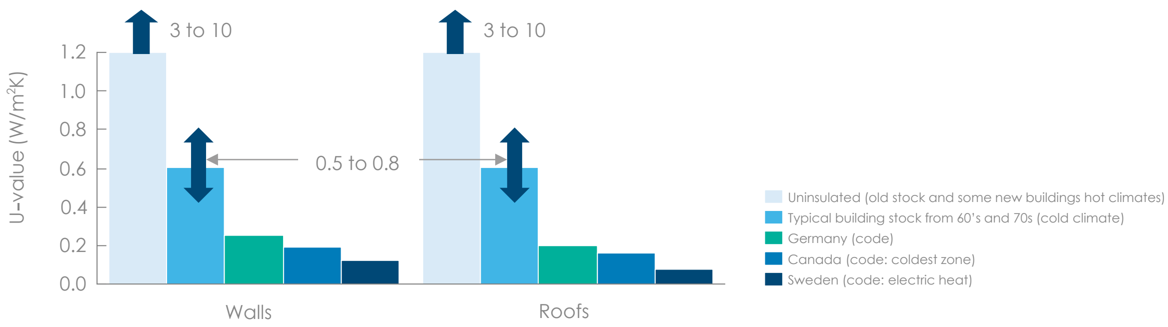
In the building sector, energy efficiency improvements have been achieved through more efficient appliances and improved buildings envelopes.

- Home appliances and air-conditioning, which account for about 20% of electricity demand in buildings and continue to grow fast, are priorities in terms of energy efficiency. New energy-efficient technologies intersect with those needed for HFC[33] phase-out. Rapid improvements have been achieved in many electrical consumer appliances, with, for instance the energy efficiency requirements for a given capacity refrigerator dropping by 60 to 80% over the last 50 years [Illustration 4, p. 62]. There are also lessons to be learned from rapid efficiency improvement in lighting, with the replacement of incandescent light bulbs by LEDs reducing energy requirements by between 80% to 90% (before rebound effects). The cost, reliability, attractiveness and performance characteristics of LED light bulbs have improved dramatically even over the past three years, and in some countries increased LED penetration accounts for up to a 2% fall in total electricity demand.
- The insulation efficiency of buildings can vary dramatically according to the materials and techniques used. Best available techniques can reduce energy consumption by a factor 2 to 6 for new buildings and up to a factor 100 for old buildings [Exhibit 36]. Denmark has for instance achieved improvements of 33% percent in average efficiency of large houses over the last 20 years. A key difficulty in developed countries is to ramp up retrofitting rates, to address the relative energy inefficiency of the buildings stock, given relatively long payback periods. [Illustration 5]
- Beyond insulation, the development of net zero energy buildings, combining smart design, efficient and connected devices and appliances enabling flexible energy consumption, and on-site renewable energy production, represents a huge opportunity, especially in developing countries where urbanization will lead to a rapid increase in the buildings stock.

In transport, significant improvements have been achieved in internal combustion engines, with average miles per gallon (mpg) in the US increasing from about 13 mpg in 1975 to almost 25 mpg in 2015, albeit this still lags significantly behind many other developed economies. [Illustration 6, p. 64]. Beyond passenger vehicles,

Stringent building codes can reduce buildings energy consumption by a factor 2 to 6 for new buildings and up to a factor 100 for old buildings

Insulation levels vary greatly, from old buildings to buildings meeting stringent current codes



SOURCE: Adapted from OECD/IEA (2013), Transition to Sustainable Buildings: Strategies and Opportunities to 2050

Exhibit 36

33) Hydroflourocarbons (HFCs) are gases primarily used in refrigeration and air-conditioning. Their use spread after the Montreal Protocol banned ozone-depleting chloroflourocarbons (CFCs), even though HFCs are strong greenhouse gases. The EU has been the first governmental body to take action to reduce HFC emissions.

Illustration 4

Appliance efficiency programs in Australia[34]

Australia has one of the most aggressive appliance efficiency programs globally, which spurred refrigerator energy efficiency, leading to a 60% reduction of refrigerator energy consumption from 1970-2020 [Exhibit 37].

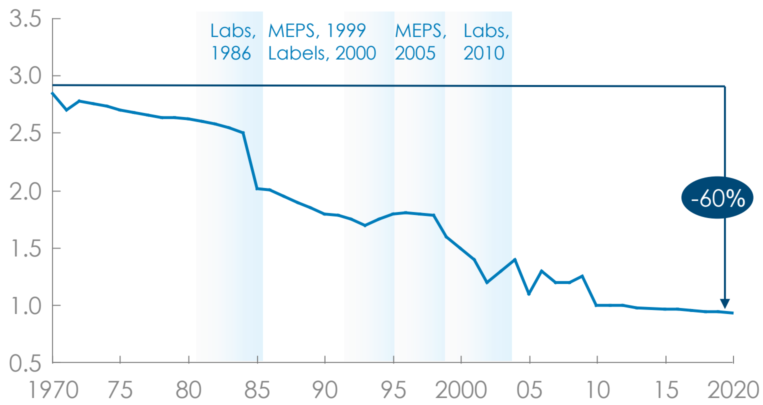
The efficiency program is composed of two simple elements: categorical energy efficiency labels for consumers and Minimum Energy Performance Standards (MEPS). The labels were the first element introduced in the mid-1980's for residential appliances to promote consumer awareness by using stars to rate the energy efficiency of products and indicate total lifecycle costs. This system was updated in 2000 and again in 2010 to retune the algorithm used to calculate the star-based rating based on a revised energy to volume relationship.

Meanwhile, the first MEPS for refrigerators were implemented in 1999. The goal of these standards is to artificially accelerate deployment of energy-efficient appliances ahead of natural market trends. This prevents manufacturers from selling products with outdated, inefficient technology in Australian markets. These MEPS were updated in 2005 to correspond with the US 2001 levels, which, at the time, were considered the most stringent globally. In fact, the target was so ambitious that just a year earlier, in 2000, not a single refrigerator on the Australian market met these standards, but domestic manufacturers began competing to develop more efficient products ahead of MEPS implementation.

The interplay between these two programs has driven down the energy consumption of Australian refrigerators. Exhibit 37 shows how, from 1980 to the introduction of MEPS in 1999, energy consumption of refrigerators decreased by ~50%. The high visibility of the labelling, combined with accelerated product efficiency gains due to MEPS, helped Australia set the standard for refrigeration efficiency through the early 2000's.

Periods of rapid improvement in refrigerator energy efficiency in Australia correspond to years between introduction and compliance deadlines of standards

Average energy efficiency of refrigerators in Australia



Other products subject to standards/labels have also improved efficiency significantly from 2005-15:

- Lighting products (lamps): 26%
- Washing machines: 21%
- Room air conditioners: 23%

SOURCE: IEA (2016), Energy Efficiency Market Report

Exhibit 37

34) Sources: International Energy Agency (2015), Achievements of appliance energy efficiency standards and labelling programs. / Harrington, L. and Holt, S. (2002), Matching World's Best Regulated Efficiency Standards: Australia's Success in Adopting New Refrigerator MEPS.

Illustration 5

Building codes in Denmark[35]

With its long, cold winters, it is little surprise that buildings, and more specifically heating, is a major source of energy consumption in Denmark. Specifically, buildings account for 40% of energy consumption in Denmark, with space heating responsible for 35% of that. That is why, in 2012, when the Danish Government set out to become fossil fuels free by 2050, making the built environment more efficient appeared as a key priority.

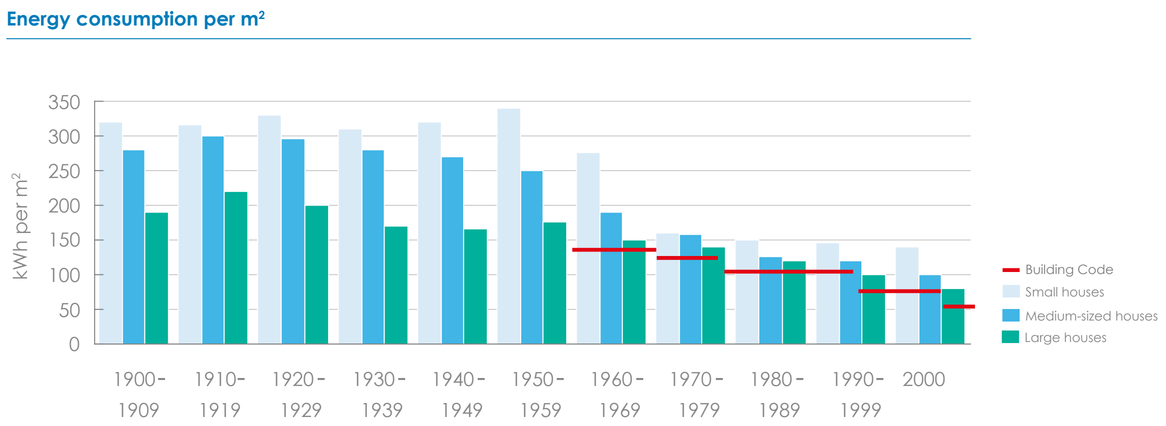
Building efficiency measures in Denmark stem back to building codes introduced in the 1960s. These relatively modest codes helped illustrate early on how simple, cost-effective solutions such as thermal insulation can significantly reduce a building's energy footprint.

Notably, these codes also targeted renovations, not just new buildings. Although innovations in technology and design, alongside continuously tightening building codes, have meant that new buildings use much less energy than old ones, annual addition of new buildings is very limited compared to the total building stock (less than 1%). That, in addition to the fact that there has historically been little demolition in Denmark, means that a majority of buildings standing today will still be standing in 2050. Energy-efficient retrofitting has therefore played a key role in reducing energy use in Denmark [Exhibit 38].

In parallel, new buildings that are constructed in accordance with "class 2015" codes have an energy consumption framework of less than 50% compared to 2006 consumption standards, while those that will be constructed according to "class 2020" will reduce energy consumption by 75% compared to 2006 buildings.

Code requirements for both new and renovated buildings are tightened regularly to ensure progress towards clear, long-term goals. These codes are among the most ambitious and strictest for comparable countries in the EU and have resulted in the final energy consumption* for Danish households decreasing by 6.2% from 2000 to 2013 (an average of -0.5% per year). The ambition is to one-day build only "plus-energy-houses" in Denmark.

Building codes in Denmark have steadily reduced residential energy use since the 1960s



SOURCE: SOURCE: Adapted from IEA (2013), Technology Roadmap: Energy Efficient Building Envelopes; IEA (2008), Energy Efficiency Requirements in Building Codes and Energy Efficiency Policies for New Buildings.

Exhibit 38

35) Sources: Danish Energy Agency (2015), Energy Policy Toolkit on Energy Efficiency in New Buildings – Experiences from Denmark. / Danish Government (2014), Strategy for energy renovation of buildings: The route to energy-efficient buildings in tomorrow's Denmark. / Energy Efficiency Watch (2016), The Danish Building Code. / Rusbjerg, J., Enghave, S.M., and Bach, P. (2016), Energy Efficiency trends and policies in Denmark, Odyssey Mure, Danish Energy Agency. / Schnapp, S. (2014), Denmark - Reducing Energy Demand in Existing Buildings: Learning from Best Practice Renovation Policies, Global Buildings Performance Network.

Illustration 6

US vehicle regulation on fuels[36]

In 1975, in response to the oil crisis, the US globally pioneered the vehicle regulations for improving fuel economy. These first standards, known as the Corporate Average Fuel Economy (CAFE), set efficiency requirements for manufacturers on passenger cars and light trucks starting in 1978 which were intended to approximately double how far cars could travel on a gallon of fuel by 1985. While these standards were a notable start, their effect relatively stagnated after 1985, with efficiency increases being neglected until 2007. During this time, the US fell behind other developed nations in vehicle standards, with higher levels of CO_2 emissions per mile, higher average fuel consumption, and lower average fuel economy. Exhibit 39 illustrates how the lag in regulation corresponds to flattened or declining productivity gains in US fleet improvements over the same period.

In 2007, escalating oil consumption (due to the static CAFE standards, as well as more people driving more miles annually in less efficient SUVs and light trucks) led to the signing of the Independence and Security Act, which once again ratcheted up CAFE required standards until 2030. In 2009, State and Federal requirements for both the CAFE program and the Clean Air Act were consolidated under the National Program through 2025. This return to more aggressive legislation has put the US back on track to become a global leader in fuel efficiency while significantly increasing the market demand for fuel-efficient gasoline, hybrid, and electric vehicles.

Going forward, the National Program is projected to significantly bolster the US auto industry[37]. It aims at:

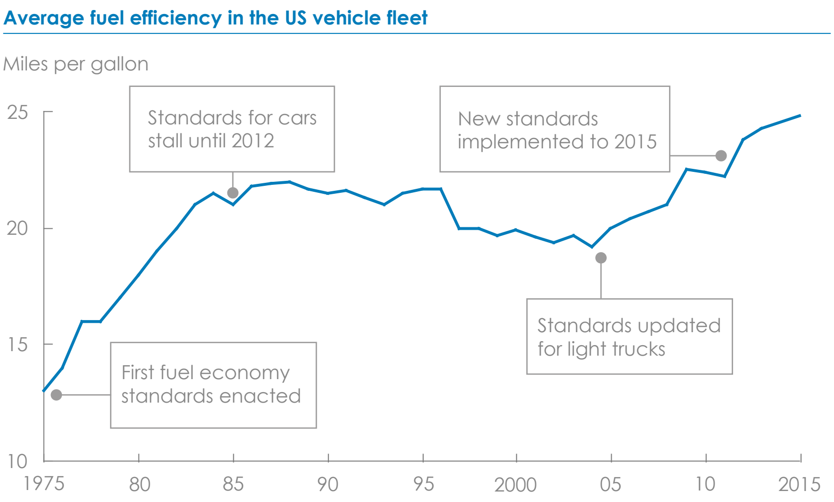
- Significantly reducing oil dependency, with estimated oil savings of 3 million barrels per day in 2030 (the equivalent of all imports from the Persian Gulf and Venezuela);
- Reducing US pollution by 570 million metric tons in 2030 (the equivalent of closing 140 typical coal-fired power plants for a year);
- Creating jobs by, for instance, stimulating investment in new technology;
- Saving consumers $140 billion by 2030 in vehicle costs compared to 2025 standards, translating to $8,000 less over the lifetime of a vehicle, even after factoring in the cost of the more efficient technology.

there is scope for further energy efficiency improvements in heavy duty road transport and aviation, where electrification or a switch to alternative fuels is unlikely to occur in the short term. Improvements in the performance of different transport modes are only a segment of the broader mobility revolution that is likely to occur through a combination of electrification, modal shifts and changes in behavior, as described in Section 3b.

"In industry, the deployment of best available technologies would be the single most important driver of energy productivity"

36) Source: The International Council on Clean Transportation (2014), The state of clean transport policy, available here: http://www.theicct.org/united-states
37) However, the new US administration might decide not to pursue this program.

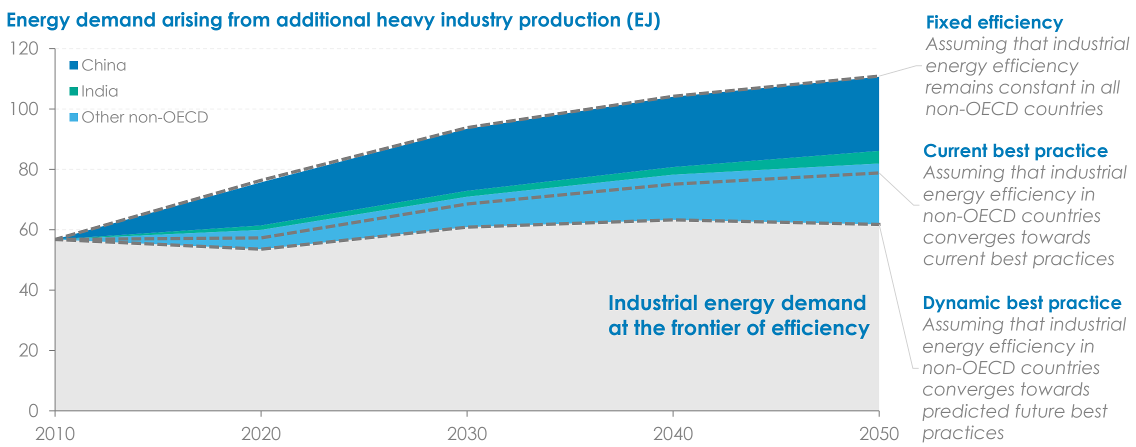
Fuel economy in the US vehicle fleet improved when new standards were introduced – and flattened or declined otherwise



SOURCE: IEA (2016), Energy Efficiency Market Report

Exhibit 39

Energy efficiency improvements in the industry sector will come from the deployment of best available technologies and techniques



SOURCE: Vivid Economics (2017), Economic growth in a low carbon world: How to reconcile growth and climate through energy productivity.

Exhibit 40

The way forward

Energy efficiency improvements

Energy efficiency improvements across sectors have to some extent been driven by autonomous technological progress, but financial incentives and rising technical standards have also played a major role as Exhibit 36, Exhibit 37, Exhibit 38 and Exhibit 39 illustrate.

In all three sectors (buildings, transport, industry), further progress is technically feasible and essential. Policies with proven results, such as those described in the illustration boxes in this section, should be a basis for formulating effective policy measures across the world. IPEEC, the World Energy Council and Enerdata have recently published a report on energy efficiency trends and policies at world level describing key successful policies that can inspire policymakers[38].

Key policy recommendations to drive progress include the following:

- The continual tightening of standards is essential, especially in consumer appliances where price signals and the potential for financial savings may not be enough to induce behavior changes. Based on past experience, policies should focus on performance standards – that combine energy-efficiency requirements with other key performance parameters – rather than technical standards. Equally important in many countries is the enforcement of these standards.
- Public spending should focus on creating markets, deploying technologies and helping to develop energy-efficient value chains, not solely on funding R&D in new technology development.
- Because of the long payback times of some energy efficiency investments, appropriate financing tools, potentially supported by fiscal incentives, can play a key role, for instance in buildings retrofitting.

In addition, **a particularly strong policy focus is required on buildings and industry**. For most appliances and consumer goods, whatever the short-term policies and pace of change in a particular country, improvements in best available performance will be driven by global technological progress, and relatively rapid stock turnover rates can allow catch up at a later date if necessary (e.g. with the average auto being used for 7 to 10 years). But if buildings and industrial plants are built to low standards today, that will depress energy efficiency several decades from now, producing a lock-in effect which will prove very difficult to reverse.

- On buildings, explicit policies are required to drive best practice in new builds (via rigorously enforced building codes) and to drive retrofit investment (where financial incentives, including subsidized household finance, have a role to play). In addition, national and municipal procurement models should consider "total cost of ownership" (including consideration of operational running cost) rather than solely focus on minimizing initial capital cost.
- On industrial plants, incentives supporting industrial companies to invest in energy efficiency measures with longer payback times should be considered. New technology including automation, big data, machine learning indeed give significant opportunities for improved industrial energy efficiency; but measures with a payback time longer than 1-3 years rarely get prioritized by industry, not least given uncertainties about future energy costs.

38) World Energy Council (2013), Energy Efficiency Policies – What works and what does not.

In the industry sector, the deployment of best available technologies and techniques, especially in newly industrializing countries, would be the single most important driver of energy productivity. With current practices, global energy demand from heavy industry is likely to double by 2050. However, consistently deploying currently available best technologies could limit energy demand growth to 40%. It is possible that deploying new best technologies, as they emerge, could even keep energy demand flat throughout the period [Exhibit 40, p. 65]. Achieving this potential would however require the retirement of less efficient capacity before end of physical life. Historically, significant energy efficiency improvements have been driven by autonomous technological progress, encouraged in some cases by explicit energy efficiency improvement programs, driven for instance via voluntary certification regimes or financial incentives. However, the cost and complexity of deploying efficient industrial processes across atomized companies in a diversity of industries can make improvements in this sector particularly difficult, especially in developing economies.

B. INCREASING GDP PER UNIT OF ENERGY-BASED SERVICES

Energy productivity can also be increased by growing GDP without matching increases in energy-based services. Achieving this will likely be the more difficult challenge over the next 25 years. There are competing underlying forces at work.

- **Some improvement may occur automatically as economies become more service-intensive.** Many services that deliver human welfare benefits are inherently less energy-intensive than physical goods (e.g. wellness services rather than automobiles). The accelerating shift in China towards a more service-based economy may in particular have a significant impact on global energy productivity.
- **Conversely, increased incomes may drive growing demand for mobility services**, some of which, in particular international aviation, are inherently energy- and carbon-intensive. Rising prosperity may also generate increased demand **for residential and office space**, and thus energy-intensive construction activity. In addition, **it could result in less attention to energy efficiency**, since energy costs fall as a percentage of income.
- **Other developing economies outside China, meanwhile, are just entering the phase of faster energy-intensive growth**, with a danger that it may be based on lower energy efficiency standards than China is now achieving.

We cannot therefore rely on the shift towards service-intensive economies to deliver the required improvement in energy productivity. Two other developments will be vital, although difficult to achieve:

- Getting urbanization right, and
- Building a circular and sharing economy which reduces the need for energy-intensive products and materials.

Getting urbanization right

Estimates suggest that up to 2.5 billion people could move to cities by 2050, resulting in a 66% overall urbanization rate by 2050[39]. How this urbanization wave plays out will have profound implications for the world's ability to stay well below 2˚C[40]. The world's urban areas account for more than 70% of global carbon emissions today[41]. **Urban densification, allowing for better public transport systems, combined with tougher building standards, is critical to meet climate and energy productivity goals**. For instance, Barcelona delivers an equally high standard of living as Atlanta while generating less than 20% of transport-related carbon emissions, thanks to a more compact urban design [Exhibit 41, p. 68].

"Infrastructure choices over the next 5-10 years will determine whether we can stay well below 2°C"

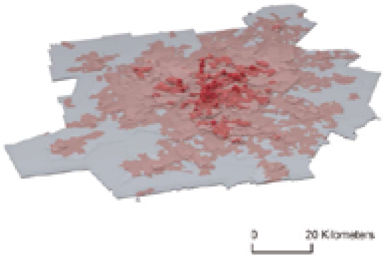
The infrastructure choices that we make over the next 5-10 years, across the transport and building sectors, will largely determine whether or not we

39) United Nations (2014), World Urbanization Prospects, 2014 revision.
40) IEA (2016), Energy Technology Perspectives. Data from 2013.
41) ARUP and C40 Cities (2016), Deadline 2020, How cities will get the job done.

Urban development is a key lever of energy productivity: Atlanta and Barcelona have similar populations and wealth but very different transport carbon emissions

ATLANTA

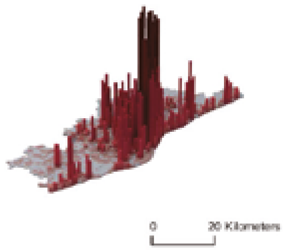
Atlanta's built-up area



Population: 5.26 million
Total area: 16,605 km²
Urban area: 7,692 km²
Transport carbon emissions:
6.9 tonnes CO_2 p.c.

BARCELONA

Barcelona's built-up area



Population: 5 million
Total area: 3,263 km²
Urban area: 648 km²
Transport carbon emissions:
1.2 tonnes CO_2 p.c.

SOURCE: New Climate Economy – LSE esearch, drawing on data from Atlanta Regional Commission (2014), Autoritat del Transport Metropolita (Area de Barcelona) (2013), GenCat (2013), UCSB (2014), D'Onofrio (2014), based on latest data

Exhibit 41

can stay within a 2˚C pathway, since the lifecycle CO_2 emissions of this urban infrastructure alone have the potential to use up all the remaining carbon budget.

But **current trends are not promising**, either in relation to urban design or to building standards:

- The benefits of better urban development – in terms of economic growth, local air quality, and congestion, as well as climate impacts – are well-known. But **in many countries, the trend is still towards unnecessary urban sprawl**. This reflects many factors including, (i) weak planning capacity, especially in those countries where urbanization is currently most rapid, (ii) inadequate pricing and incentives, which fail to take account of congestion and local air quality effects, and (iii) perverse urban financing models, which can result in municipal authorities (and/or farmers) selling land at the city edge to property developers to fund short-term service delivery.
- **Equally the benefits of tougher building standards are already well recognized, but these standards are often hard to enforce**. They typically require higher levels of construction skills; and often about 10-20% greater upfront capital costs.

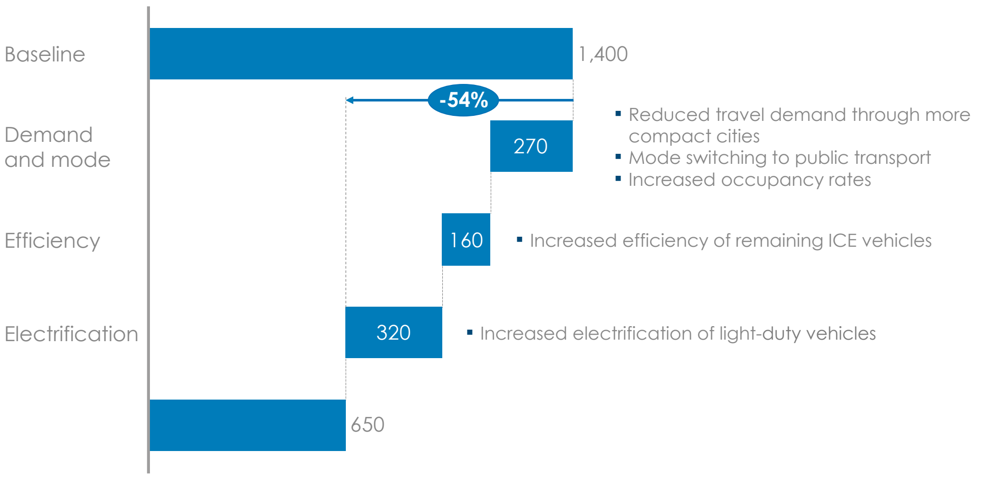
There are shining exceptions to this general picture. But along this dimension of required change (unlike in relation to decarbonization, wider electrification and improvements in appliance performance), **the ETC is not confident that the required public policies or private actions are currently in place to drive sufficient positive change, either in developing or developed countries**. Action to ensure more rapid and certain change along this dimension is therefore among the highest priorities.

Building a circular and sharing economy

The other area of great – though also sometimes difficult-to-grasp – potential lies in what is labelled the "circular"* and "sharing"* economy. There is a huge opportunity to deliver the end services which support prosperous lifestyles while achieving dramatic reductions in the consumption of energy-intensive inputs. Indeed, the Ellen MacArthur Foundation has identified for Europe that a circular economy development path across mobility, food systems, and the built environment

A combination of less transport-intensive cities, modal shifts, car sharing, electrification, and vehicle efficiency could reduce energy requirements for city mobility by half

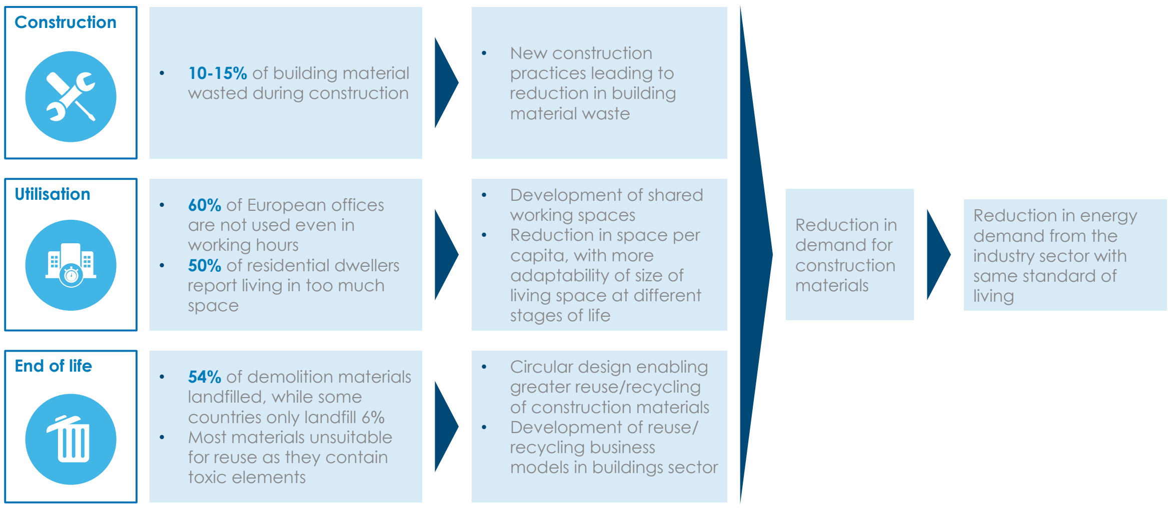
Urban passenger travel in 2040 – Illustrative case
Mtoe



SOURCE: Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission.

Exhibit 42

The development of circular economy and sharing economy models could have a significant downward impact on the demand for energy services



SOURCE: Growth Within: A circular economy vision for a competitive Europe, Ellen MacArthur Foundation, SUN Project, McKinsey Center for Business and Environment, 2015

Exhibit 43

could reduce CO_2 emissions by 48% by 2030, relative to today's levels, or 83% by 2050[42]. Similar conclusions were reached by a recent study by Deloitte[43].

"A circular economy development path could reduce CO_2 emissions by 48% by 2030 in Europe"

One clear example is in surface transport, where the current auto-based urban transportation model is deeply inefficient. Cars are used on average only 8% of the time, and when they are used, about 30% of the time is wasted either in traffic jams and/or looking for parking. Most of the kinetic energy is used to move the car, not the person. Over 20% of urban land is used for parking, land which could be used to either densify cities or develop public spaces[44]. In addition, we know that: (i) there are massive problems of local air pollution, a significant proportion of which derives from cars, and (ii) there are over a million deaths per year from road traffic accidents, plus many more accidents that cause serious injury[45]. This is a set of inefficient economic activities crying out for disruption.

In principle, these huge inefficiencies could be overcome. Estimates suggest that the combination of a modal shift from road to public transport, and increased occupancy rates through greater use of car sharing systems, combined with denser urban design, could reduce kilometers travelled in 2040 by at least 20%. Combined with increased electrification of light-duty vehicles and increased efficiency of remaining ICE vehicles, these structural shifts could lead to **a reduction in energy demand from passenger travel of more than 50% compared to business as usual by 2040** [Exhibit 42, p. 69]. In addition, this would produce a reduction in the total number of vehicles bought, leading to a 5-10% reduction in steel demand[46].

Dramatic reductions in energy and other inputs could also in principle be achieved in the construction industry, with 10 to 15% of building material currently wasted during the construction process, 60% of European offices not used even in working hours, and 54% of demolition materials deposited in landfills. Demand for virgin steel from the buildings sector could potentially be significantly reduced by a combination of improved buildings design – reduced steel use, longer buildings lifecycle, and increased recyclability of materials – as well as reduced requirements in new office floor space – enabled by optimized internal office design and new working practices such as hot desking, working from home, and even shift working. The replacement of multiple white-collar jobs by AI applications could further reduce the need for office space, potentially leading to significant asset stranding (as e-commerce is doing to various categories of bricks-and-mortar retail assets) [Exhibit 43, p. 69].

Circular and sharing economy models could therefore play a significant role, alongside supply-side low-carbon technologies described in Section 2, in cutting carbon emissions from "hard-to-electrify" sectors. Across multiple activities, there are huge opportunities to reduce demand for energy-intensive materials and products through increased product longevity, greater re-use and recycling of materials and subcomponents, and new consumer and business practices, provided the commitment to a "circular" system is designed in from the start. The development of new business models, shifting from product-based to service-based approaches, could help unlock this potential, especially in heavy industries. Such an evolution would likely exacerbate the existing overcapacity situation in some heavy industries, such as steel, leading to a need for early retirement of some industrial capacity.

Many of these developments may occur without specific policy intervention, reflecting a private commercial response to material and labor cost increases, but the extent to which the full potential is grasped will depend crucially on key aspects of public policy.

42) Ellen MacArthur Foundation, SUN Project, McKinsey Center for Business and Environment (2015), Growth Within: A circular economy vision for a competitive Europe.
43) Deloitte Sustainability (2016), Circular economy potential for climate change mitigation.
44) Ellen MacArthur Foundation, SUN Project, McKinsey Center for Business and Environment (2015), Growth Within: A circular economy vision for a competitive Europe.
45) World Health Organization Statistics (2016).
46) Ellen MacArthur Foundation, SUN Project, McKinsey Center for Business and Environment (2015), Growth Within: A circular economy vision for a competitive Europe.

C. A STRETCH SCENARIO – AND HOW TO ACHIEVE IT

A study from Vivid Economics produced for the ETC[47] assessed the stretch potential to increase energy productivity over the next 35 years focusing on the three key sectors of buildings, transport and industry which account for over 95% of final energy consumption*[48]. **The main finding is that it is technically possible to keep global energy requirements more or less flat versus today in a world of economic growth by delivering a 3.5% average annual rate of energy productivity improvement** [Exhibit 44, p. 72].

"It is technically possible to keep energy demand more or less flat versus today"

The following rough estimates provide a sense of the relative importance of different levers to achieve this stretch scenario, but are likely to significantly underestimate the potential impact of structural changes, which are not well-captured in existing models:

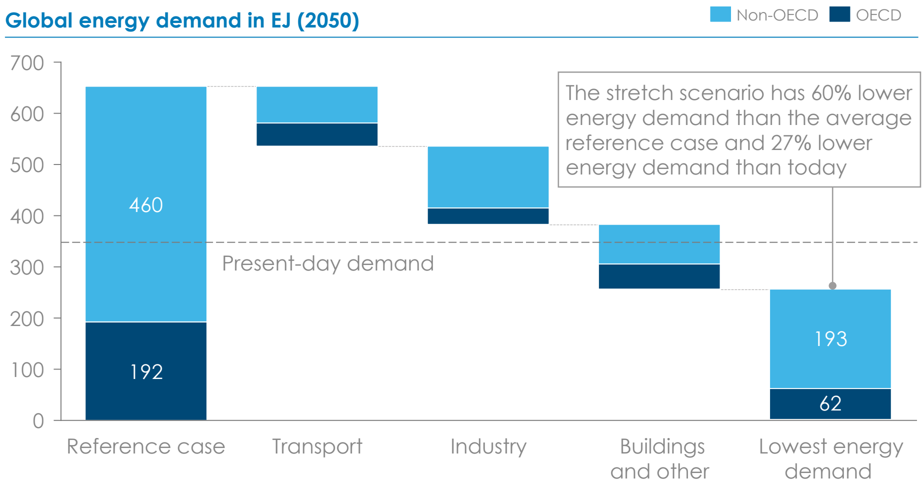
- 38% of energy demand reduction versus business as usual by 2050 would come from reduction in energy demand from industry, mostly thanks to increased technical efficiency of industrial plants in non-OECD countries. This does not capture the potential impact of the shift towards a more circular and sharing economy.
- 32% would come from reduction in energy demand from buildings, of which we would expect approximately half to be generated by increased equipment efficiency, a quarter by higher buildings envelope efficiency, and the remaining quarter by a range of improvements related to demand management and reduction in network losses.
- 30% would come from reduction in energy demand from transport, mostly through improved technical efficiency of vehicles, electrification of the fleet and modal shift. The impact of better urban planning and car sharing practices may be underestimated[49].

The good news from this research paper is that there are multiple levers which can be pulled. However, **achieving the stretch scenario would require more-or-less perfect execution on all the levers described above** [Exhibit 45, p. 71]. A range of implementation challenges make this unlikely, in particular institutional weaknesses (e.g. related to building code enforcement), behavioral barriers (e.g. rebound effects or limited focus on energy savings both in households and in non-energy-intensive commercial sectors) or the under-development of innovative financing mechanisms to support energy efficiency improvements (e.g. ESCOS).

The acceleration in the pace of energy productivity improvement that we have observed in the past 10 years – from 1.4% per annum over the period 1990-2005 to 1.7% on average over the period 2005-2015 and 1.8% in 2015 – resulted from significant efforts across the developed and developing worlds to create the right incentives for behavior changes and energy productivity investments across the transport, buildings and industry sectors. **Given the complexity and difficulty of achieving simultaneous improvements across multiple sectors, it is unlikely that the simple acceleration of on-going progress will be sufficient to achieve the 3% per annum improvement in energy productivity** that is required for a well below 2˚C trajectory. Achieving the required energy productivity revolution will require a step-change in the way that Governments, businesses and investors prioritize this agenda. The tools are available – but institutional commitments are not yet sufficiently in place.

47) Vivid Economics (2017). Economic growth in a low carbon world: How to reconcile growth and climate through energy productivity. Research paper for the Energy Transitions Commission.
48) IEA (2016). Energy Technology Perspectives. Data from 2013.
49) Vivid Economics (2017). Economic growth in a low carbon world: How to reconcile growth and climate through energy productivity. Research paper for the Energy Transitions Commission.

A stretch scenario can achieve a 60% improvement in energy productivity relative to the reference case, with roughly equal proportions coming from each sector



NOTE: The reference case is the average of ETP 6DS, AIM Reference, Greenpeace Reference, and GEA Reference; Lowest energy is based on a combination of GEA Efficiency and Greenpeace Revolution and Greenpeace Advanced

SOURCE: Vivid Economics (2017), Economic growth in a low carbon world: How to reconcile growth and climate through energy productivity.

Exhibit 44

Realizing this stretch scenario would require to simultaneously achieve major shifts across multiple levers in the transport, buildings and industry sectors, including decarbonization

Transport
- 70% fall in energy demand[1]
- 50% electrification
- 40% alternative fuels

Increased efficiency of air, road and rail travel achieved through:
- Electrification of passenger vehicle travel (60-90% of vehicle sales in 2050)
- Development of alternative fuels for long haul transport
- Drastic vehicle efficiency improvements (by a factor 7 for light road vehicles)

Modal shift:
- From individual to public transport
- From air and road to rail

Reduction in miles travelled, especially in passenger transport, thanks to:
- Better urban design
- Digitization
- Behavior change (e.g. higher occupancy of vehicles)

Industry
- Energy demand halved[1]
- Full substitution of fossil fuels by electricity and alternatives

Increased process efficiency:
- Improved process efficiency
- Improved industrial energy systems, including greater heat waste recovery
- Innovation enabling electrification and switch to alternative fuels in energy-intensive industries

Accelerated deployment of best available technologies and techniques:
- Retirement of less efficient capacity
- Deployment of BAT in newly industrializing countries

Reduction in demand for energy-intensive industrial products:
- Substitution of energy-intensive materials by alternatives
- Development of circular and sharing economy models

Buildings and other
- Energy demand divided by 3[1]
- 55% electrification
- Full substitution of biomass

Improved buildings envelopes:
- Widespread construction of high performance building envelopes (reaching 100% of new buildings globally in 2050)
- Tripling of historical retrofitting rates (reaching 3% per annum)

Improved energy efficiency of buildings equipment:
- Improvements in energy efficiency for a range of appliances (by 50-100%)
- Smart management of appliances
- Electrification of heating and cooling
- Development of district heat (up to 20% of buildings energy demand)

Lifestyle changes:
- Reduced demand for commercial buildings space

1. Evolution of energy demand by sector in the stretch scenario compared to the average of reference cases

SOURCE: Vivid Economics (2017), Economic growth in a low carbon world: How to reconcile growth and climate through energy productivity.

Exhibit 45

The way forward

An energy productivity revolution

Achieving an energy productivity revolution will require strong policy action. In addition to the push on electrification described in Section 1 and accelerated efforts on energy efficiency improvement described in Section 3a, the ETC believes that the following actions are particularly important:

- **A major push on urban planning and development**. We are already seeing a significant scale-up in funding by the development banks, together with the formation of many horizontal networks among city mayors. However, this is still not a sufficient response to the challenge, especially given the lock-in consequences of getting it wrong over the next 15 years. Consideration should be given to the creation of a new Global Urban Fund, designed as a public-private partnership, which would be able to provide programmatic funding and support to countries, regions and cities that are putting in place ambitious, sustainable urban development projects.

- **Further actions to drive a more circular economy**. The European Union is putting in place an ambitious agenda to accelerate "zero waste to landfill" and the phase-out of inefficient, polluting methods of incineration over the next decade. China is embedding the principles of the circular economy into its five-year plans. What is now needed is a set of public-private partnerships in key sectors – construction, electronics, energy, mobility, food, packaging – to set specific targets for materials re-use, to drive the introduction of take-back systems for all end-of-use materials that cannot be converted into high-value feedstocks, to create secondary markets for materials (e.g. plastics) with clear trading standards, and to develop better regulatory frameworks.

4. Optimization of Fossil Fuels Use within Overall Carbon Budget Constraints

Fossil fuels today account for 70% of final energy demand. That must fall to approximately 50% by 2040 if global warming is to be limited below 2°C[50]. The potential for decarbonization of power and wider electrification described in Section 1 makes such a reduction possible. But even after such a fall, fossil fuels will remain the main source of energy for the growing world economy over the next 25 years. That creates major challenges for policymakers and the fossil fuels industry: how to manage the medium-term volume decline while fossil fuels still play a major and vital role today, and how to ensure adequate investments in capacity without leaving behind stranded assets, or undermining the required transition.

Meeting this challenge requires:

- Developing a realistic vision of the sustainable scale of fossil fuels production compatible with a well below 2˚C pathway;
- Optimizing the use of different fossil fuels within the overall carbon budget;
- Scaling carbon capture, conversion and storage as a back-stop carbon abatement technology, as well as natural carbon sinks;
- Establishing a robust carbon price regime.

A. A REALISTIC VISION OF THE SUSTAINABLE SCALE OF FOSSIL FUELS PRODUCTION

If the world is to have a reasonable chance of limiting global warming to 2°C, **future cumulative CO_2 emissions from the energy system must be limited to less than 900 Gt** [Exhibit 46, p. 76] The implications of this "carbon budget" for maximum possible fossil fuels consumption depends in turn on two factors: (i) what assumptions we make about the feasible future scale of carbon capture and sequestration*, and (ii) whether it is acceptable and realistic to allow carbon emissions to "overshoot" desirable levels across the next, say 50 years, relying on "negative emissions"– achieved for instance via a combination of bioenergy plus carbon capture (BECCS)* – to offset the adverse climate effect in subsequent years.

Copenhagen Economics was commissioned by the ETC to **analyze a wide range of existing third-party 2˚C scenarios* and shed light on their key underlying assumptions**, about (i) the feasible annual scale of CO_2 capture in 2040, (ii) the average annual rate of carbon capture from 2040 to 2100, (iii) the average rate of BECCS between 2040 and 2100. Three archetypical scenarios are presented on Exhibit 47, p. 76, which illustrates the impact of assuming high, medium, or no carbon sequestration on the required trajectory for fossil fuels use[51].

"Future cumulative CO_2 emissions must be limited to less than 900 Gt"

The third-party medium CS scenario shows that, even if 7-8 Gt of carbon sequestration per annum could be achieved by 2040, fossil fuels use would still have to fall by one third to meet climate objectives. Exhibit 48, p.78 sets out more detail on this third-party scenario. It assumes a significant role for BECCS, which, in this scenario, would account for 3 Gt of carbon capture out of 7-8 Gt in 2040, starting to build the infrastructure required to make negative emissions possible in the second half of the century. This could only be delivered by stretching assumptions on the technical and economic feasibility of BECCS, especially in terms of land use.

Apart from this medium scenario with 7-8 Gt of carbon sequestration, multiple other pathways are also possible. For instance, **the illustrative pathway presented by the ETC on Exhibit 4 in the Executive Summary would deliver a similar decrease in fossil fuels use with only 3-4 Gt of carbon capture per annum by 2040, since it assumes slightly higher emissions in 2040 and faster reduction later in the century.** These 3-4 Gt would be concentrated in industry, include some share of CO_2-based products and would not involve any BECCS.

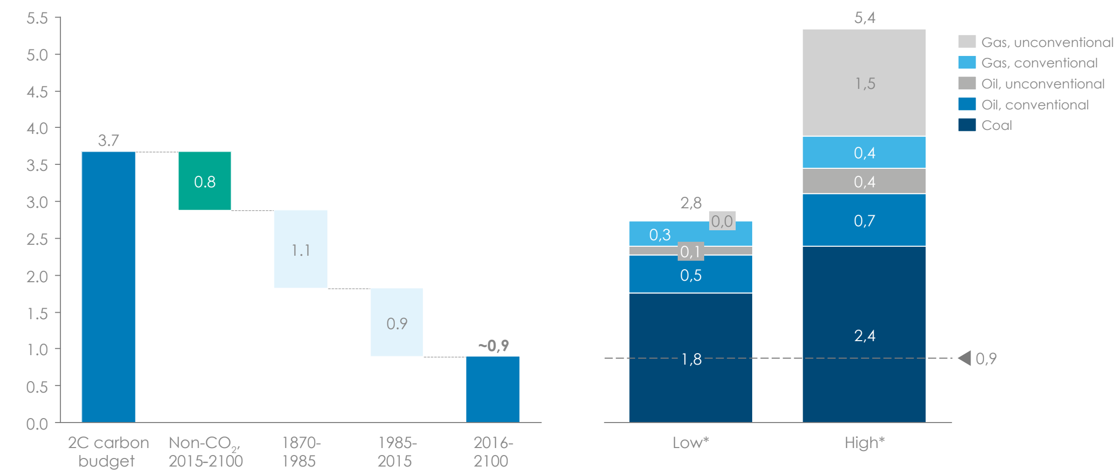
50) Copenhagen Economics (2017). The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system. Research paper for the Energy Transitions Commission.

51) These three scenarios are archetypes, which are representative of existing 2˚C scenarios developed by a range of institutions, which have been previously screened for their robustness. The full methodology is described in Copenhagen Economics (2017). The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system. Research paper for the Energy Transitions Commission.

Fossil fuel reserves are 3-5 times larger than the remaining carbon budget of 900 Gt CO_2

Carbon budget emissions to 2100
1000 Gt CO_2-eq.

Emissions implied by fossil fuel reserves
1000 Gt CO_2-eq.

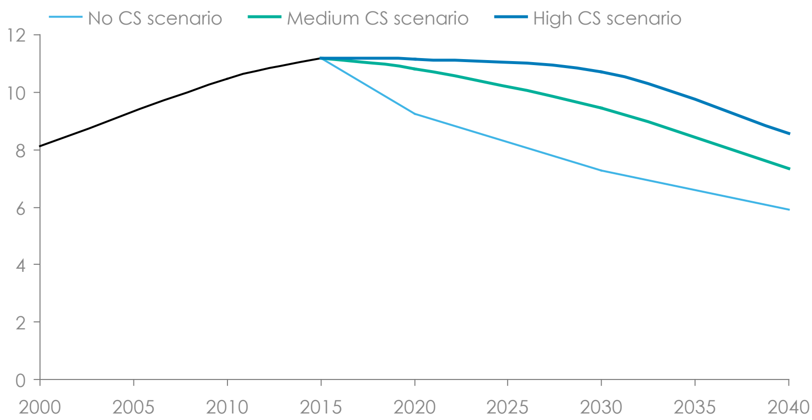


NOTES: Low values show the sum of the lowest estimates across sources; high shows the maximum across sources.
SOURCE: IPCC (2013); La Quéré et al (2014); BGR (2013); GEA (2012); WEC (2013); BP (2013); BP (2016); Copenhagen Economics analysis

Exhibit 46

Fossil fuel consumption must fall to meet climate objectives; by one third to 2040 even if significant carbon sequestration is eventually available, but nearly by half if it is unavailable

Fossil fuel consumption
1000 Million tonnes of oil equivalent per year



Average annual total CO_2 removals
Gt CO_2 per year

	2040	2040-2100
High CS scenario predictions	7-8	18
Medium CS scenario predictions	7-8	11
No CS scenario predictions	Nil	Nil

- In the medium and high carbon sequestration scenarios, necessary CO_2 removal increases significantly after 2040.
- With no carbon sequestration, fossil fuel demand drops dramatically.

NOTE: Medium scenario is based on scenarios limiting the risk of a global temperature rise of more than 2 degrees to less than one third, with 2020 emissions of at least 30 $GtCO_2$ and with no more than 15 $GtCO_2$ removal from CS in any given year. No CS scenario fulfils the same criteria as the Medium scenario and in addition requires 0 $GtCO_2$ removal from CS in any given year. High CS allows for CS capture rates of between 15 and 40 Gt in any given year.
SOURCE: Historic data from BP, future trajectories based on Copenhagen Economics analysis of the AR5 scenarios database

Exhibit 47

If the world is to limit global warming to 2˚C, let alone to well below 2˚C, we need **both a sharp decline in fossil fuels use and a ramp-up in carbon capture and various forms of sequestration (including CCS on fossil fuels*, CO_2-based products*, natural carbon sinks* and BECCS*)**. The precise amount of carbon capture and sequestration required will depend on the pace at which we decarbonize power, expand electrification and improve energy productivity, as well as on the uptake of alternative solutions for industrial decarbonization.

This in turn will have implications for allowable and required fossil fuels use. Thus, if the pace of carbon capture and sequestration deployment were significantly less than the 7-8 Gt per annum assumed by 2040 in the third-party medium CS scenario, and if higher emissions up till 2040 could not be offset by lower emissions later in the century, the required reductions in fossil fuels use would logically have to be considerably greater to remain consistent with the carbon budget.

"Overall fossil fuels use must start falling"

Under any reasonable scenario, however, **overall fossil fuels use must start falling**. Exhibit 49, p. 78, shows the pace of reduction that would be required if the third-party medium scenario of 7-8 Gt of carbon sequestration was feasible:

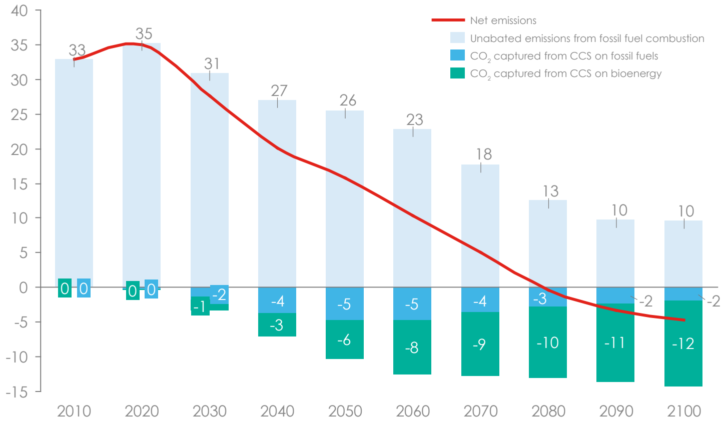
- Coal consumption beginning to fall almost immediately, with a reduction of something like 70% by 2040[52] – in fact, global coal consumption already started declining since 2014, but this fall, driven by China, needs to accelerate;
- A limited increase in gas production, but with a flat profile beyond the 2020s, and with a total volume in 2040 only 2% higher than today – provided methane leakages can be ended;
- Oil consumption peaking sometime in the mid-2020s, and falling some 30% below today's level by 2040.

These trajectories are achievable: the illustrative ETC pathway presented in the Executive Summary would result in similar trends.

52) These numbers are calculated in tonne of coal equivalent, since the energy content of coal varies a lot. The world average is 1.4 tonnes of coal for 1 tonne of coal equivalent. Indian coal is roughly 1.7 tonnes of coal for 1 tonne of coal equivalent. The required decrease in the volume of coal consumption is therefore even sharper.

In a medium CS scenario, carbon capture would have to run at 11-14 Gt per annum throughout the second half of the century, with net negative emissions after 2080

CO_2 emissions from fossil fuel combustion and emissions captured through carbon sequestration in medium CS scenario
Gt CO_2 per year



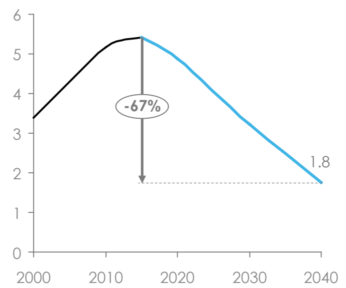
- Negative emissions through BECCS remove ~3 Gt CO_2 of emissions in 2040, and 12 Gt CO_2 emissions in 2100
- Cumulative CO_2 emissions would have been ~500 Gt larger to 2100 without negative emissions.
- Atmospheric CO_2-concentrations would be 25-30 ppm higher in 2100 without negative emissions, roughly equal to between ¼ and ⅓ of a degree.

NOTE: Increased PPM based on 1 ppm CO_2 concentration = 2.12 Gt C = 7.77 Gt CO_2. ~45% of this ends up in the atmosphere. Potential temperature increase is based on a climate sensitivity of 3 (i.e. the resulting temperature increase resulting from a doubling of atmospheric CO_2 concentration).
SOURCE: Copenhagen Economics analysis based on AR5 database

Exhibit 48

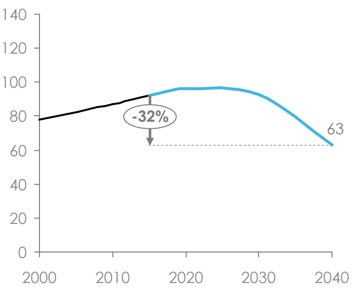
In a 2°C pathway, coal, oil and natural gas would fare differently

Coal consumption
Billion tonnes per year



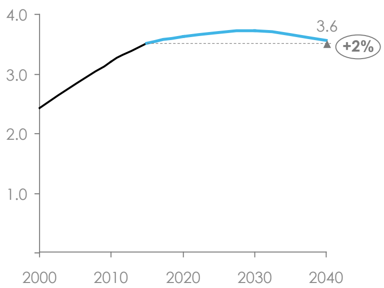
- Coal consumption falls sharply, peaking in the early 2020s at the latest, before declining to one third of current levels.
- The line in the chart above includes both thermal and metallurgical coal but the former can and must fall far more rapidly than the latter.

Oil consumption
Million barrels per day



- Oil must stop growing in the 2020s, and then rapidly decline to a third below current consumption levels by 2040.
- Use is increasingly concentrated in heavy and long-distance transport, as well as feedstock for chemicals.

Natural gas consumption
Bcm per year



- Natural gas may continue to increase slightly to 2040, but must fall thereafter.
- Natural gas is used across the energy system, with a particular role in industry.

Notes: All fossil fuel trajectories are based on scenarios reaching a 2°C objective with at least two-thirds probability. The charts show median fossil fuel use in 21 scenarios with less than 15 $GtCO_2$ removal in any given year. Average removals 2050-2100 are 3 Gt/year through CCS on fossil fuels and 8 Gt/year through BECCS or other negative emissions.
SOURCE: Historic data from BP. Projects are Copenhagen Economics calculations on data from IIASA AR5 database

Exhibit 49

"These fossil fuels use trajectories are achievable"

The more consensus there is among public policymakers and the fossil fuels industry that these scenarios are required and likely, the greater the chances that we will achieve cost-effective transition to a low-carbon economy minimizing wasteful investment. The later these changes in trajectory occur, the more challenging and expensive it will become to remain within an overall 2˚C pathway, let alone a well below 2˚C pathway. The next section describes how these trajectories can be driven by changes in demand patterns and how to optimize remaining fossil fuels use.

B. OPTIMIZING FOSSIL FUELS USE BY TYPE

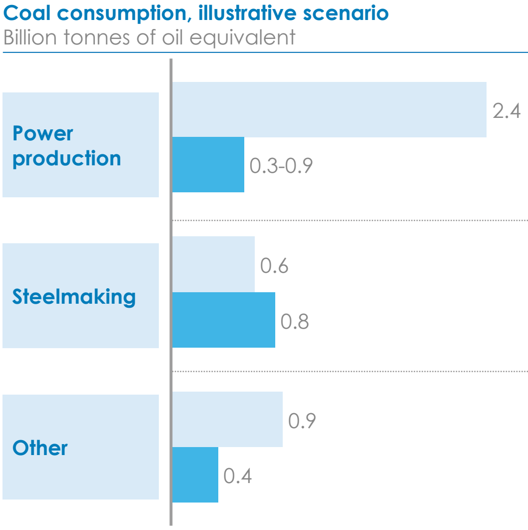
A successful energy system transition and a growing global economy will be best supported if the available carbon budget is used in as optimal fashion as possible, in particular:

- **The need for overall coal production to decline is clear.** Coking coal will remain a key input to the iron and steel industry for several decades, whereas thermal coal used in power generation can increasingly be replaced either by gas, renewables, or nuclear. Limited coal-fired power generation capacity is also likely to be added to the global power mix, primarily in emerging economies where growing power demand needs to be met at low cost in the short term. It is therefore essential (i) to eliminate the use of unabated coal in developed world power generation as rapidly as possible, (ii) to strengthen financial incentives and support for fast-growing developing countries to grow their non-coal-fired power generation capacity, and (iii), as a last resort, to consider whether there are policy mechanisms and global financial flows which can make it possible for countries like India to develop coal-fired power generation but close these plants before their end of life if CCS has not by then become cost-effective [Exhibit 50, p. 80].
- **Within overall flat production, the use of gas in industry and as feedstock could increase even as total use in power generation declines.** We may also see increased penetration of gas into long-range shipping, replacing highly-polluting bunker fuels [Exhibit 51, p. 80]. In countries with fast-growing demand, where renewables, nuclear and hydro cannot develop fast enough, gas may replace coal in power generation, potentially reducing CO_2 emissions by 1.5 Gt per annum [Exhibit 52, p. 81]. But **this will only be clearly beneficial if accompanied by forceful action to ensure minimum methane leakage.** If methane leakage were to be as high as 5%[53], switching from coal to gas could actually have a short-term adverse effect on global warming. Industry and Governments must therefore place a high priority on eliminating methane leakage throughout gas production, transmission and distribution systems and should only seek to substitute gas- to coal-fired power generation if low leakage rates can be assured [Exhibit 53, p. 81]. In addition, there is a danger that large-scale new investments in gas-related infrastructure (e.g. pipelines and LNG terminals) could produce a lock-in effect, resulting in excess long-term gas consumption unless either carbon capture becomes cost-effective and/or it is feasible to ensure that assets are not run for their full technically feasible life.
- **Oil will likely have to play the dominant role in long-distance road freight, shipping and aviation for several decades**, even though progressively replaced by either biofuels, hydrogen, or the further extension of electrification. But rapid progress towards electrification of light vehicles will likely mean a decline in total volume used within the transport sector, partially offset by a rise in use as a chemical industry feedstock [Exhibit 54, p. 82]. **Continued oil production demands forceful action to end flaring**, which still represents 300 MT of CO_2 emissions annually. The World Bank's Global Gas Flaring Reduction (GGFR) partnership promotes and facilitates progress to reduce flaring. Key oil majors have committed to the Zero Routine Flaring by 2030 initiative, led by the World Bank, alongside Governments and development organizations. These initiatives are important to stop routine flaring as soon as possible and no later than 2030.

53) Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission.

By 2040, coal is still used as a feedstock in industry, whereas its use as a fuel in power productions falls significantly

Coal consumption, illustrative scenario
Billion tonnes of oil equivalent



Power production
- The share of coal may fall from 40% today to ~5-10% by 2040 in a WB2C scenario, replaced by renewables, natural gas, and nuclear
- Carbon capture strongly determines the feasible share; by 2040, more than half of thermal coal may be need to be used with CCS

Steelmaking
- The use of coal for steelmaking is likely to increase even with very ambitious energy efficiency, process change, materials substitution, and recycling
- CCS or process technological breakthroughs would be required for further deep reductions emissions

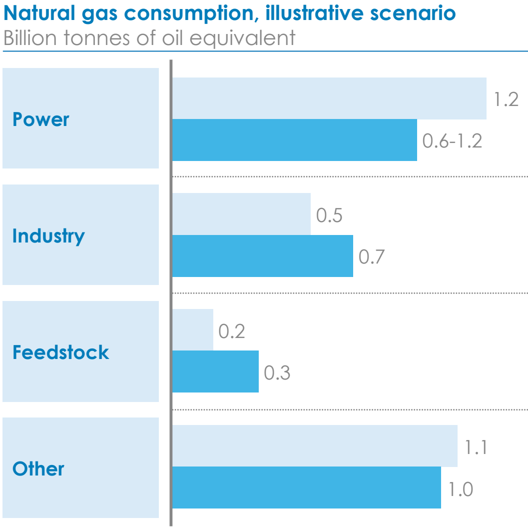
Other
- Coal use also persists to some degree in high-temperature industrial processes as well as residential and commercial heating

SOURCE: Copenhagen Economics (2017), The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system.

Exhibit 50

By 2040, natural gas use stays at today's level, with increased use in industry and as a feedstock, where there are few alternatives

Natural gas consumption, illustrative scenario
Billion tonnes of oil equivalent



Power
- Natural gas may provide 10-15% of power generation in 2040 (against 20% today)
- Carbon capture may lead to a lower gas share, by enabling a higher share of coal; however, some share of natural gas plants may also need to be equipped with CCS

Industry
- Much of remaining gas is used in industry, where it may increase in absolute terms as a cleaner fuel and substitute for coal in high-temperature applications

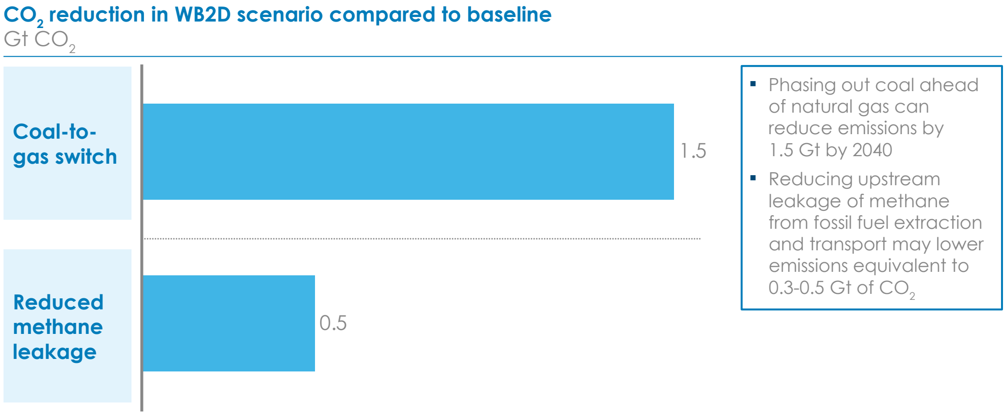
Feedstock
- The use of gas as a feedstock will increase, driven by increasing demand for chemicals (e.g. fertilisers)
- 10% of natural gas may be used as feedstock by 2040, as compared to around 5% today

Other
- Remaining gas use in buildings depends on the rate of energy efficiency improvements, renewables deployment, and electrification
- Gas also could become more common as a transport fuel, but emissions gains depend on low end-to-end methane leakage

SOURCE: Copenhagen Economics (2017), The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system.

Exhibit 51

Phasing out coal ahead of natural gas and reducing upstream leakage of methane are the two key drivers of emission mitigation within the fossil fuels sector beyond CCS

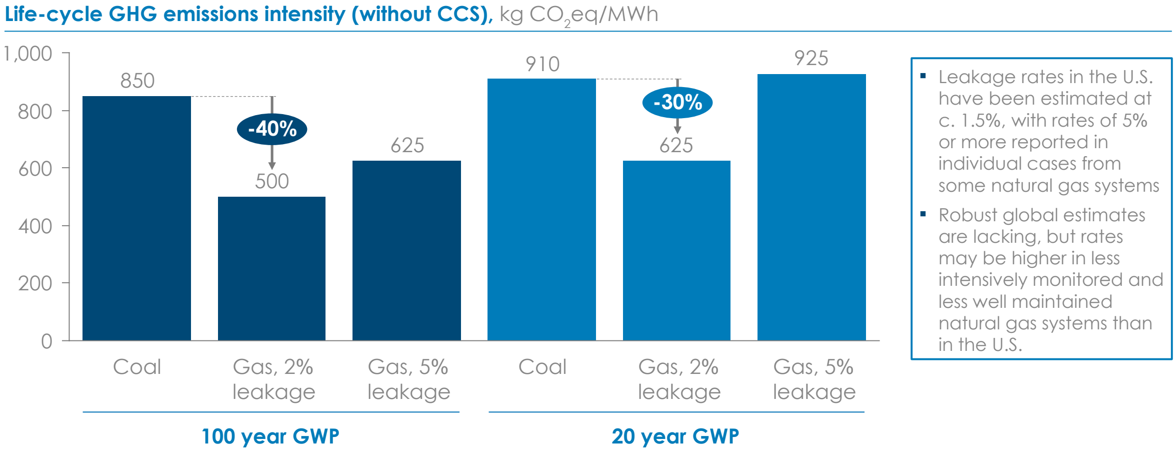


Note: Methane leakage rates based on global warming potential of methane 35 times higher than that of CO_2

SOURCE: Copenhagen Economics (2017), The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system.

Exhibit 52

Controlling methane leakage is key to enabling climate benefits from switching from coal to natural gas

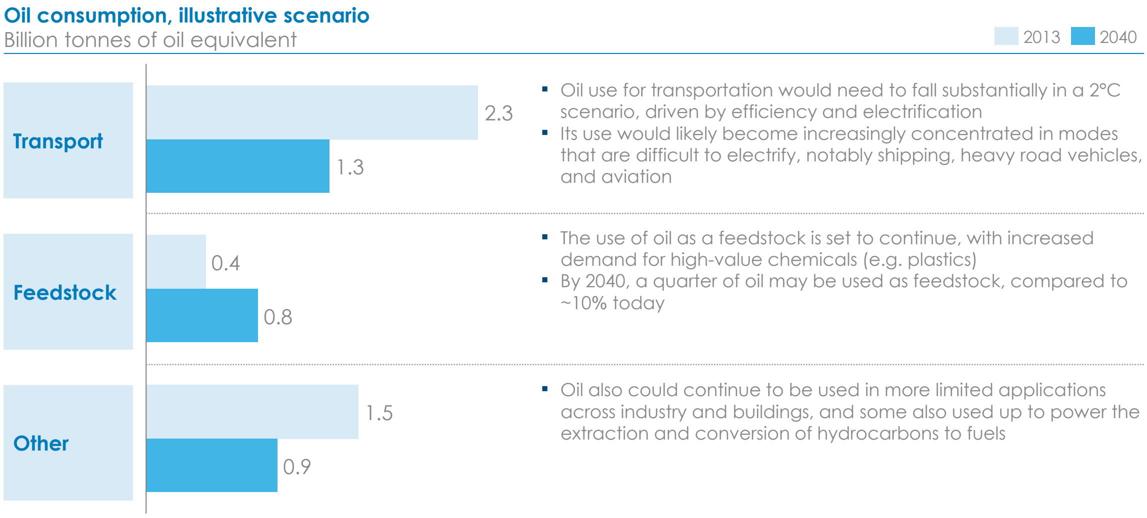


NOTE: Life-cycle emissions associated with the production of equal amounts of electricity from newly constructed power plants that operate for 30 years and then retire. Methane leakage rates (%) are in parenthesis. Comparison based on 100-year and 20-year Global Warming Potential (GWP) for methane. Coal refers to the average emissions of pulverized coal and ultra-supercritical pulverized coal plan; Gas referse to a combined cycle natural gas turbine plant.

SOURCE: Copenhagen Economics analysis based on Farquharson et al (2016); Lazarus et al (2015).

Exhibit 53

By 2040, oil is still used as a transport fuel, and, increasingly, as a feedstock for production of plastics and other high-value chemicals



SOURCE: Copenhagen Economics (2017), The future of fossil fuels: How to steer fossil fuels use in a transition to a low-carbon energy system.

Exhibit 54

C. SCALING ALL FORMS OF CARBON CAPTURE AND SEQUESTRATION

The decarbonization of our energy system required to meet 2 °C objectives depends on significant levels of carbon capture and some form of permanent sequestration taking CO_2 out of the atmosphere. The third-party medium CS scenario for future fossil fuels use set out above (on Exhibit 47, Exhibit 48 and Exhibit 49) assumes that some 7-8 Gt of CO_2 per annum need to be captured and sequestered in carbon-based products*, underground storage*, or natural carbon sinks* by 2040.

The amount of CO_2 that will need to be captured and sequestered to ensure that the world is on a well below 2˚C trajectory will depend on the pace at which we decarbonize power, expand electrification and improve energy productivity, as well as on the uptake of alternative solutions for industrial decarbonization. **If accelerated transitions in both energy demand and supply lead to a faster decrease in fossil fuels use, the level of carbon capture and sequestration required to meet 2˚C objectives would be lower than in the third-party medium CS scenario.**

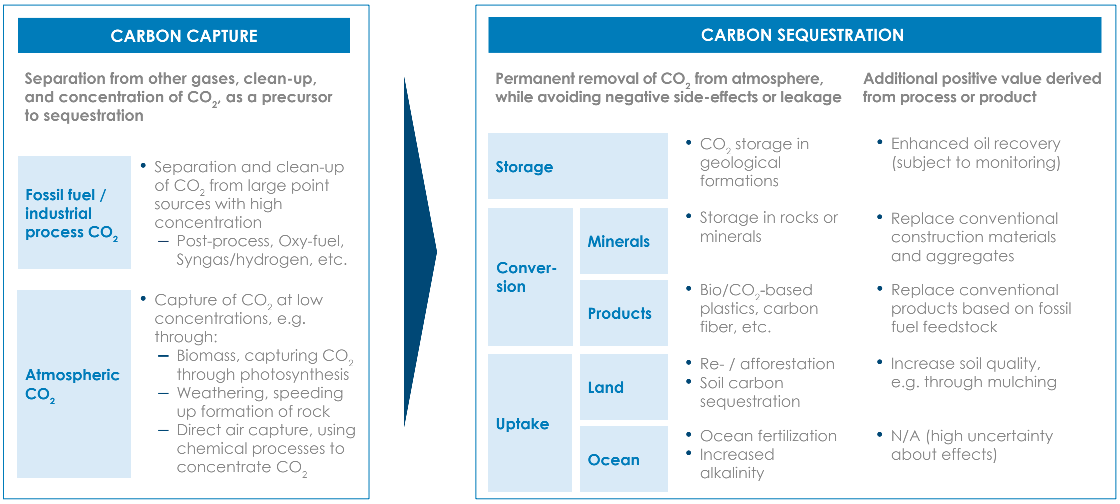
In all realistic scenarios, achieving a step-change in the scale of carbon capture and sequestration volumes will be essential. Exhibit 55 describes the different routes to carbon capture and sequestration through which this could be achieved.

Carbon capture on fossil fuels, bioenergy and industrial processes

While Section 1 concludes that the feasibility of a low-cost renewable-based power system is likely to limit the role of CCS in the power sector to specific circumstances in developing economies, **carbon capture, conversion into products and storage remain vital technologies for three reasons:**

- As discussed in Section 2, it may be the only cost-effective way to decarbonize some industrial processes.

Carbon capture and sequestration can employ a large number of routes

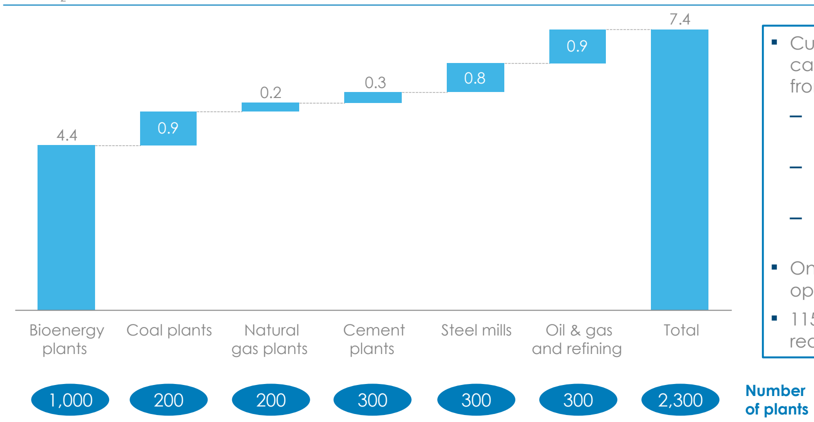


SOURCE: Ad hoc analysis developed by Copenhagen Economics for the Energy Transitions Commission.

Exhibit 55

Scaling up CCS to reach 7-8 Gt by 2040 would require building ~2,300 CCS installations or 2.2 plants per week in the period 2020-2040

Illustrative example: How much CO_2 could a mix of 2,300 CCS installations capture per year?
Gt CO_2 per year



- Current operating and planned CCS capacity is 55 million tonnes CO_2 per year from 33 plants:
  - 15 plants with 28 Mt CO_2 / year capacity currently operating
  - 7 additional plants with 12 Mt CO_2 / year capacity opening by 2018
  - 11 plants with 15 Mt CO_2 / year capacity are in advanced planning
- One large-scale operation entered into operation every other year over 2000-15
- 115 plants per year will be required to reach 7 Gt over 2020-40

NOTE: Estimated potential share of CO_2 captured with industrial CCS technology varies between sources. Typical ranges for plants are: steel 40-80%; chemicals 50-95%; cement 60-90%; refineries ~80%; other 30-100%. Conservative point estimates have been chosen where available. CCS projects under advanced planning stage consist of 11 projects expected to take final investment decisions by mid-2016. Global CCS Insitute (2015), The global status of CCS 2015: Summary report

SOURCE: Copenhagen Economics analysis based on IEA (2013) – Technology Roadmap Carbon capture and storage; Global CCS Institute (2016) – Introduction to industrial carbon capture and storage; Global CCS Insitute (2015), The global status of CCS 2015: Summary report

Exhibit 56

- In some developing economies, where renewables cannot be deployed quickly or cheaply enough to meet rapidly growing energy needs in the short term and where, therefore, some fossil fuels power plants will inevitably be built, carbon capture will be essential to eliminate emissions at a later date. The IEA argues that retrofitting CCS will be needed to reconcile the world's existing 1950 GW of existing coal-fired power generation capacity with a 2 °C pathway[54]. In addition, some fast-growing economies may be challenged to achieve energy security without new fossil fuels-fired power generation. These facilities cannot operate to the end of their natural life without breaking the carbon budget, and it may therefore be essential to retrofit with CCS technologies.
- CCS would clearly be essential if the global strategy to address climate change relied to any degree on the assumption that negative emissions could be achieved at a future date via BECCS.

"Achieving a step-change in the scale of all forms of carbon capture and sequestration is essential"

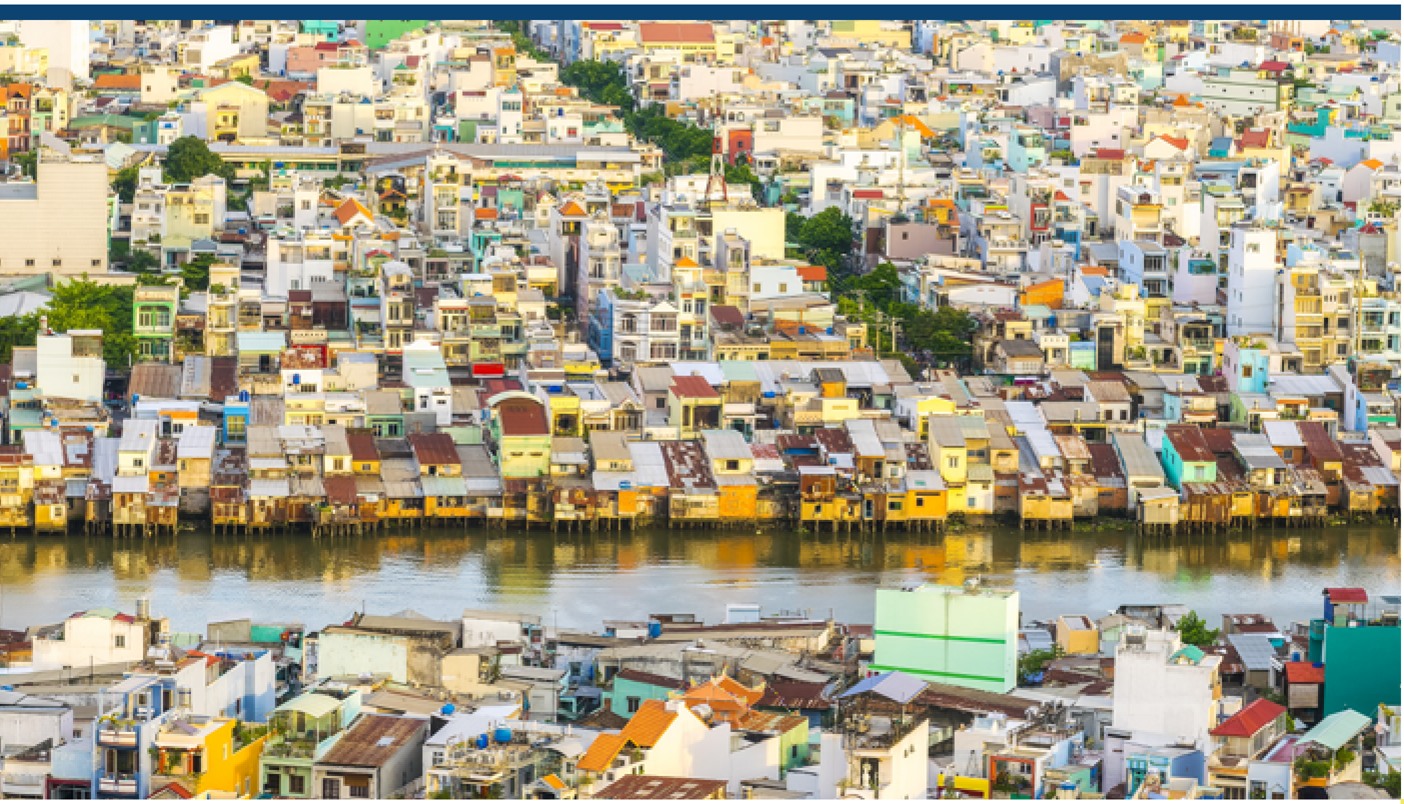
For Governments, key industries such as steel and cement, and the fossil fuels industry, the development of a cost-effective carbon capture and sequestration value chain, with as much conversion of CO_2 into valuable products as economically viable, must be a high priority, with far greater investment in development and deployment than so far planned. However, as noted in Section 2, the pace of development of carbon capture, conversion and storage options – in terms both of scale of deployment and estimated future costs – has been far slower than that of renewables and battery technologies. The number of large-scale operational CCS projects is expected to increase from 10 in 2010 to 21 by the end of 2017, with a total CO_2 capture capacity of approximately 40 MT per annum[55]. However, the number of large scale initiatives have slowed significantly in recent years with only limited new capacity expected to be developed over the coming years.

To meet the third-party medium scenario for carbon sequestration described in Section 4a through CCS on fossil fuels, bioenergy and industrial processes would require the construction of some 2,300 installations between 2020 and 2040, a pace of about 2.2 installations per week. This compares with an expected stock of just 33 plants by end 2017, capturing just 55 MT of CO_2 [Exhibit 56, p. 83].

This is a huge undertaking, but so too is the scale of investment required in renewable power if the decarbonization described in Section 1 is to be achieved. The crucial difference, however, is that huge solar and wind investment is already occurring, with 147 GW of renewable capacity installed in 2015, and with further massive investments almost certain to occur over the next two decades. According to the Global CCS Institute, around US$1.8 trillion has so far been invested in wind and solar technologies driven by strong and sustained policy support. By contrast, investment in CCS during the same period was only around US$20 billion[56].

The huge investments in wind and solar, initially stimulated by infant industry subsidies, have driven learning curve effects, which produced cost reductions and yet more investment. As discussed in Section 2, for CCS and the development of CO_2-based products, there have not been the same infant industry policies and no such virtuous circle has been achieved. **Making carbon capture, conversion and storage cost-effective will depend not only on increased expenditure to develop and demonstrate the technology, but, crucially, on large-scale deployment**. Optimal policy should therefore support the development of the full range of options described in Section 2 and in Exhibit 55, p. 83. This will require a range of infant industry supporting actions including proper funding of R&D and deployment (e.g. for CO_2 reduction catalysis and more cost-effective hydrogen production as a complementary input), a strengthened supply infrastructure, and appropriate carbon pricing resulting from public policy to create a level playing field with polluting alternatives.

54) IEA (2016), 20 years of Carbon Capture and Storage – Accelerating future deployment.
55) The Global CCS Institute (2016), The Global Status of CCS 2016.
56) Ibid



Natural carbon sinks

In parallel, the potential of natural pathways to mitigate climate change is probably larger than previously estimated. Recent analyses from The Nature Conservancy[57] indicate that **20 natural carbon sequestration pathways could offer roughly 40% of carbon emissions reduction needed by 2030 to keep global warming below 2°C**. This would represent approximately 11 Gt CO_2 per annum captured at less than $100 per tonne of CO_2. Approximately 7 Gt CO_2 of this could come from natural forest management, avoided forest conversion and reforestation efforts. Of this potential, more than 2 Gt CO_2 is projected at low-cost – less than $50 per tonne of CO_2.

“Natural carbon sinks could capture 11 Gt of CO_2 per annum”

However, in order to seize this potential, we must redouble global efforts to reverse deforestation. This can be achieved by pursuing three strategies: protecting key ecosystems, transforming how we use working lands, and restoring ecosystems on a massive scale[58]. However, this is not “low-hanging fruit”. It is hard to get the right governance and ecosystem payment regimes in place. More fundamentally, the core challenge – as described earlier in Section 2 and in Exhibit 5, p.22 in the Introduction – is that **there are competing demands for land** between food, bioenergy (indeed, renewable energy more generally), other agricultural products and natural carbon sequestration. However, recent progress in Brazil in significantly slowing down deforestation in the Amazon does show what is possible with sufficient public support. Biologically informed management of natural systems (through farming, grazing, forests management, and wetlands management) shows strong promise of rapid scaling and would also have large positive externalities on ecosystems.

None of these strategies can be achieved through policy-changes alone and some in the private sector are already stepping up to develop new business models. However, the financing challenge remains. **One way to mitigate this is to explicitly link climate mitigation with other**

57) Adams, J. (2016): This Decade's Most Important Climate Solution, The Nature Conservancy, available here: https://global.nature.org/content/this-decades-most-important-climate-solution

58) bid

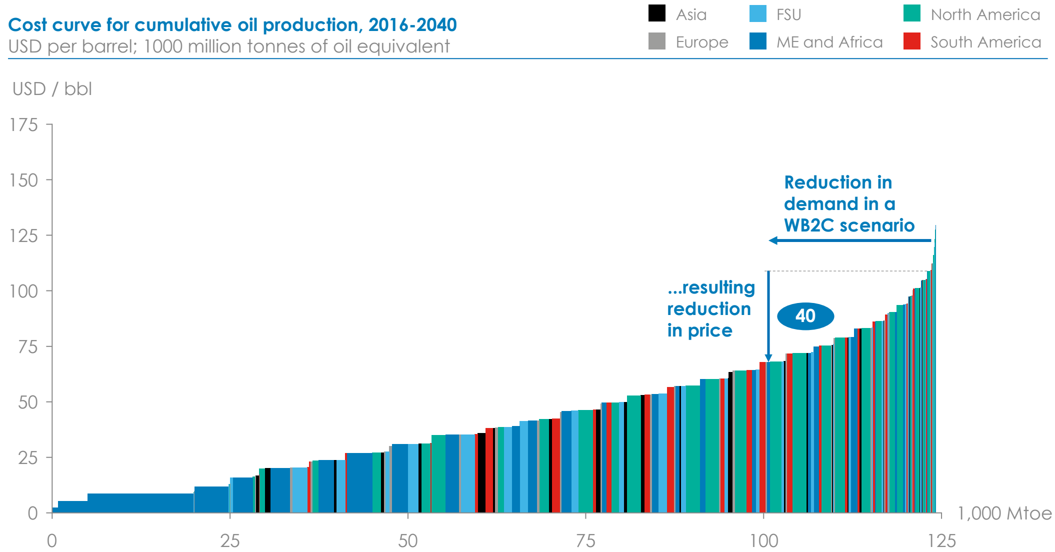
critical improvement priorities, such as better food production, indigenous land rights (combined with tackling pervasive illegalities in resource use), soil health, drought and storm resilience, biodiversity stewardship or drinking water protection. This brings in a more diverse range of investors and stakeholders (from major water users and managers, food and beverage companies, to insurance and engineering industries) who are investing to achieve other business and sustainability objectives, beyond those related to climate mitigation.

D. THE NEED FOR CARBON PRICES

The scenarios for fossil fuels use together with the rapid progress of renewables technologies described in Section 1 also have major implications for the likely evolution of fossil fuels prices. Lower total volumes would reduce the need for high-cost oil and gas production, with prices increasingly set by some lower cost sources. If renewables increasingly compete with coal and gas in power generation, that could both depress prices and spur cost reductions in, for instance, shale production. But lower fossil fuels prices could undermine the required energy transition, both by slowing the pace of renewables investment, and by generating demand rebound effects [Exhibit 57].

An effective carbon price*, resulting from public policy, which introduces a wedge between production costs and consumer prices, is therefore essential to ensure an optimal transition, and is discussed further in Section 6a. It could also play a very useful role in driving the shift from coal to gas within the constraints of already existing capacity, and in encouraging investment in gas-fired rather than coal-fired power plants.

Lower oil demand in a well below 2°C scenario means fewer high-cost resources need to be mobilized to meet demand



SOURCE: Copenhagen Economics oil market model; Rystad data; IEA data

Exhibit 57

The way forward

Optimization of fossil fuels use within the carbon budget

In summary, recommendations relating to fossil fuels use are:

- Governments, the fossil fuels industry and other stakeholders should debate reasonable assumptions about the deployment of carbon capture and sequestration, aiming to achieve consensus around a narrower set of "realistic scenarios" for future fossil fuels use in total and by fuel type. They should also develop a credible plan for ensuring large-scale deployment of carbon capture and sequestration technologies, since no well below 2°C scenario requires less than 3 Gt of carbon capture per annum by 2040.

- INDCs should include clear strategies to ensure that fossil fuels use is optimized around highest economic benefit – for instance by driving EV penetration to allow the final budget for oil to be concentrated on long-distance road freight and aviation.

- Developed countries should commit to eliminate unabated coal from power generating systems within the next 5 years.

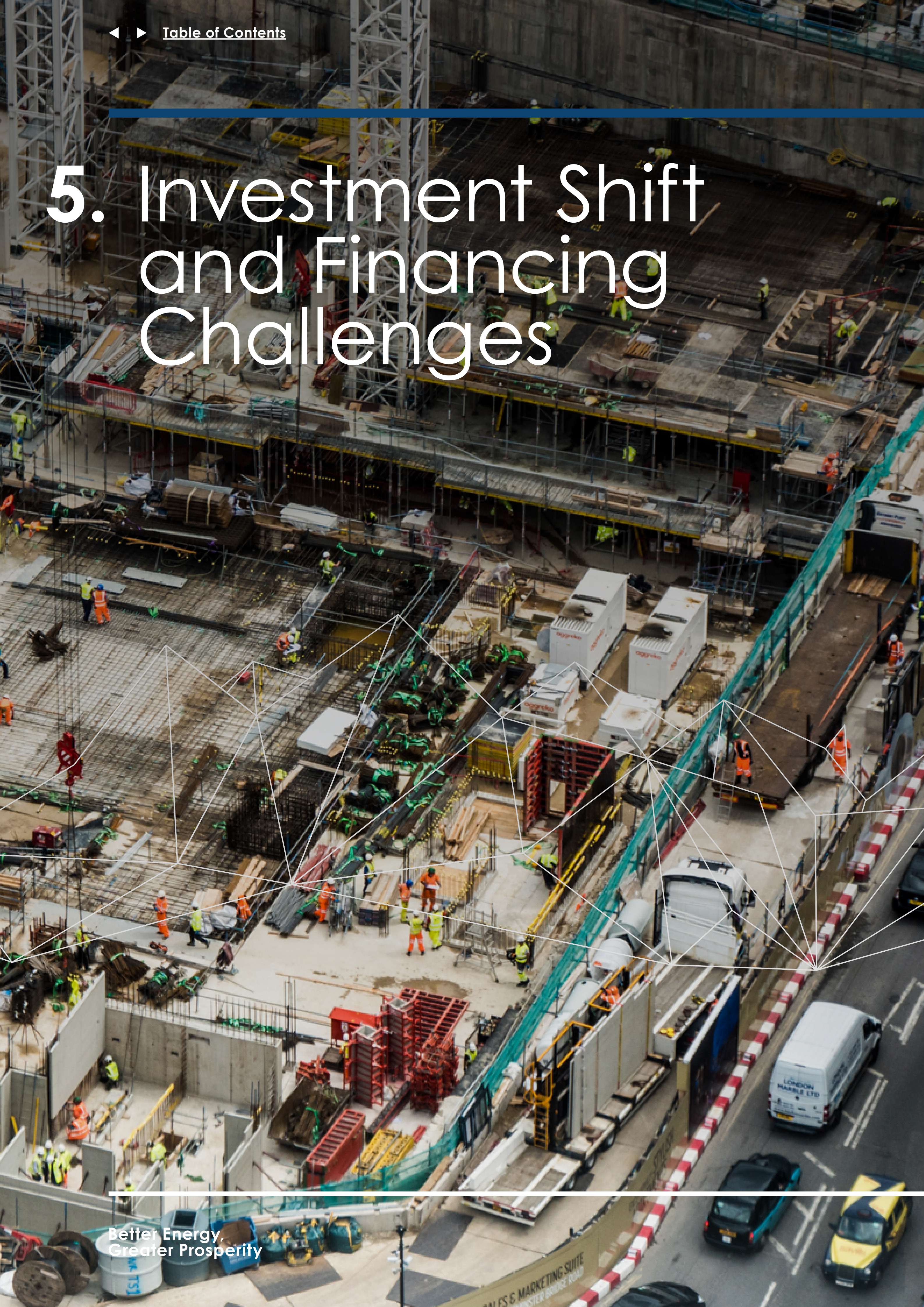
- Developed countries and the multinational institutions should design concessional finance schemes* which could compensate developing economies for the costs of investment in coal-fired power plants which they commit to run for less than their technically feasible life (see Section 5 for further discussion of this proposal).

- Fossil fuels companies should make strong commitments to reduce methane leakages as well as to end routine flaring as soon as possible and no later than 2030. Both are essential to ensure that the remaining use of fossil fuels stays compatible with a well below 2˚C pathway.

- Governments, together with the multilateral development banks and major emitting industries (e.g. aviation, shipping, steel), should work to accelerate the growth in markets and other business-to-business / government-to-government payment mechanisms for natural carbon sinks, embedded within the overall land use strategies that countries develop for their INDCs.

- Fossil fuels companies should recognize that high-cost production resources are likely to become uneconomic. They should plan new investments on the assumption that, given likely future carbon taxes, regulations and the progress of alternative technologies, the economically profitable life of many investments may be considerably less than their technically feasible life. They should therefore provide financial markets with sufficiently detailed information on assumptions regarding future scenarios to enable balanced assessments as to the economic viability of their long-term assets (see Section 5b for further discussion of this proposal).

5. Investment Shift and Financing Challenges



Large capital investments and a major shift in the mix of investment are required to facilitate the four energy transitions we have outlined. In macroeconomic terms, the absolute scale of investment required is clearly manageable. But carefully designed public policies, underpinned by broad stakeholder consensus about the overall direction of change, are needed to ensure as cost-effective a transition as possible.

A. INVESTMENT SHIFT

Between 2015 and 2030, the base case scenario set out in the New Climate Economy (NCE) report[59] **suggests that capital investment in energy production and in energy using equipment could amount to around $46.5 trillion** [Exhibits 58-59, p. 90].

- **Total capital investment in the production and supply of energy could amount to $22.6 trillion**, comprising $5.8 trillion in power generation, $4.3 trillion in electricity transmission and distribution, and $12.5 trillion in fossil fuels exploration, production, transport and refining.
- Estimates of **total investment in energy using equipment** such as rail, auto engines or heating, ventilation and air conditioning systems (HVAC) depend on the definitions assumed (e.g. whether to count all of the cost of a new automobile or only the engine), but broadly relevant expenditures are at least as large as the energy production system, with one estimate suggesting **about $24 trillion**.
- In addition, it is useful to note that **total prospective capital investments in other categories of "infrastructure"** – including transport (e.g. roads, railways and airports), water and waste, and telecoms – **could amount to as much as $42 trillion over 15 years**.

Overall investment in the energy system will have to increase significantly versus this base case scenario to achieve emission reductions in line with a low-carbon scenario[60] [Exhibits 58-59, p. 90].

- **The largest increase seems likely to be needed not in production and generation, but in machinery which uses energy, which could increase by $8.8 trillion**, as a result of large additional expenditures on electric vehicles (EV), HVAC systems, and in several industrial processes. Some of this expenditure, in particular household purchases of EV, will not however count as "investment" in national income accounts and does not raise issues relating to the allocation of capital by the financial markets.
- **Total required investment in the energy production and distribution system by contrast may change less** – indeed the NCE scenario suggests a slight fall from $22.6 trillion to $21.3 trillion. **But there will be a very significant change by categories of spend** – with the NCE scenario suggesting $3.7 trillion less investment in fossil fuels exploration, production and distribution, $2 trillion less in fossil fuels-fired power generation, but $4.7 trillion higher capital investment in renewables, nuclear power, and carbon capture combined with either storage or conversion into products. **It is likely that required investment in low-carbon power will be even higher than these NCE figures suggest**. Delivering the 6,000 additional TWh of electricity envisaged under the broader electrification scenario considered in Section 1b could itself require a capital investment of some $3 to $4 trillion in wind and solar installations. In addition, higher investments in carbon capture and sequestration – both CCS and natural carbon sinks – would also be needed: achieving the 7-8 Gt per annum of carbon capture which the third-party medium CS scenario in Section 4 assumes by 2040 could require capital investment of some $2 trillion to capture CO_2 from coal- or gas-fired power plants, plus potentially still larger investments in storage and transport.

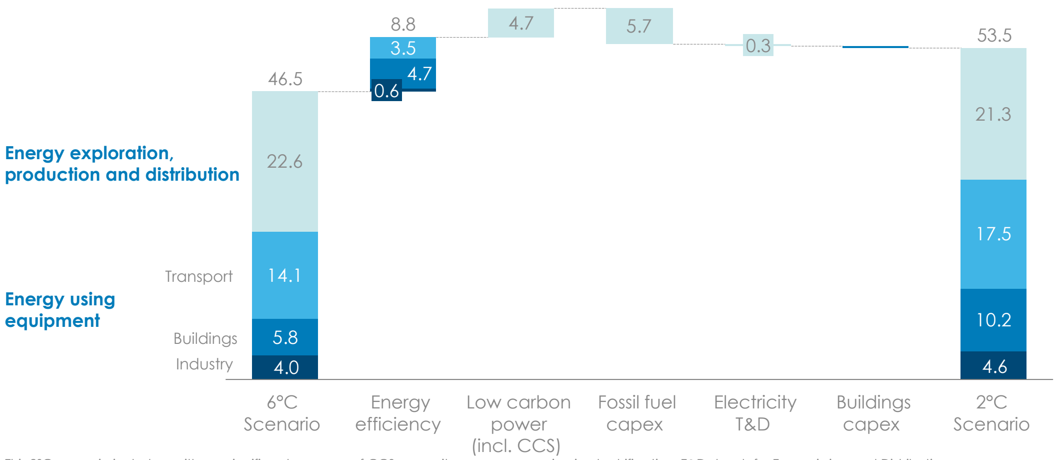
"Global investment needs over 2015-2030 might increase from $89 to $93 trillion in a low-carbon scenario"

- **Capital investment in other infrastructure meanwhile could fall** – by an estimated $3.4 trillion – if a move to more compact dense urban development reduces expenditures on roads, buildings, water and waste. This of course depends on much more effective urban planning and implementation of these plans, so there is no guarantee that this saving will be achieved.

59) The New Climate Economy (2014), Better Growth, Better Climate
60) Ibid

In a low carbon pathway, investments in the energy sector remain relatively stable while investments in energy efficiency across transport, buildings and industry sectors increase

Investment requirement in energy and energy efficiency, 2015-2030
US$ trillion, constant 2010 dollars

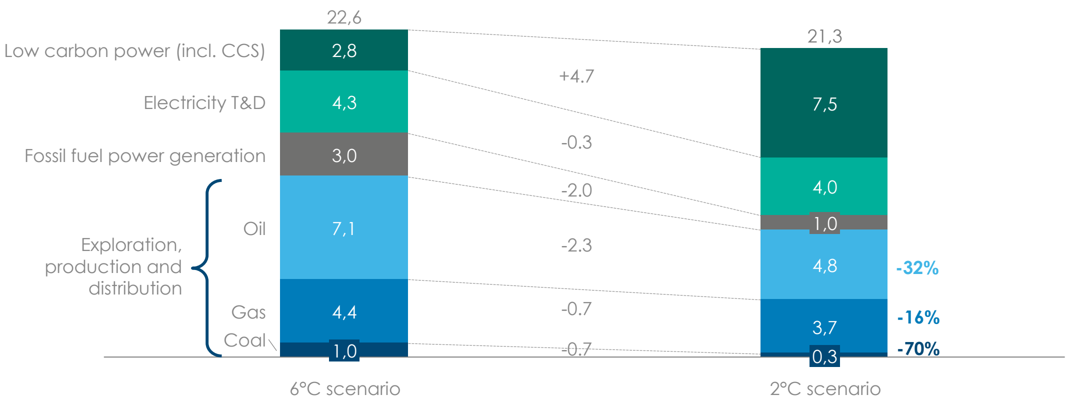


NOTE: This 2°C scenario includes neither a significant ramp up of CCS capacity, nor an expansion in electrification. T&D stands for Transmission and Distribution.
SOURCE: The New Climate Economy (2014), Better Growth, Better Climate

Exhibit 58

However, within the energy sector, significant investment shifts occur between fossil fuels and low carbon energy sources

Investment requirement in energy, 2015-2030
US$ trillion, constant 2010 dollars

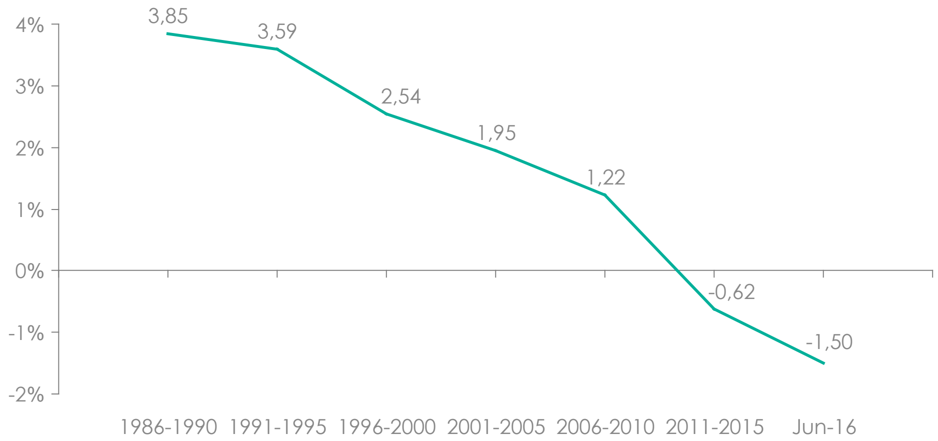


NOTE: This 2°C scenario includes neither a significant ramp up of CCS capacity, nor an expansion in electrification. T&D stands for Transmission and Distribution.
SOURCE: The New Climate Economy (2014), Better Growth, Better Climate

Exhibit 59

Historically low interest rates in developed countries provide a favorable context for increased investment in low carbon infrastructure

Sterling 10 year index-linked gilt (YTM, 1985-2016)



SOURCE: Bank of England Statistics

Exhibit 60

In total, and if we include both household "investment" in electric vehicles and investment in other infrastructure as well as in the energy system itself, the NCE estimates **global investment needs over the period 2015 to 2030 might increase from around $89 trillion under a base case scenario to around $93 trillion in a low-carbon scenario**[61]: adding additional allowance for wider electrification and carbon capture and sequestration deployment could increase this by some $3 to $5 trillion between today and 2030 (with significant further investments in the 2030s).

"The absolute scale of the required investment does not create a major macroeconomic problem"

But even with this additional adjustment, **the absolute scale of this investment challenge is clearly manageable**. With total global savings and investment now running at around $20 trillion out of a global GDP of $78 trillion[62], the incremental capital investment required – around $300 billion to $600 billion per annum – is not large enough to create a major macroeconomic problem.

Meanwhile, global long-term real interest rates are at historically low levels – a fact which some economists believe reflects inadequate global investment demand relative to global desired savings [Exhibit 60]. In a global economy which may be suffering from a "saving glut" which threatens "secular stagnation", the incremental investment required to build a low-carbon economy could well be a positive factor underpinning global demand and growth, rather than a problem necessitating a difficult-to-achieve increase in savings. By simultaneously driving resource productivity (e.g. through better infrastructure), it could also contribute to longer-term growth potential. In addition, public investment required as part of this global effort can be facilitated by low interest rates and by the ability to use the revenues from carbon pricing and from the phase-out of fossil fuels subsidies (as described in Section 6a).

61) The New Climate Economy (2014), Better Growth, Better Climate
62) World Bank Data, Global GDP and global savings figures are for 2014.

B. FINANCING CHALLENGES

Despite this optimistic overall picture, **three key characteristics of the changing mix of investment mean that carefully designed public policies are essential, while another feature poses a complex challenge for fossil fuels companies.**

The cost structure of low-carbon power

The economics of low-carbon power – whether renewables or nuclear – are driven by a very distinctive cost structure, with very high initial capital costs followed by minimal marginal operating costs over subsequent decades. This makes the attractiveness of low-carbon investment crucially dependent on the cost of capital, i.e. on the rates of return which investors require. The cost of capital is in turn strongly influenced both by perceived risks and by the total scale of the global investment opportunity (since increased financial market focus on a particular sector can itself drive down capital costs). If required returns can be reduced by 100-300 basis points, the levelized cost of renewable energy would fall by 10-20%.
Three important implications for policy and for industry follow:

- First, **the greater the cross-stakeholder consensus** among industry participants, Governments and energy users on the broad shape of the required transition (e.g. the vital importance of decarbonization and wider electrification discussed in Section 1, and the implications of the carbon budget constraint discussed in Section 4), **the more likely that sustainable investments will be made and wasteful investments avoided**.
- Second, while a clear and rising carbon price is vital for the reasons which Section 6a will discuss, **policy regimes providing certainty of future prices for low-carbon electricity** will often be an even more effective way to drive low-carbon power investment.
- And third, in a world where the cost of funds to Governments has fallen even more than overall required rates of returns, **Governments' ability to borrow at low rates may in some circumstances deliver better value for money to taxpayers than other forms of policy intervention or subsidy**.

Forms of public-private partnerships in which the Government simultaneously reduces project risk and uses its own balance sheet to provide some investment funds may be very effective in this environment.

"The attractiveness of low-carbon investment crucially depends on cost of capital"

The importance of energy efficiency investment

As stressed above, the largest increase in required investment may not relate to energy production and distribution, but take the form of multiple investments in energy saving equipment (e.g. electric vehicles, HVAC[63] systems, building insulation, and multiple industrial process systems). Some of this expenditure, particularly but not limited to the household sector, may be actually counted as "consumption" rather than "investment" in national income accounts. These multiple smaller scale "investments" do not raise the same issues about capital market allocation posed by needed investments in low-carbon power; but it is still important to ensure appropriate supporting policies. As Section 3 discussed, regulatory standards, rather than the availability of finance, may often be the most important policy lever; but **fiscal incentives can also play an important role (delivered either directly or via the banking system), by helping to offset the high upfront capital cost of energy saving investments for households or companies**.

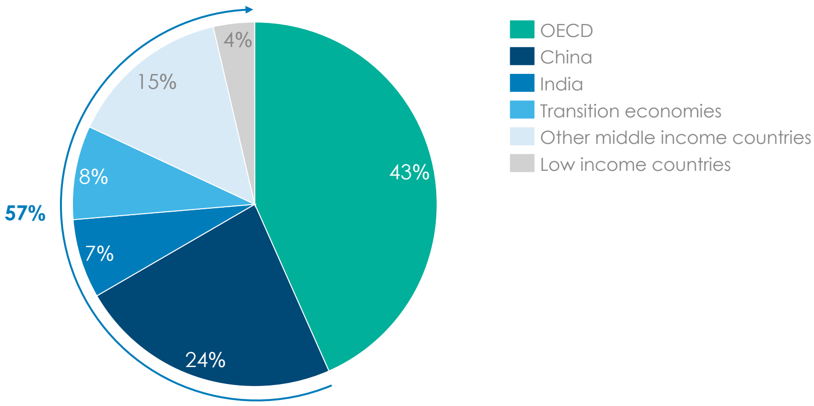
High investment needs in developing economies

Even over the next 15 years, more than half (55%) of the estimated required investment will be in developing economies. That percentage will likely increase in subsequent years, as developed economies complete a major wave of renewable investment, while currently low-income economies (e.g. in Africa) continue to need large capital investments to meet growing energy demand [Exhibit 61].

63) Heating, ventilation and air conditioning

Half of the global investment needs in energy are located in middle income countries, a quarter are concentrated in China only

Investment needs in energy in a low carbon scenario, 2015-30



SOURCE: The New Climate Economy (2014), Better Growth, Better Climate

Exhibit 61

But many of these economies can suffer from capital scarcity and high interest rates, due to macroeconomic instability and institutional failures. It can also be hard to mobilize international commercial capital at acceptable rates, given the prohibitive cost of long-term currency hedges. Achieving optimal energy transition in developing economies may well therefore require:

- An increased role for multilateral and national development banks; and
- Global concessional finance* flows of well over $100 billion per year by the 2020s, which address the key impediments of elevated risks and high required returns.

Reduced investment in fossil fuels

Shifting from a business as usual to a low-carbon scenario implies a very significant decrease in required fossil fuels investment. Precise estimates of the change required can vary significantly depending on assumptions made about the future feasibility and costs of CCS and CO_2-based products. However, the estimates produced by the NCE – which are aligned with the findings from the analysis undertaken by the ETC on fossil fuels in transition – suggest that **total investment on exploration, production, refinery and transport could fall from $12.5 trillion to $8.8 trillion through 2030**, with coal investment falling 70% (from $1 trillion to $300 billion), gas investment falling by 16% (from $4.4 trillion to $3.7 trillion), and all oil investment falling by one third (from $7.1 trillion to $4.8 trillion). Over the same period, **cumulative investment in fossil fuels power generation plants would fall from $3 trillion to $1 trillion** (see Exhibit 60, p. 91).

These figures illustrate the very complex transition challenge facing the fossil fuels industry and financial investors:

- On the one hand, **exploration and production investment will need to fall** relative to business as usual assumptions – and quite dramatically so for coal and oil. Fossil fuels companies (and their investors) will need to be careful to ensure that investment in high-cost production is not left stranded.
- But **major new investments will still be required** in both oil and gas production – where additional expenditure is often needed simply to maintain existing output levels as well as to address energy security concerns (which may result in development of some more expensive hydrocarbon resources). Large investments

The way forward

Climate-related financial disclosure

Transparent communication by fossil fuels companies, as well as by a broader set of market players, on their assumptions about how the balance in fossil fuels investments can be managed is essential. Public markets rely on transparency to function efficiently and allocate capital to the right investments. Inadequate information can lead to abrupt repricing, which may create sudden investor losses and economic instability. For this reason, listed companies with public debt or equity have a legal obligation to disclose material risks in their financial filings. Climate-related risks, including risks related to new fossil fuels investments, are now regarded as material risks that need to be measured, reported and priced.

In 2016, the Task Force on Climate-Related Financial Disclosures published its recommendations on the development of voluntary, consistent and comparable climate-related financial disclosures[64]. Recommendations are targeted at investors, lenders and insurance underwriters.

Climate-related risks [Exhibit 62] **have been defined as:**

- Risks associated with the transition to a low-carbon economy, including policy and legal risks – e.g. carbon pricing or energy regulation, markets risks arising as the pattern of demand for products changes, and reputational risks;
- Risk associated with the physical damage caused by the effects of climate change, including acute and event-specific effects, such as storms which may damage property, or chronic effects, such as weather patterns change which may disrupt supply chains.

The taskforce recommended scenario analysis as an important tool to understand the strategic implications of climate related risks and opportunities. Key recommendations focused on:

- **Governance** – disclosure of governance around climate-related risks & opportunities;
- **Strategy** – disclosure of actual and potential impacts of climate-related risks & opportunities;
- **Risk management** – disclosure of how the organization identifies, assesses, and manages climate-related risks;
- **Metrics and targets** – disclosure of the metrics and targets used to assess and manage relevant climate-related risks and opportunities – e.g. for a power generation firm, the carbon intensity of their portfolio, in gCO_2/kWh, provides a relatively simple measure of their exposure to carbon price rises.

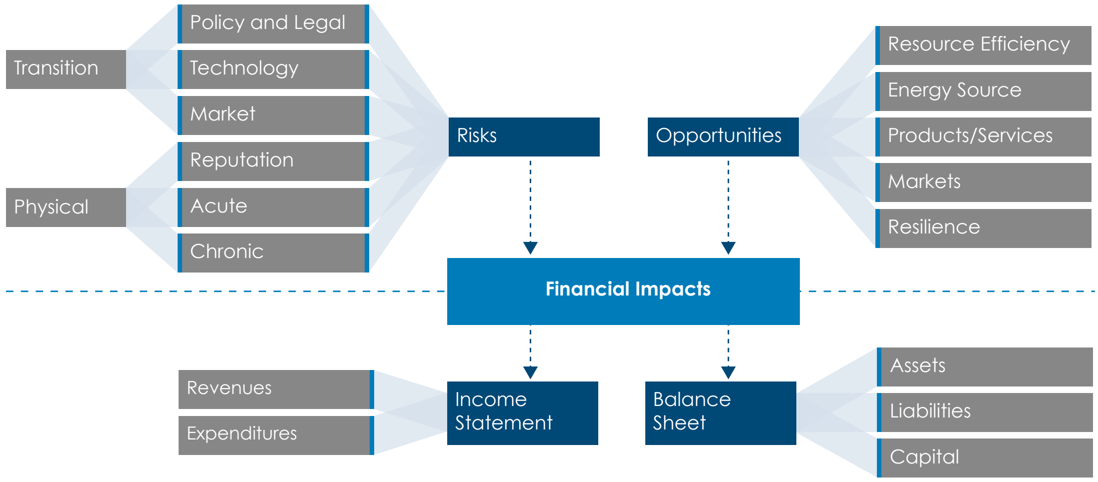
The taskforce has proposed that:

- Reporting should be voluntary to ensure widespread support and to encourage innovation in the development of best practices;
- Additional analysis is required to reach a broad understanding of the concentration of carbon-related assets in public financial markets and of the financial system's exposure to climate-related risks.

64) Task Force on Climate-Related Financial Disclosures (2016). Recommendations of the Task Force on Climate-Related Financial Disclosures.

Financial disclosure on financial risks and opportunities related to energy transitions is essential to facilitate the shift in the mix of investment required to achieve these transitions

Climate-related Risks, Opportunities and Financial Impacts



SOURCE: Task Force on Climate-Related Financial Disclosures (2016), Recommendations of the Task Force on Climate-Related Financial Disclosures

Exhibit 62

may also be needed in gas distribution systems, given the positive role which gas could play in replacing coal.

- In the generating sector, even $1 trillion of fossil fuels-based power generation investment could result in a **capacity level incompatible with further necessary emissions reductions after 2030**, unless either CCS becomes cost-effective, or coal/gas-fired power plants are closed well before the limit of their technically feasible life.

C. FINANCIAL INNOVATION TO ACCELERATE ENERGY TRANSITIONS

Given the new financing challenges arising from the required investment shifts, **financing the transition to new energy systems will require fresh thinking in terms of product innovation, or new applications of tried-and-tested tools from other sectors, to keep the costs of financing as low as possible**. There are many tools available to the finance industry, public finance and multilateral development banks, including:

- Project finance* and its variations to leverage greater sources of capital and optimize financing costs;
- Corporate finance* and growth equity to accelerate the development of robust companies in the sector;
- Green bonds* to facilitate investment into a range of project and corporate activities;
- Concessional debt to address incentive problems and market inefficiencies;
- Risk mitigation instruments to overcome policy-related barriers/risks (e.g. of retroactive tariff changes) and reduce finance costs;
- Carbon markets and the related finance to internalize environmental benefits;
- Innovation finance to unblock and accelerate the development of new technologies and concepts; and,
- Consumer finance and consumer aggregation to unlock the potential of smaller investors in small-scale renewables and energy efficiency projects.

Each of these tools, and others to be developed, will have a role in the transition, but that role is likely to be very different for each of the four energy transitions and different again by region.

Finance for decarbonization of power is, arguably, the most sophisticated and advanced area of financial innovation for the energy transition, although the scale of investment needs to increase and there may still be room for significant reductions in finance risks and costs.

- Corporate project finance debt and equity have become well established in renewable energy investments in developed markets, but there may be room to reduce finance costs significantly for utility-scale projects by tailoring new investment vehicles for institutional investors such as pension funds and insurance companies.
- For small-scale and roof-top projects, project finance and corporate finance are usually less of an option, but some progress has been made through consumer loan programs, Government-assisted finance, and aggregation through techniques such as solar leasing where solar installers or larger investors finance small-scale projects through lease arrangements that guarantee consumers fixed energy bills.
- In emerging markets, there have been multiple attempts to apply each of these techniques, with varying degrees of success. Higher interest rates and debt costs, less robust credit markets and currency risk are among the problems that slow progress and increase costs. Specific instruments to address these and other emerging market risks are being developed, but require more innovation.
- The development of green assets securitization (or green securitization bonds)* could also be a useful tool to help scale investment in renewables, by bringing down long-term financing costs. Securitization facilitates capital recycling and risks transfer from early stage project developers and private equity investors to long-term institutional investors. Early experiences, for instance with US rooftop solar Asset Backed Securities or European solar portfolios, show that demand is strong. However, further standardization of green bond performance metrics is a prerequisite for further development of green assets securitization. We have yet to see green bonds trading at a premium to their grey equivalents.

Finance for decarbonization beyond power is less developed and faces a different set of challenges. CCS, second- and third-generation biofuels, hydrogen, CO_2-based products or newer low-carbon industrial processes are typically in an earlier stage of development than renewable energy. Venture and scale-up finance are therefore important, as is learning the lessons from decarbonization of power as the technologies mature and move into mass deployment. Given regulatory and business model uncertainty, it is not a surprise that there has been a high "valley of death" rate for enterprises trying to develop clean products/processes beyond power.

"Finance for decarbonization of power is the most advanced area of financial innovation for the energy transition"

Most energy productivity investments, particularly on the energy efficiency side, are not tied up in a single piece of equipment, but rather are an integral part of a business' or household's operations. Furthermore, energy efficiency improvements often comprise many multiple small-scale investments and maintenance improvements, which defy simple evaluation. For finance to be effective, energy efficiency requires guidelines and standards, as well as methods for aggregating multiple investments. Well-designed household finance products also have an important role to play and may be particularly important in countries which currently have less developed credit markets.

The need to reduce and optimize, but not immediately eliminate, fossil fuels use provides another distinct challenge. There may be a need for financing options that prevent lock-in of carbon emissions for the entire life of a capital asset, especially coal-fired power generation plants, through mechanisms that require either retrofit of carbon capture, or early closure of the plant.

Multilateral Development Banks (MDBs)* and Development Financial Institutions (DFIs)* have an important role to play in the allocation of financing. By financing investments and risks that the private sector is unwilling to fund (or only willing to do at a high cost of capital), these institutions can help crowd in private capital. In 2013, MDBs committed more than $28 billion for climate action in developing economies, bringing total commitments over the past four

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Illustration 7

Best practices in MDBs and DFIs

Crowding in private capital through risk-sharing
In 2014, Danish Climate Investment Fund raised $94 million from the Danish Government and IFU Development and $142 million from Danish institutional investors to invest in projects that reduce greenhouse gas emissions, directly or indirectly, including renewable energy. The DCIF structure includes a preferred return for institutional investors set in a pre-defined profit distribution model. Returns are distributed equally until initial investments are paid back, then private investors receive all returns up to 6% IRR. As compensation, the Danish Government receives an additional share of the return above 8% IRR at the expense of the private investors. Risk sharing mechanisms such as preferred return can make investment attractive for institutional investors by mitigating both project non-completion risk and political risk of investing in emerging markets. This approach crowds in institutional investors such as Danish pension funds that would otherwise not have invested[65].

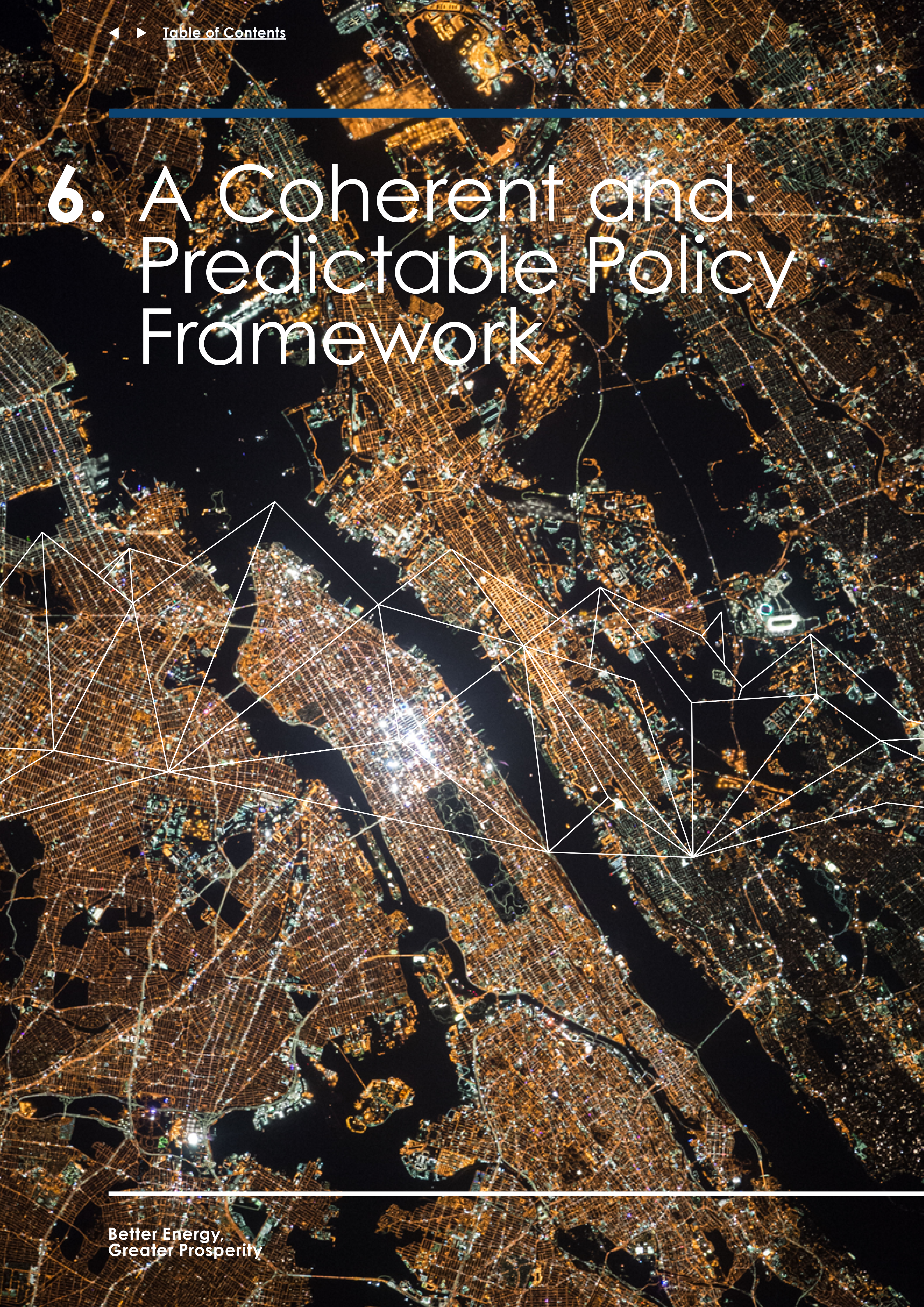
Managing currency risk
In August 2015, the International Finance Corporation (World Bank) issued the first "green masala bond", i.e. bonds that are issued in rupees on a global exchange, raising 3.15 billion rupees. Proceeds were invested in Yes Bank's onshore green bond for renewables projects. IFC assumed a pivotal role in shaping this bond, but exited in time to crowd-in rather than crowd-out other capital. A year later, the state-owned energy major National Thermal Power Corporation (NTPC) raised $300 million (Rs 2,000 crores) with its "green masala bond" to invest in solar and wind projects as part of India's target of reaching 175 GW installed capacity by 2022. Those first experiences played a crucial role in creating demand for "green masala bonds". As a result, we have recently seen "green masala bonds" issued directly by Indian clean energy producers with no DFI involvement.

years to over $100 billion. For example, in 2016, the World Bank approved a $390 million loan for the Tarbela Fourth Extension Hydropower Project in Pakistan, co-financed with the Asian Infrastructure Investment Bank (AIIB). This project will help cope with increasing power demand during the summer season.

Beyond this type of 'traditional' development finance product – which adds value to private markets because of the long-term maturity of the debt finance provided (often over 15 years) –, MDBs and DFIS have an important role to play in:

- Crowding in greater shares of private and blended finance, i.e. strategically using development finance and philanthropic funds to mobilize private capital flows to emerging markets through a combination of instruments from public and private sources including grants, debt, equity, first-loss guarantees, and policy-related risk insurance;
- The development of green bonds through demonstration issuance, providing credit enhancements or serving as an anchor investor for green bonds;
- Managing currency risk, which can be a major barrier to domestic borrowers accessing international funds.

65) World Economic Forum (2015): Blended Finance Vol. 1: A Primer for Development Finance and Philanthropic Funders.



6. A Coherent and Predictable Policy Framework

All four elements of the energy transition described above will be driven by changes in the investment plans and behaviors of companies and households. There is intrinsic value in establishing a clear consensus on the key transition drivers to reduce uncertainty and increase the chance of aligned, decentralized decision-making. Government policy has a vital role to play in sending trusted market signals and designing the incentives and constraints which will influence private behavior. Carbon pricing* resulting from public policy must play a central role, but other policies and regulations, at national, state and city level, are also vital [Exhibit 63].

A. ENERGY AND CARBON PRICING

Carbon pricing

Effective publicly mandated carbon pricing* must play a central role in helping to drive all dimensions of the transition. Many countries and regions already recognize this and over 13% of CO_2 emissions are already covered by some form of explicit carbon pricing scheme, albeit typically at prices around or below $10 per tonne. As China, South Korea and Canada put in place national carbon pricing schemes, the proportion of emissions covered will increase to over 30% within the next 12 months. Some of these schemes (certainly that of Canada) will probably have price floors with some upward ratchet mechanism that would lead to $25 carbon prices (or more) over the next 5 years.

However, most carbon pricing mechanisms to date have been weak and inconsistent. **Further and rapid progress towards significant, predictable carbon pricing remains essential.** An increased sense of urgency also arises from the fact that the expectation of a future publicly mandated carbon price has encouraged a growing number of companies to introduce internal project screening values for CO_2 emissions associated with investment decisions. There is a risk that these internal project screening values, sometimes referred to as "internal" or "shadow carbon prices", might be dropped (or treated only as advisory) in the absence of tangible policy moves toward meaningful carbon pricing mechanisms resulting from public policy.

Multiple policy levers need to be leveraged simultaneously to achieve the 4 transition strategies

	Decarbonization of power & Electrification	Decarbonization beyond power	Energy productivity improvements	Optimization of fossil fuels use
Adequate carbon and energy pricing	✓	✓	(✓)	✓
Integrated energy planning	✓	✓	✓	✓
R&D	(✓)	✓		(✓)
Industrial policies	(✓)	✓		✓
Market design	✓	✓	(✓)	
Standards & Regulations			✓	
Urban design & infrastructure			✓	

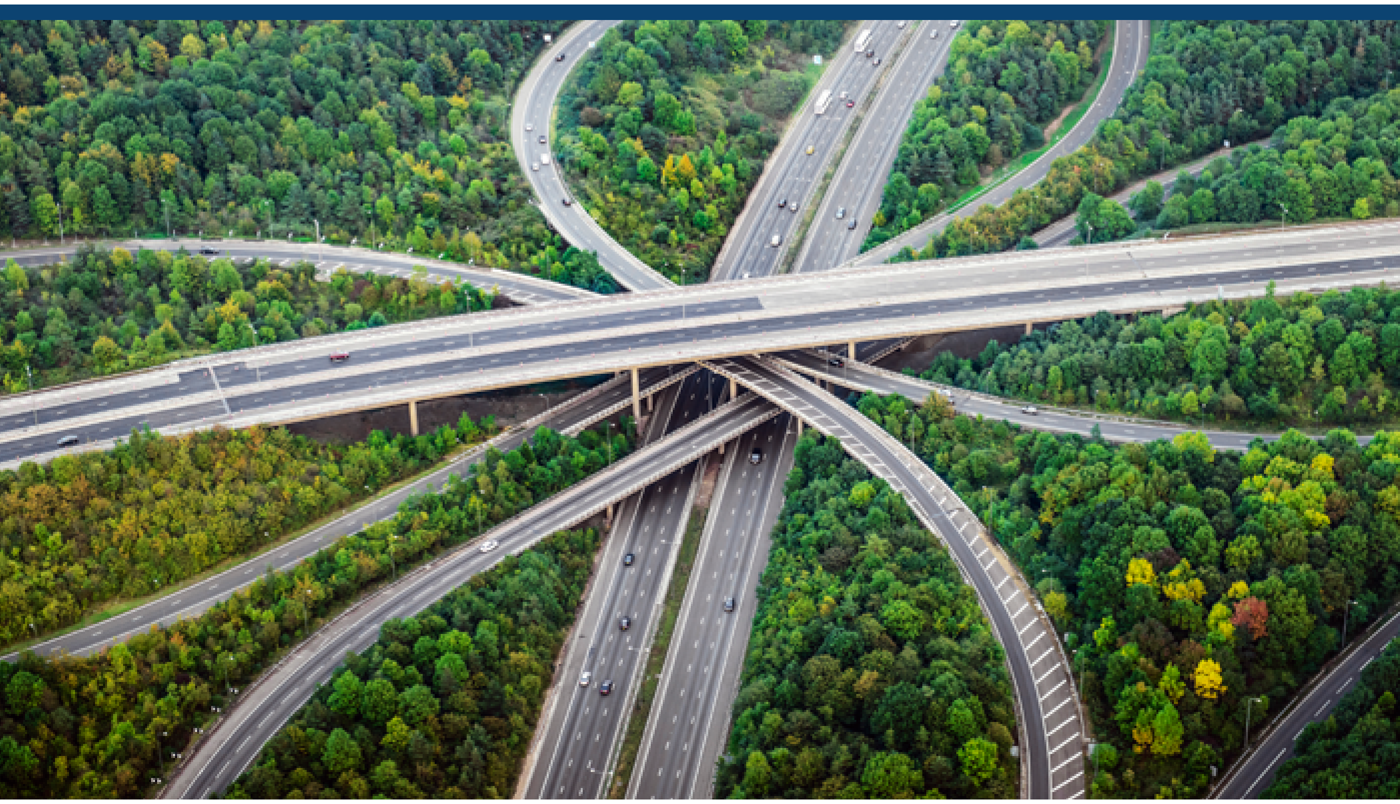
Exhibit 63

"Rapid progress towards significant, predictable carbon pricing either as a tax or resulting from a trading system is essential"

Momentum has recently increased in making a strong case for carbon pricing, either as a tax or resulting from a trading system. At the World Economic Forum in January 2017, the Carbon Pricing Leadership Coalition announced its Doubling the Wave initiative to double the coverage of emissions subject to carbon pricing by 2020, and double it again in the following decade. Meanwhile, the Carbon Disclosure Project launched its Carbon Pricing Corridors Initiative to look at the range of carbon prices required to decarbonize power generation and a coalition of leading Republicans have begun an attempt to introduce a $40 per tonne carbon tax (and dividend scheme) in the US. It seems unlikely that we will move to a "global carbon price" any time soon – there are both political and technical reasons why the road to such a global pricing regime is likely to be long and uneven. However, there is an emerging consensus around the rationale for carbon pricing and the key features required which are relevant across many different national systems.

Carbon prices will play a differentiated role in enabling different dimensions of the energy transitions, with different levels of carbon prices required to trigger progress in different areas.

- **Power decarbonization:** Even without a carbon price, we anticipate that a renewable-based power system could be cheaper than a fossil fuels-based system by 2035. However, expectations of a significant future carbon price can **reinforce the already rapid move to low-carbon power**, and over time reduce the need for other forms of subsidy. A carbon price above $50 per tonne of CO_2 would add more than $5 cents per kWh to the cost of coal-fired power generation and $2 cents per kWh to the cost of gas-fired power generation. These impacts would certainly be sufficient to make renewables cheaper than new coal- and gas-fired power generation in many locations (except those with abundant domestic supplies of gas) and would certainly improve the competitiveness of renewables compared to existing fossil fuels power plants with which they are competing at the margin.
- **Decarbonization beyond power**: Future carbon prices may play a crucial role in **driving the search for ways to decarbonize economic activities that cannot be electrified**. Given the multiple possible routes to such decarbonization and the difficulty of defining in advance which technologies will be most effective, a pervasive carbon price would help to spur multiple alternative approaches and incentivize the development and deployment of low-carbon technologies, in particular CCS and CO_2-based products. A predictable price of $50-$100 per tonne of CO_2 in the 2030s seems likely to be sufficient to spur the large-scale deployment of these technologies, provided there has been sufficient earlier investment into development, demonstration and the first generation or two of deployment. That early deployment may well require a range of supporting actions, including but not limited to some kind of feed-in-tariff and concessional capital.
- **Energy productivity improvement**: Here carbon prices have **a role to play in making energy efficiency improvements economic, but will often not be the most important policy tool**. Many improvement opportunities already are cost-effective with moderate or even zero carbon prices, but have not yet been seized – implying that there are other barriers to implementation, such as high initial capital costs, principal-agent market imperfections and ingrained consumer behaviors, which together mean that only extremely strong price signals (which might have adverse distributional consequences) would stimulate energy savings investment.
- **Optimizing fossil fuels use**: Significant carbon prices will help **drive the necessary shift from coal to gas** within the overall carbon budget constraint. A carbon price of $50 per tonne gives gas a cost advantage versus coal of $3 cents per kWh, if all other costs are equal.
- At a macro-level, carbon prices may also have an important role to play (though again not necessarily the dominant one) in ensuring that **increasing efficiency and falling fossil fuels prices do not drive strong demand rebound effects** and in **offsetting the danger that falling fossil fuels demand will produce lower fossil fuels prices which slow the deployment of low-carbon technologies**. Carbon prices are precisely the right instrument to provide a wedge between the price that producers of fossil fuels get paid and the prices that consumers experience.



For all of these reasons, carbon pricing appears to be an essential, though not sufficient policy driver for energy transitions. A predictable rising, forward price curve for carbon would support the right capital deployment and create a growing wedge between the supply cost and demand price of fossil fuels. Existing studies indicate that a possible pathway to trigger change could be to reach approximately $50 per tonne in the 2020s and rise to around $100 per tonne in the 2030s, with still higher prices applicable to specific consumption and investment decisions.

The initiatives mentioned above will analyze **alternative forms of carbon pricing** and their strengths and weaknesses in different contexts. Options include:

- **Explicit carbon prices**, through either a carbon tax – with a fixed carbon price driving fluctuations in emissions volume – or a cap and trade scheme – with a steadily declining cap on carbon emissions for various parts of the economy (such as power plants, the aviation industry or manufacturing) determining the market price of carbon. Explicit carbon pricing for industrial sectors is likely to require a coordinated move from a set of countries representing a significant share of the world economy, given the risks in terms of economic competitiveness for trade-exposed industries of a unilateral carbon price.
- **Implicit carbon prices**, that effectively put a price on carbon either by taxing end-use of fossil fuels-based products and services – e.g. a tax on gasoline – or by giving tax exemptions to low-carbon products and services, such as electric vehicles. As described in Section 3, implicit carbon prices have already driven energy productivity improvements in several end-use sectors, especially transportation. They can be easier to implement unilaterally, as they apply to both local and imported goods and services. In many cases, the implicit carbon tax rates are likely to be far higher than the economy-wide explicit taxes – for instance some European gasoline taxes are equivalent to over $200 per tonne of CO_2 –, but this can be appropriate given the crucial need to drive transitions in key sectors, and given other important externalities such as local air pollution and congestion.

Achieving as much global support as possible for a coordinated move towards significant carbon prices is therefore vital; but even without international agreement on an explicit carbon price, **countries or regions can use carbon pricing unilaterally in many economic sectors**, making selective exceptions to protect trade-exposed industries.

Illustration 8

Sweden's carbon tax[66]

Since 1991, Sweden has been able to decouple GDP growth from CO_2 emissions after the introduction of a CO_2 tax across several sectors. The price was set at approximately $30 per tonne, and it has since risen to a price today of $137 per tonne, which is currently the highest CO_2 tax rate in the world. It is also coordinated with the European Union's Emissions Trading Scheme, by making industrial installations that are covered by the EU ETS exempt from the Swedish national CO_2 tax. Likewise, in order to avoid threatening the competitiveness of sectors exposed to international competition, the Swedish tax distinguishes two levels for heating fuels: one lower level for industry and agriculture, and one higher level for households and services. The gap between these two levels has been narrowed over the years through gradual increases in the lower level tax. The Swedish Government is considering aligning both rates entirely in the future.

The most obvious effect of this tax has been the development of district heating for private and commercial buildings. This more energy-efficient system was taxed less than the more carbon-intensive traditional heating methods. This also had the added benefit of reducing waste (which was instead used as the main fuel for district heating). The switch to central heating has spurred sustainable innovation in Sweden. As Magdalena Andersson, Swedish Minister of Finance, described at the 2015 High Level Assembly of the Carbon Price Leadership Coalition, beyond the global benefits of reduced emissions, "new technologies have been developed by small and medium sized companies in Sweden that now have opportunities to gain market shares in the world economy. So, putting a price on carbon is not only the morally right thing to do, it's also economically smart politics."[67] The full implementation of the tax was accompanied by a 25% reduction in emissions, in absolute terms from 1991 to 2013, while the country enjoyed a GDP growth of 60%.

Energy pricing

Many countries currently have large fossil fuels subsidies, which are effectively negative carbon prices. These subsidies, which continue to represent over $600 billion per year globally, should now be eliminated [Exhibit 64]. In developed economies these appear to amount to some $130 billion per annum (mainly around forms of production support). In developing countries, despite significant reform efforts in countries ranging from Indonesia to India to Egypt, the subsidies still amount to more than $500 billion. The stated objective of these is usually to subsidize poorer household energy bills, but the actual impact often disproportionately benefits higher income households who use more energy.

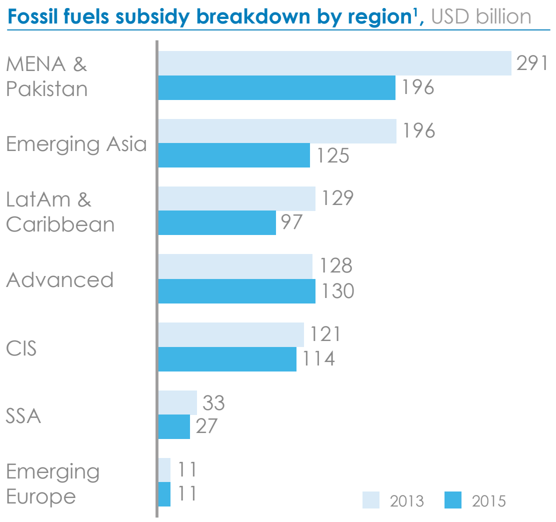
Over 70% of these subsidies are in countries with very substantial energy resources. These countries operate with very poor energy productivity relative to other peer countries at a similar per capita income level. If current policies continue, they are at risk of becoming structurally uncompetitive in terms of energy productivity, with ever greater domestic consumption of energy resources.

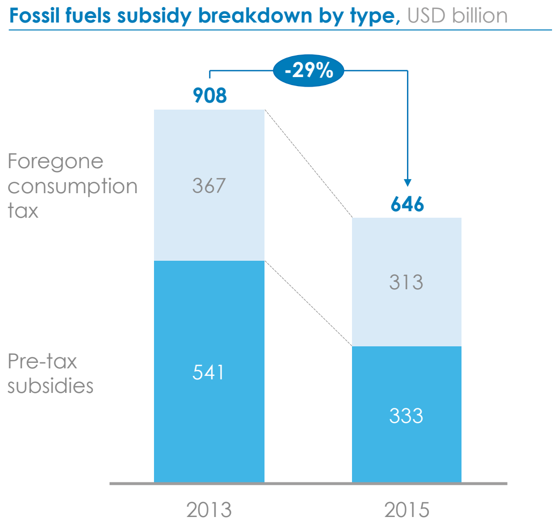
In some specific categories of energy use, it is clear that prices play a major role in driving energy-efficient purchasing decisions. Even over the past 2-3 years, we have seen that low gasoline prices have led to a major increase in the sales of SUVs and other larger vehicles. Equally, we know that higher energy prices, if predictably maintained, translate into a long-run demand-side

66) Sources: Andersson, M. and Lövin, I (2015), Sweden: Decoupling GDP Growth from CO_2 Emissions Is Possible. / FORES (2011), The Swedish Example: The Reduction of Greenhouse Gas Emissions. / Johannson, B. (2000), Economic Instruments in Practice 1: Carbon Tax in Sweden, Swedish Environmental Protection Agency. / World Bank (2016), When It Comes to Emissions, Sweden Has Its Cake and Eats It Too.

67) World Bank (2016), When It Comes to Emissions, Sweden Has Its Cake and Eats It Too, available here: http://www.worldbank.org/en/news/feature/2016/05/16/when-it-comes-to-emissions-sweden-has-its-cake-and-eats-it-too

Fossil fuels subsidies still represent about USD 650 billion globally, equally distributed between pre-tax subsidies and foregone consumption taxes



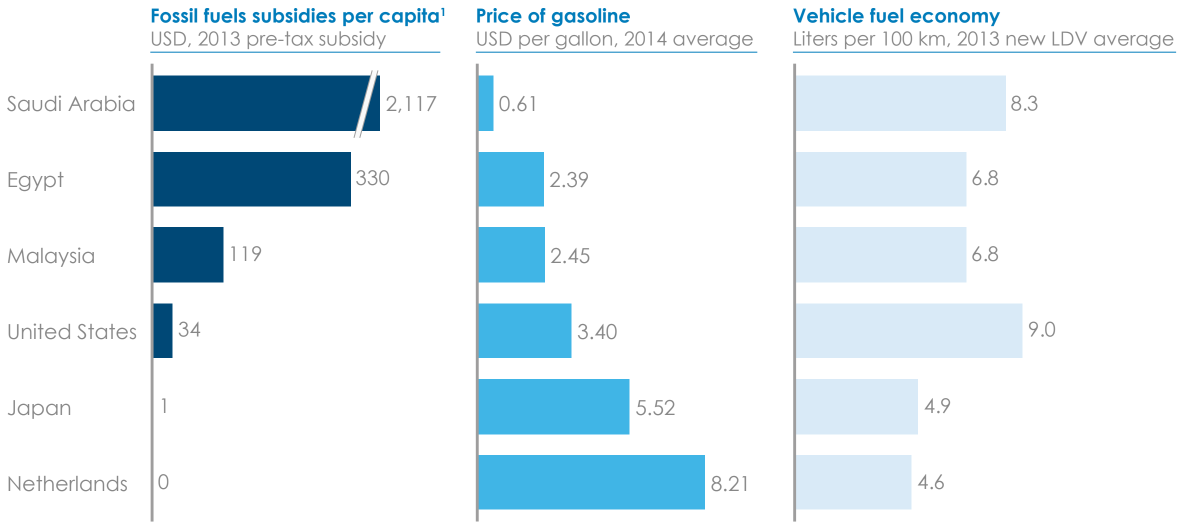


1. Fossil fuels subsidies include Pre-tax subsidies and foregone consumption tax revenues

SOURCE: IMF Energy Subsidy Database

Exhibit 64

Fossil fuels subsidies inhibit energy productivity improvements and should therefore be phased out



1. Fossil fuels subsidies include Pre-tax subsidies and foregone consumption tax revenues

SOURCE: IMF Energy Subsidy Database, Bloomberg Gasoline Prices Around the World, GFEI Working Paper 11

Exhibit 65

The way forward

Carbon and energy pricing

The ETC recommends a further push toward significant carbon pricing combined with a phase out of fossil fuels subsidies, focusing especially on untargeted subsidies which provide large benefits to middle and high income earners, but at substantial fiscal and environmental cost.

Detailed recommendations on government-led carbon pricing will arise from the conclusions of the various initiatives currently analyzing this issue, but the way forward should reflect:

- The need to see carbon pricing as part of a wider package of measures such as those described below in Section 6b;
- The case for differentiated carbon pricing to support the scale-up of specific carbon abatement technologies, with no single economy-wide carbon price to drive all aspects of efficient decarbonization;
- The need for rising future carbon prices, with general economy-wide prices reaching $50+ per tonne in the 2020s and $100 or more in the 2030s, but with higher implicit prices applicable to specific activities; and
- The value of mechanisms that can link carbon pricing regimes – whether through some form of international trading mechanisms (between countries which establish markets) or through sector schemes (as in the case of airlines or other energy-intensive, traded commodities such as steel).

Countries should therefore set out in their INDCs what carbon prices they intend to impose over time (and through what specific tax or trading system mechanisms) and how they plan to reduce any fossil fuels subsidies. Around 90 countries referred to carbon pricing in their INDCs, but often without much specificity. In the next round of INDCs, more specific plans for carbon pricing could be the basis for achieving greater global alignment on appropriate minimum carbon prices over time.

Eliminating fossil fuels subsidies and introducing carbon taxes will provide large tax revenues to Governments, some of which will need to be devoted to targeted support of lower income households, but some of which can finance other elements of Government support for the energy transition, with the appropriate balance differing between countries.

response. The vehicle fleets in the EU and Japan are significantly more fuel-efficient than those of the US or Saudi Arabia because drivers know that, irrespective of the current market price for oil, pump prices for gasoline will remain high through the cycle [Exhibit 65, p. 105].

B. OTHER POLICIES

While effective carbon pricing resulting from public policy is essential, it is far from a sufficient policy, with some aspects of the energy transition more likely to be driven by other policy levers. **Five other types of policy levers must play an important role** [Exhibit 63, p. 101].

Research and development

Governments should play a significant role in financing and encouraging adequate research and development expenditures. Some key technologies – for instance solar PV and lithium ion batteries – are now sufficiently advanced to attract massive private R&D expenditures. But public support for research and development must still play a major role in other forms of battery technology (which might eventually deliver step-change improvements in energy per weight), in next generation nuclear (including fusion) and in the multiple technologies still needed to drive decarbonization of economic activities which cannot be electrified at reasonable cost.

Roadmaps defining feasible performance improvement targets over time can improve coordination between public and private research and development efforts, accelerating the rate of discovery.

Focused deployment support – new industrial policy

Given the importance of economies of scale and learning curve effects in driving cost reductions for specific technologies, **"infant industry" subsidies will often be a more effective policy tool than carbon prices alone. Thus in power decarbonization, initial subsidies for wind and solar power have been essential to drive the industries to sufficient scale to achieve dramatic cost reductions** [Exhibit 66]. Pre-commitments to maintain the subsidy regime for long enough to achieve adequate scale have played an important role. Since low-carbon power has high capital costs and minimal marginal costs, the most cost-effective form of subsidy has been via contracts which provide fixed price certainty to the supplier. Carbon prices alone would probably have been less effective in getting renewables close to the point where no further subsidy is required.

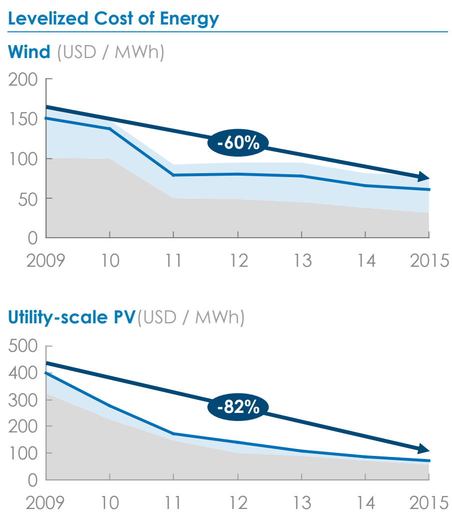
But, while long-term price certainty is an essential lever to drive "infant industry" learning curves, it is not sufficient. For maximum impact, it should be combined with other policies:

- Shifts in market design and regulation (as described below),
- Risk-sharing financing models (i.e. with development or green investment bank support to mitigate initial project/policy risks),
- Smart use of public procurement (an under-utilized tool across the board); and
- Incentives for local communities to host utility-scale renewable energy projects.

Infant industry programs are also best designed with a sunset clause* (e.g. shifting from feed-in-tariffs to auction models), encouraging industry players to aggressively lower costs and become competitive. By contrast, programs that are too expensive and open-ended risk being reversed by future Governments in a fashion that can generate investment risk.

The success of infant industry policies simultaneously implemented across multiple countries for renewables should set an example for new low-carbon technologies

Policy types	Examples	Adoption (countries)
Pricing and market design	▪ Feed-in Tariffs (FIT) ▪ Auctions/tendering ▪ Net metering	73 (+35 states) 60 48
Generation/ capacity mix targets	▪ Quotas ▪ Renewable Obligations ▪ Renewable Portfolio Standards ▪ Typically includes compliance scheme (e.g. tradable credits)	26 (+ 72 states)
Subsidies	▪ Investment and production tax credits ▪ Low-interest loans ▪ Green banks ▪ Green bonds	126



SOURCE: Renewable Energy Policy Network (2015) & Climate Policy Initiative analysis

Exhibit 66

Illustration 9

Regulatory Indicators for Sustainable Energy (RISE)[68]

In the wake of the COP 21 Climate Agreement, countries had to develop INDCs to define their contribution to the global mitigation effort. This required evaluation of their starting positions. That process revealed important data gaps and an absence of robust and comprehensive knowledge base enabling comparison between national policy frameworks, leading to a lack of clarity about the likely effectiveness of different policy tools.

To combat this, the World Bank developed a tool designed to show how policies and regulations in 111 countries support energy access, energy efficiency, and renewable energy. The tool, known as Regulatory Indicators for Sustainable Energy (RISE), provides interactive data and concrete ideas that Governments can use to strengthen policies, to increase investments, to improve lives, and to reduce the impact of climate change. The 27 indicators that RISE uses are organized around the three pillars of the Sustainable Energy for All initiative: Energy Access, Energy Efficiency, and Renewable Energy.

RISE aggregates data representing 96% of the world population. Each country is classified into green (strong), yellow (middling) or red (weak) rankings for each of the three pillars, and these are then aggregated into an overall score. For policymakers, RISE provides a regional or global reference point against which they can benchmark their own policy or regulatory regime, as well as a toolkit of best practices to develop the right framework to advance sustainable energy goals.

Focused deployment support is required to achieve some key aspects of wider electrification. Direct Government subsidies for electric vehicles have played a vital role in driving initial growth, but with battery costs now falling rapidly and multiple vehicles being introduced, the highest leverage form of public support may now be to provide subsidies or low-cost, long-term financing for widespread charging infrastructure. Focused subsidies for heat pump installation could help create scale economies and learning curve effects in manufacture and installation.

> ***"Infant industry policies are essential to achieve rapid cost reduction in low-carbon technologies"***

Such deployment support may also now be essential to achieve rapid cost reduction in the technologies likely to be needed to drive decarbonization beyond power. As mentioned in Section 4, current estimates for business as usual scenarios suggest that CCS investment over the next 15 years might be only 1% of investment in wind and solar. If this is the case, technically feasible cost reductions will not be achieved. Many CO_2-based products (e.g. for low-carbon cement) face a similar challenge and deployment support will be essential to help these products to scale and become cost-competitive in markets that are very price-sensitive. Cost reductions in hydrogen manufacture, storage and distribution will also likely depend significantly on learning curve effects only achievable with large-scale deployment. In biofuels, there is also a major role for fundamental research and development (especially for second- and third-generation biofuels which would limit potential competition with food for land), but, here too, deployment support will be critical, especially in a world with relatively low but potentially volatile fossil fuels prices. Evidence from both the US and EU show that it has been difficult to get second-generation biofuels to scale, given cheap competition from first-generation biofuels (often delivering questionable environmental benefits).

68) Sources: Regulatory Indicators for Sustainable Energy (RISE) data, available here: http://rise.esmap.org/ & Sustainable Energy For All (2013), Global Tracking Framework (Vol.3).

The way forward

Integrating energy system planning

To drive energy transitions, we must simultaneously and coherently leverage the multiple policy drivers outlined in this section – i.e. carbon and energy pricing, R&D and deployment policies, market design, standards and regulations, and urban design. Governments should therefore strengthen their capacity to develop/deploy integrated energy system policy frameworks and investment plans, and ensure that these integrated plans are as clear and stable as possible to provide investors with strong and reliable signals.

In previous periods, it has been possible to plan the energy system in silos – with different dedicated approaches for the power sector, transport, industrial development, or urbanization. Each application and energy source could be separately optimized, with different weighting for cost, energy security and environmental impact. Today's planning challenge is different. In large part, this is because electrification has the potential to spill over the divisions between previously segregated energy sub-systems. But it also reflects the need to optimize fossil fuels use within ever-tighter carbon budgets and to take account of the potential for inter-temporal effects in how these budgets get used. For example, an integrated energy model might still encourage EV scale-up ahead of decarbonization, provided that there is a clear plan to clean up the power system over a defined time.

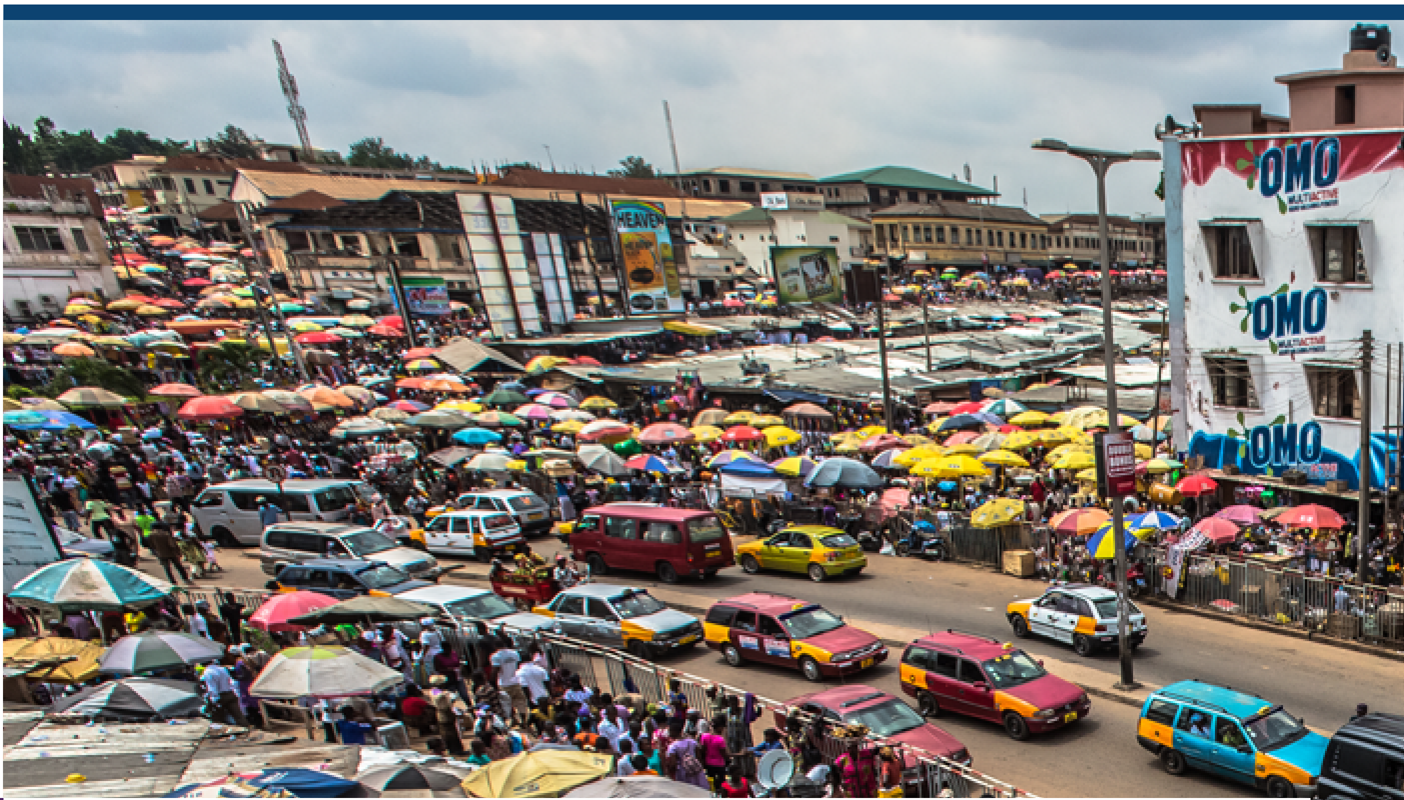
Beyond these technical questions, integrated energy system planning is essential to build national consensus around (i) the appropriate shape of future energy systems and how best to manage the required energy transition with its potential winners and losers and (ii) how to best reconcile environmental objectives with economic development and social equity. This requires considerable political leadership and societal engagement, not least given the long time-horizons within which any set of decisions plays out.

Institutional boundaries complicate integrated energy system planning, with different ministries (including the finance ministries) often working on the basis of different assumptions. Some countries, retain central planning functions and these can, with the right technical inputs, play the coordination role. However, in many countries, either these central planning functions no longer exist or, if they do, they lack the technical know-how to develop complex integrated plans.

The INDCs provide a great opportunity to develop the required national consensus not only around the future energy system, but how that system can contribute positively to more sustainable, inclusive forms of growth. While the Paris round of INDCs was a hugely important first step, it is clear that much more work, both political and technical, will be required if the next iteration of national commitments is to drive change at the required speed and scale.

Market design and regulation

Developing appropriate market design and regulation will be essential to drive efficient integration of renewable energy into the power mix, as indicated in Section 1. Power markets need to provide better long-term signals to encourage investment in, and deployment of, flexibility technologies, such as lithium batteries, and therefore drive their cost reduction. Market design is also essential to unlock other low-cost flexibility solutions: efficient transmission investment would best be driven by locational pricing and the expansion of power markets between regions, and short-term pricing is required to reach the full potential of demand management. By contrast, poor market signals could add to flexibility shortages and to the cost of electricity.



Standards and regulations enforcement

Carbon prices – by increasing the cost of energy – can play a role in increasing incentives to achieve energy efficiency improvements. **But the very fact that many energy efficiency improvements deliver positive returns even with a zero-carbon price suggests that non-price levers such as product standards and regulations will be more effective**. Standards for lightbulbs, automobiles or electrical appliances are more likely to drive efficiency improvement than expectations of future carbon taxes and higher energy prices. Performance standards for low-carbon building materials may accelerate progress in the energy-intensive sectors and may be more effective than over-reliance on carbon pricing policies, given the lack of a global carbon price. Better building insulation depends primarily on the definition and enforcement of building standards.

> ***"Standards and regulations will be more effective than carbon pricing to drive energy efficiency improvements"***

There is also a good case for forms of concessional or blended finance to speed up deployment of more efficient appliances. Some countries have experimented with "feebate" models which encourage consumers to "retire" their inefficient appliances earlier, through subsidies in the form of either concessional finance or VAT exemptions on the new purchase. Done in the right way, these may also be helpful in stimulating local industry and employment.

Urban design

High quality urban planning to create compact, dense and energy-efficient cities will be among the most important drivers of increasing energy productivity (i.e. higher income or welfare per unit of energy-based service consumed). This inevitably requires a major role for public authorities, with carbon pricing incentives of only minor importance. It also requires much greater engagement from finance ministries who, in most countries, provide the bulk of urban infrastructure funding and in principle could provide stronger incentives to encourage city authorities to develop their investment plans around more compact models.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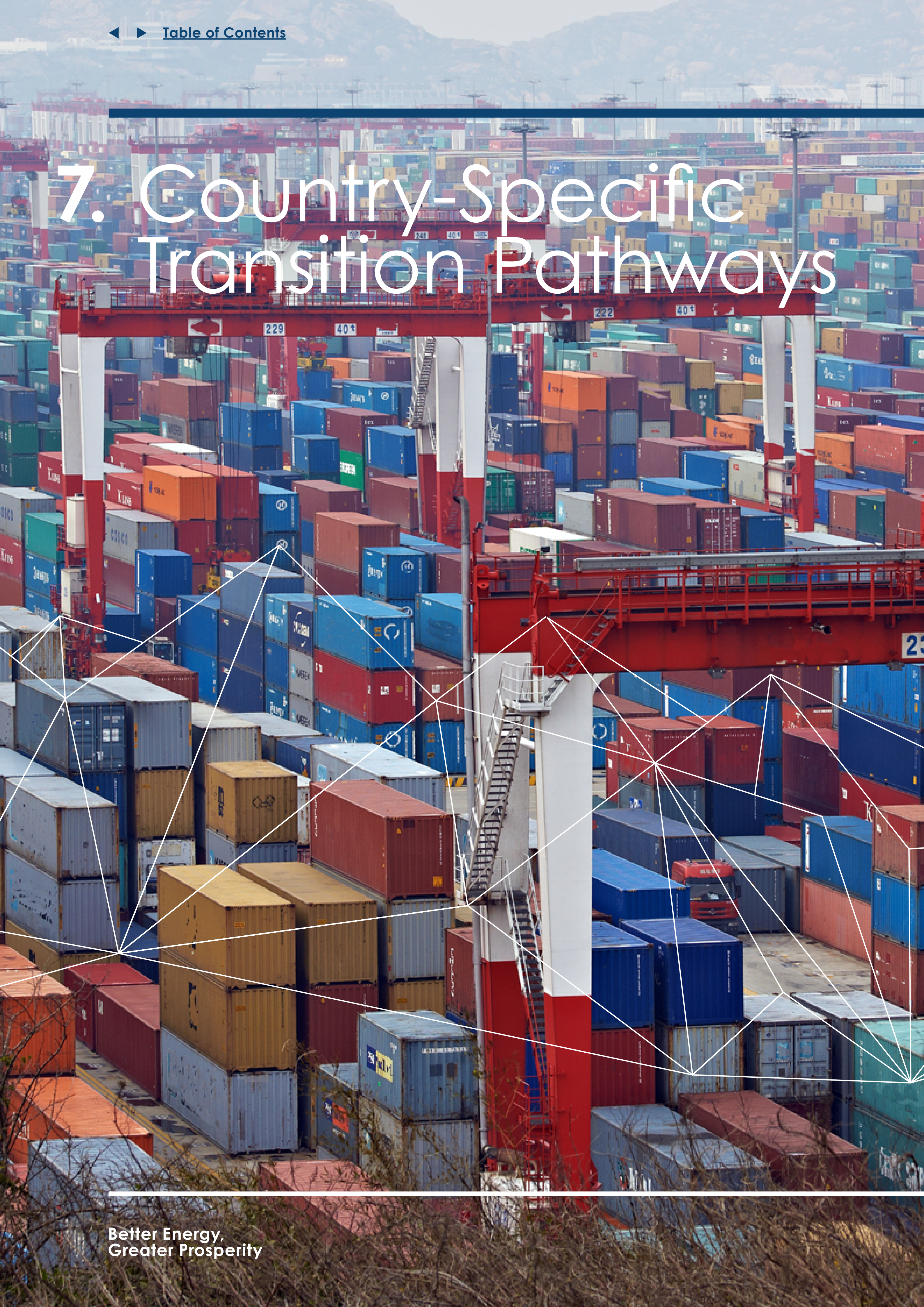
MULTIACTIVE
HAND WASHING POWDER



7. Country-Specific Transition Pathways

The broad features of the required energy transitions are common to all countries: in all, a combination of the four dimensions of the transition is required. The policy implications described throughout this document are relevant across the globe. But it is also important to recognize that different countries will inevitably follow different transition pathways.

The overall global challenge is to achieve rapid decarbonization of energy supply together with a huge acceleration of the pace of energy productivity improvement (see Exhibit 2, p.14 in the Executive Summary). But the optimal balance between progress on these two dimensions, and the precise means by which to achieve progress, will and should vary according to differences in initial starting positions and natural endowments.

A. ENSURING ENERGY ACCESS FOR ALL IN DEVELOPING COUNTRIES

A number of developing countries and regions, especially concentrated in Sub-Saharan Africa and South Asia, are still struggling to provide access to affordable, reliable, sustainable and modern energy services to their population. Some 1.1 billion people do not have access to electricity and 2.9 billion people do not have access to clean cooking[69]. **Providing universal access to affordable, reliable, sustainable and modern energy services by 2030 is therefore a key Sustainable Development Goal.**

"The world is not on track to achieve universal access to affordable, reliable and sustainable energy access"

However, latest data indicates that the world is not on track to achieve this objective[70].

Many Governments facing access challenges are considering a variety of options to meet their development and energy needs, including grid-based, distributed and off-grid solutions that incorporate innovative and emerging technologies, business and finance models. There is a strong expectation that finance should flow from both the public and private sectors to help address these needs – and indeed the scale of the energy transition demands it. Yet many countries still face challenges in moving from project concepts to actual investment and in using public funding to crowd-in private finance. These countries need increased capacity to develop coherent strategies that integrate centralized and decentralized access modes, establish effective enabling environments for both access and energy productivity, and improve the governance and capacity of power utilities and regulators so they can raise financing for new infrastructure development.

On a more positive note, these countries also have an opportunity to leapfrog to new and better technologies, and avoid unnecessary investments in fossil fuels and centralized power systems wherever distributed renewables are more economic. Decentralized clean energy business models powering super-efficient devices mean that the "last person" can now be among the first person to be reached with new forms of energy services. **This is a true grassroots revolution in the energy system** – and one which implies no significant trade-off between energy access and delivering a well below 2˚C pathway.

B. EASIER AND HARDER DECARBONIZATION

Using renewables to drive power decarbonization plus wider electrification will be easier and cheaper to achieve in some countries than others. Renewables costs are coming down across the

69) Sustainable Energy For All (forthcoming), 2017 Global Tracking Framework.
70) Ibid.

world, but the lowest prices for renewable power are now being achieved in specific locations, such as the Chilean desert, which are blessed with high-quality wind and solar resources and low population density. Countries such as Chile (with a population density of 24 per square kilometer) Australia (3) and the US (35)[71], are well placed to drive massive renewables investment in locations where land costs are low, and where lack of competition with other land uses facilitates fast and cheap development. Other countries, such as Brazil and Ethiopia, can rely on huge hydro resources[72] to support low-carbon power systems even as electricity demand increases.

But some developing economies will find it more difficult to build low-carbon power systems solely or primarily on renewables for two reasons: (i) first because the pace of electricity demand growth is likely to be huge – with, for instance, India's electricity demand forecast to grow from 900 TWh in 2013 to 3,000 TWh in 2030[73]; and (ii) second because high population density (e.g. 441 in India, and 1,237 in Bangladesh)[74] will in some locations create competition for land use between renewables and food production, increasing costs and slowing the feasible pace of renewables deployment.

It is therefore likely that such countries will have to rely on a mix of different technologies, including nuclear and some fossil fuels-based power generation, to meet growing power needs over the next 15 years. But any fossil fuels-based power generation, especially coal-based, will only be compatible with a long-term low-carbon economy if either (i) carbon capture can be applied cost-effectively beyond some date (e.g. 2030); or (ii) those plants are only used for a limited life, for instance 20 years, and then either closed or used only as flexibility back-up to renewables or nuclear.

Ensuring that some lower income countries can achieve an adequately rapid transition may therefore require both:

- **Strong global support for the development and deployment of CCS**;
- **Financial aid or concessional finance flows from richer countries** to make limited-life coal-fired power plants economically acceptable. Many routes to achieve this effect could be imagined, but, simply by way of illustration, it might entail: (i) the creation of a global fund of $50-100 billion over the next decade to be allocated to lower income countries against commitments to retire coal-fired plant early at some future specified date; (ii) with the payout to be made only at the date of plant closure and/or installation of effective CCS retrofit; and (iii) with the allocation per country determined by an auction designed to achieve maximum carbon emissions reductions per dollar granted.

In reality, the need for new fossil fuels-fired power generation in the transition period could also end up being lower than generally thought. As described in Illustration 3, p.36 in Section 1, latest study on the Indian electricity sector shows that high expansion in renewables facilitated by falling all-in cost could remove the need for additional coal-fired power generation capacity beyond the 50 GW already planned[75].

C. ENERGY PRODUCTIVITY: LOCK-IN RISKS VS. RIGHT-FIRST-TIME ADVANTAGES

By contrast, some of the rich and lightly populated countries best placed to achieve rapid decarbonization at low cost will find it more difficult to achieve high levels of energy productivity, because of lock-in effects arising from already built infrastructure. **Overall the pattern must be one in which rich developed economies reduce energy use per capita, and developing economies achieve rapid economic growth while keeping energy use flat. But it seems unlikely that a country like the US**, with energy use per capita currently 60% higher than even the developed country average, **will be able to reduce energy use to the global average level during this century**, and certainly not by 2050, given that many of its cities (such as Atlanta or Los Angeles) were built in a low-density and auto-dependent fashion, in part in response to low overall population density. A fair but optimal

71) World Bank data, 2015.
72) Albeit that there are now growing concerns about the predictability of hydro-power resources as a result of climate change and changes in precipitation/discharge patterns.
73) IEA (2016), Energy Technology Perspectives. Data from 2013.
74) World Bank data, 2015.
75) The Energy and Resources Institute (2017), Transitions in Indian electricity sector, 2017-2030.

US contribution to the global emissions reduction challenge is likely to entail more rapid and complete decarbonization than in other countries, but, at least for many decades, a higher than average energy use per capita.

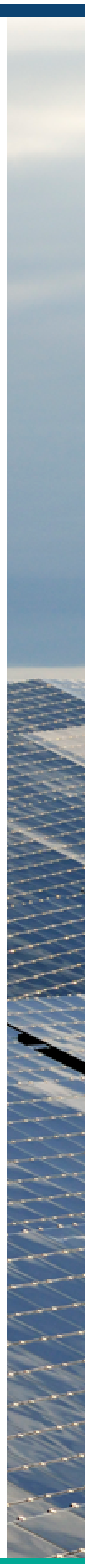
“Developed economies must reduce energy use per capita, while developing economies keep it flat”

Conversely some of the developing countries, which may find rapid power decarbonization more difficult, **have an opportunity to do urbanization “right first time”** by building economically dynamic cities which are dense, environmentally attractive, and energy-efficient. Seizing that opportunity is vital.

All developing economies could dramatically improve energy efficiency, by imposing best practice global standards for appliances, auto efficiency, and building standards. In many such countries however, **the greatest challenge is not the definition of those standards but their effective enforcement**.

D. FOSSIL FUELS EXPORTERS

Finally, **countries whose economies are heavily reliant on fossil fuels production and export will clearly face large challenges** if, as seems likely, the consequence of the fossil fuels volume scenarios outlined in Section 4 leads to lower oil and gas prices than these countries would have enjoyed under a business as usual scenario. These challenges are already apparent in the large fiscal deficits now being run by countries such as Saudi Arabia (13% of GDP in 2016), Nigeria (4.6%) and Venezuela (26%). They will be most severe for countries with large and rapidly growing populations, which already face declining per capita natural resource rents. In these countries, designing and implementing economic development strategies to achieve more diversified sources of economic growth is essential.



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