

# Sectors that are challenging to decarbonise

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## Question

*Which sectors that employ fossil fuels are considered to be difficult to decarbonise due to technology availability, cost of large-scale deployment or feasibility of deployment in a development context? Are there technological solutions in the horizon?*

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# 1. Summary

Achieving the goal of limiting global warming as set out in the Paris Agreement will require large reductions in carbon dioxide (CO<sub>2</sub>) emissions. All economic sectors will need to work towards achieving net zero emissions of CO<sub>2</sub> and reduce emissions of other greenhouse gases such as methane (Energy Transitions Commission, 2018b, p. 15; Fay et al., 2015, p. 1).

The Energy Transitions Commission, led by commissioners from industry, academia, civil society, government, and intergovernmental agencies, asserts that it is technically possible to decarbonise the economy by mid-century through a combination of measures including more efficient use of materials, increasing re-use and recycling of materials, improving energy efficiency, using alternative fuels and technologies, electrification of industrial processes, use of biomass for heat, and carbon capture and storage (Energy Transitions Commission, 2018b, pp. 16–17).

The World Bank similarly asserts that there is ‘full consensus’ that decarbonisation requires, and can be achieved by decarbonised electricity production; electrification using low-carbon electricity, or switching to cleaner fuels where electrification is not possible; improved efficiency and reduced waste in all sectors; and preserving and increasing carbon sinks such as forests and other vegetation and soils (Fay et al., 2015, pp. 27–28).

Some sectors are considered to be, from a technological standpoint, relatively easy and cost-effective to decarbonise using known technologies. These sectors include light-duty transportation, heating, cooling, and lighting, rail, pulp and paper, aluminium, buildings, agriculture, and fishing, and to a large degree the electricity-generating sector (Davis et al., 2018, p. 1; Energy Transitions Commission, 2018b, p. 11). In the electricity generation and personal transportation sectors, low-carbon technologies are already sufficiently competitive, or nearly competitive, with older technologies that the low-carbon transition has developed its own momentum (Spencer & Mathur, 2019, p. 1).

Other sectors, particularly in heavy industry and heavy transport, are considered more difficult to decarbonise, and are particularly relevant for developing countries which have large material and freight transport needs (Spencer & Mathur, 2019, p. 1). Globally, the sectors most often identified as difficult to decarbonise are aviation, long-distance road freight transport, shipping, cement, steel, plastics, and generating electricity that can respond rapidly to changing demand and compensate for the intermittency of energy sources like solar and wind power (Davis et al., 2018, p. 1; Energy Transitions Commission, 2018b). CO<sub>2</sub> emissions from the most difficult-to-decarbonise sectors account for 25% to 30% of global emissions, and current trends suggest that these emissions are likely to increase substantially in the future, and to account for a growing proportion of global emissions as other sectors decarbonise (Davis et al., 2018, p. 7; Energy Transitions Commission, 2018b, p. 15).

This report focuses on eight sectors or issues that have been identified as having particular relevance to developing countries: cement, steel, captive coal, shipping, road freight, railway electrification, and electricity generation in centralised grids and in decentralised situations. It briefly describes each sector and identifies technologies that have some potential for use in decarbonising these difficult sectors. It is important to also recognise that decarbonisation is a contentious and highly political challenge, and that institutional and governance issues, which are not the focus of this report, will be critically important in any transition.

<b>Sector</b>	<b>Promising technologies</b>
Cement	<ul style="list-style-type: none"> <li>Demand reduction (building design, recycling, reuse)</li> <li>Changing composition (clinker-cement ratio, alternative formulations)</li> <li>Switching from coal to gas</li> <li>Carbon capture and storage</li> </ul>
Steel	<ul style="list-style-type: none"> <li>Increased scrap recycling</li> <li>Demand reduction through improved design</li> <li>Recovery and use of waste heat and gases</li> <li>Coke dry quenching</li> <li>Increasing reliance on electric arc furnaces, especially with low-carbon electricity</li> <li>Direct reduced iron (DRI) and electric arc furnaces, especially hydrogen DRI</li> <li>Carbon capture and storage</li> </ul>
Captive coal	Industry-dependent
Shipping	<ul style="list-style-type: none"> <li>Slow steaming</li> <li>Ship design, drag reduction, and energy efficiency</li> <li>Wind assistance</li> <li>Ammonia and hydrogen fuels, if produced using low-carbon electricity</li> </ul>
Road freight	<ul style="list-style-type: none"> <li>Electric vehicles</li> <li>Shifting traffic to rail</li> <li>Vehicle energy efficiency</li> <li>Freight system optimisation</li> </ul>
Railway electrification	Overhead line electrification on high-traffic lines only
Electricity generation: electrical grids	<ul style="list-style-type: none"> <li>Solar and wind power</li> <li>Natural gas with carbon capture and storage</li> <li>Hydropower</li> <li>Pumped-hydro storage</li> <li>Compressed air storage</li> </ul>
Electricity generation: backup generation and mini-grids	Mini-grids with solar photovoltaic (PV) <sup>1</sup> and battery storage

*Source: Author's own*

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<sup>1</sup> Solar panels that generate electricity directly from sunlight.

## 2. Cement

Cement is one of the ingredients used to make concrete, which is essential for building a wide range of types of infrastructure. 'There is no other material currently available that is available in the quantities necessary to meet the demand for buildings and infrastructure. (International Energy Agency, 2018, p. 8). Demand for cement is currently flat in many high-income countries, and may decrease from the current extremely high levels in China which has undergone a long construction boom, but rapid growth is likely in India, Southeast Asia and Africa (Energy Transitions Commission, 2018b, p. 55). Annual cement production in Africa is expected to more than treble from 2014 to 2050 (Energy Transitions Commission, 2018b, p. 56).

Cement is manufactured from naturally-occurring rocks that contain calcium carbonate, such as limestone, marl, or chalk, mixed with smaller quantities of other materials, which are quarried, crushed, and heated to undergo chemical reactions at temperatures up to 1450 °C. The process requires energy to transport the heavy minerals, operate crushing and grinding equipment, and create the high heat necessary for chemical reactions in the cement kilns (International Energy Agency, 2018, pp. 12–14). Typically, 30-40% of direct CO<sub>2</sub> emissions come from the combustion of fuels, and 60-70% come from the chemical reactions that take place during the cement-making process to convert limestone to calcium oxide (International Energy Agency, 2018, p. 12). While it may be possible to substitute some of the energy inputs with low-carbon energy sources, the chemical reactions that release CO<sub>2</sub> are a fundamental part of the production process and are more difficult to eliminate.

Technology and processes in the cement industry are relatively slow to change. Furthermore, the infrastructure and equipment used in cement manufacture has a long lifetime – cement kilns may operate without fundamental retrofit for 30 to 40 years – making replacement of equipment a long-term affair (Energy Transitions Commission, 2018b, p. 66).

**Energy efficiency** measures such as using raw materials with a lower moisture content in dry-process kilns, using preheating systems called precalciners to prepare incoming raw materials, using more efficient grinding and milling technologies, recovering and re-using waste heat in the production process, and improving control systems could reduce industry CO<sub>2</sub> emissions. However, these reductions are small: the International Energy Agency (IEA)'s scenarios for emissions reductions in the cement industry suggest that these measures might only contribute 3% of the reductions that would be needed to limit average global warming to 2 °C.<sup>2</sup> Capital costs of retrofitting equipment can be high, new operating procedures and retraining would be required, and the feasibility and effectiveness of measures can vary depending the local raw materials available and local market requirements (International Energy Agency, 2018, pp. 23–28).

**Alternative fuels** could offer moderate reductions of CO<sub>2</sub> emissions (12% of the reductions needed by 2050 to achieve the IEA's two-degree warming scenario). Globally, coal is currently

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<sup>2</sup> The International Energy Agency (IEA) has developed two scenarios for carbon emissions to 2050 in the global cement industry: a 'reference technology scenario' which takes into account energy consumption trends and national commitments to limit carbon emissions and improve energy efficiency, and a 'two-degree scenario' which is an ambitious pathway for the industry consistent with resulting in at least a 50% chance of limiting average global temperature rise to 2 °C by 2100 and implies CO<sub>2</sub> emission reductions of around 60% from current levels by 2050. References to the scale of contribution of various approaches to decarbonisation in the IEA scenarios refer to the reductions in emissions that would be achieved by going from the reference scenario to the two-degree scenario.

used for 70% of the thermal energy used for cement production, and oil and gas contribute 24%, with only slightly more than 5% coming from alternatives (International Energy Agency, 2018, p. 28). Switching from coal to gas could be a practical intermediate step, particularly if carbon capture systems could be used as well (Energy Transitions Commission, 2018b, p. 67). Existing cement plants can be modified to burn a wide range of industrial and municipal waste products have potential to be used as a source of heat, but are less efficient than fossil fuels and require careful management of toxic combustion by-products (International Energy Agency, 2018, pp. 28–31). Biomass from agricultural products (wood, grass, and algae) could in principle be a source of energy but is not currently cost-effective for the cement industry (International Energy Agency, 2018, pp. 28–31).

**Changing the composition of cement** could reduce carbon emissions substantially. Replacing a portion of the clinker, which normally makes up 90% of cement, with other materials could allow production of cement with as much as 37% less CO<sub>2</sub> emissions by 2050 in the IEA's two-degree-warming scenario (International Energy Agency, 2018, p. 32). Potential alternative materials include gypsum, natural volcanic materials (pozzolan), limestone, and industrial by-products such as ground granulated blast furnace slag (a by-product of producing iron), fly ash (a by-product of burning coal), ash from agricultural residues, and silica fume (a by-product of silica and ferro-silica alloy production processes) (International Energy Agency, 2018, pp. 32–36). Current building standards around the world specify the blends of cement that are permissible, and any changes would have to be carefully tested at scale to ensure that there are no long-term adverse effects on the strength or durability of the resulting concrete (Davis et al., 2018, p. 5; International Energy Agency, 2018, p. 35). Feasibility of substitutes will vary from place to place depending on local availability of suitable materials (International Energy Agency, 2018, pp. 32–36).

**Renewable power generation** including wind, solar, and hydropower can be used to decarbonise electricity consumption for grinding and milling activities, although they are not practical to supply the high heat requirements of the cement-making process (International Energy Agency, 2018, p. 37)

**Reducing the demand for new cement and concrete** through changes in building design could reduce the need for concrete by 34% (Energy Transitions Commission, 2018b, p. 16). **Recycling** cement and concrete could further reduce demand by 34% by 2050 in a circular-economy scenario (Energy Transitions Commission, 2018b, p. 58). There could also be opportunities to use **timber**, rather than concrete, in new construction, which would reduce carbon emissions and also provide a carbon sink. The key constraint on this is the available supply of timber: to replace 25% of the concrete used each year with timber would require an increase of global forest cover of about 14% (Energy Transitions Commission, 2018b, p. 58).

**Carbon capture and storage** technologies could be retrofitted to existing cement kilns, but these are in the early stages of development, mostly still experimental, and are likely to be expensive. Chemical absorption is the most-proven technology, and has been used in other industries, but has only undergone limited testing in the cement industry (International Energy Agency, 2018, pp. 37–41)

**Electrification of kilns** is not currently practical. Technologies for electric kilns are unlikely to be commercially feasible until the 2040s and would require complete replacement of existing kilns, which would be very expensive (Energy Transitions Commission, 2018b, p. 66).

### 3. Steel

Steel is an essential component for infrastructure and manufacturing around the world. In high-income countries, the stock of steel typically stabilises at about 12-13 tonnes per capita; in China, it is over 5 tonnes per capita and growing fast; in India and Africa, it is less than 1 tonne per capita. China is the dominant steel producer in the world today, with nearly 50% of total global production, but future demand will be driven by India (the world's second-largest producer) and Africa (Energy Transitions Commission, 2018b, p. 55; Hall, Spencer, & Kumar, 2020, p. 24). Annual steel production in Africa is expected to increase by seven times from 2014 to 2050, and production in India to increase by more than five times (Energy Transitions Commission, 2018b, p. 56).

Two methods of producing steel account for almost all production worldwide: the basic oxygen furnace, which is used to produce new steel from iron ore and accounts for 70.8% of global production, and the electric arc furnace, which is used to recycle existing steel and accounts for 28.8% of production. In Africa, 28% of steel production is new steel produced in basic oxygen furnaces and 72% is recycled steel from electric arc furnaces; for Africa excluding Egypt and South Africa these proportions are 12% and 88% respectively (World Steel Association, 2019, p. 10). The basic oxygen furnace process begins by mixing iron ore with coke (a purified form of carbon produced by crushing and heating coal), and burning the coke to produce temperatures of more than 2000 °C to melt the iron ore. Impurities are drawn off, and the resulting molten iron is then mixed with up to 30% scrap metal and oxygen is blown through it to convert the iron into steel. The electric arc furnace process uses scrap steel, possibly combined with direct reduced iron (iron produced by reacting iron ore with carbon monoxide and hydrogen from coal or natural gas) and melts this raw material by passing a very high-energy electrical current through it (British Steel, n.d.; World Coal Association, n.d.).

Steel production is complex, with multiple steps and options. The process tends to be highly dependent on coal and/or gas for energy, for carrying out chemical reactions, or both. There are possibilities for reducing CO<sub>2</sub> emissions at several points, some of which are interdependent (for example, recycling steel is highly effective if the electric arc furnaces that process the scrap metal can be powered by renewable energy sources, but less effective if they are powered by coal). The cost and feasibility of each approach varies depending on local conditions. The Energy Transitions Commission concludes that 'the two main routes to decarbonisation will certainly be hydrogen-based reduction and carbon capture, combined with either storage or use (CCS/U), but the optimal decarbonization pathway will differ by location depending on local electricity prices, and CCS cost and feasibility' (Energy Transitions Commission, 2018a, p. 2).

**Recycling** steel is very effective because steel can be repeatedly recycled with no loss in its properties or performance (World Steel Association, 2020, p. 3). Steel already has a high recycling rate, with a global average of 83% of end-of-life steel being collected for recycling (Material Economics, 2018, p. 66). Recycling could be increased further if products were redesigned to facilitate disassembly and recycling and limit downgrading in the recycling process (Energy Transitions Commission, 2018b, p. 58). Although steel can be recycled indefinitely, scrap metal frequently contains a mix of materials, and impurities, particularly copper, means that the quality of recycled steel cannot be maintained, and can only be used where low quality standards can be accepted (Material Economics, 2018, p. 68). Recycled steel is processed in electric arc furnaces, which can be low-carbon if the electricity they use is generated from low-carbon, especially renewable, sources (Davis et al., 2018, pp. 4–5).

**Demand for steel** could potentially be reduced by 38% globally by 2050 through reducing waste across the value chain, improving the recycling process, promoting re-use of steel-based products, reducing demand for cars, and optimising the design of products, buildings and infrastructure to use less steel (Energy Transitions Commission, 2018b, pp. 16, 58).

**Energy efficiency:** There are multiple points across the steel-making process where energy efficiency could be improved without fundamentally changing the process. **Coke dry quenching** is a well-established way to recover heat from coke early in the production process and use the energy to generate electricity or for other purposes (Energy Transitions Commission, 2018a, p. 12; Pardo et al., 2012, pp. 16–18). **Recovery of waste heat and gases** can take place at several points in the production process and can be used to generate electricity or used for other purposes in the production process. An EU study that examined twelve 'best available technologies' for steel production found that the greatest reduction in CO<sub>2</sub> emissions was achieved through an on-site state-of-the-art power plant using waste heat and gases from the steel production process to produce electricity and steam (Pardo, Moya, & Vatopoulos, 2012, pp. 16–18). **Continuous casting** is the process of rolling molten steel directly into desired forms instead of first casting the steel into ingots, as was previous practice. This reduces the energy needed for re-heating and rolling the steel, and reduces material losses (Pardo et al., 2012, pp. 17–18). Energy efficiency measures could theoretically achieve up to 37% higher energy efficiency, but in practice retrofits of existing equipment are not always possible and many such improvements have high up-front capital costs that companies may not be able to afford, especially in developing countries (Energy Transitions Commission, 2018a, p. 12; Pardo et al., 2012, pp. 16–18).

**Direct reduced iron:** Electric arc furnaces are used to recycle scrap steel, but can also use direct reduced iron (DRI) as their input material, which enables them to produce new steel, replacing the coal-dependent coking process that feeds basic oxygen furnaces. DRI is currently produced through chemical reactions with gases derived from coal or natural gas; the latter produces significantly less carbon emissions than coke-based iron production (Energy Transitions Commission, 2018b, p. 67). **Hydrogen** is perhaps the most promising candidate for a low-carbon replacement, as it could offer significant climate benefits if the hydrogen can be produced in a low-carbon way (such as using hydro, wind, or solar energy), but the technology is not yet proven in large-scale deployment. Construction began on the world's first pilot plant in Sweden in 2018, which is expected to become operational soon (Energy Transitions Commission, 2018a, p. 13).

**Carbon capture and storage (CCS)** techniques are being tested and may be feasible to reduce CO<sub>2</sub> emissions during the iron production process in certain types of furnaces (Davis et al., 2018, p. 5; Energy Transitions Commission, 2018b, p. 62). CCS can be retrofitted to blast furnace – basic oxygen furnace production without significant changes to existing equipment. Experimental installations are being tested at scale, but the technology is not fully mature and further research and development are needed especially to reduce costs to the level where systems can be widely used (Davis et al., 2018, p. 7; Energy Transitions Commission, 2018a, p. 13).

**Biomass** may be able to replace coal as a fuel and reducing agent. This has been done in Brazil using **charcoal** produced from eucalyptus, but producing sufficient charcoal to meet demand would require hundreds of millions of hectares of productive land (Davis et al., 2018, p. 5). An alternative would be to use **biogas**, which is methane produced from biomass sources including waste decomposition, but the supply of biogas is also likely to be too limited (Energy Transitions Commission, 2018a, p. 13). **Plastic waste** has also been explored as a reducing agent in the

iron production process, and has been used in some European steel plants (Energy Transitions Commission, 2018a, p. 13).

**Electrolysis** is a process that would involve reducing iron ore via direct electrolysis, which is the technology already extensively used in aluminium production. However, this technology is still at a basic research phase (Energy Transitions Commission, 2018a, p. 13).

Other emerging technologies that have the potential to reduce carbon emissions include using more iron ore in pellet form rather than as sinter, since CO<sub>2</sub> emissions for pellet production are lower than for sinter production; using oxy-fuel burners in electric arc furnaces to heat the scrap metal more uniformly; and using pulverised coal to replace some of the coke normally used in iron ore processing, which saves energy on the coke production process (Pardo et al., 2012, pp. 17–18).

## 4. Captive coal

'Captive coal' refers to the mining and use of coal by a company for use within that company to generate heat or electricity (International Energy Agency, 2017, p. 172). Captive coal is used in many energy-intensive industries, including the production of cement, aluminium, steel, and nickel, as well as electricity generation (Naik & Ghatak, 2019; Philalay, Drahos, & Thurtell, 2019; PwC, 2016a, p. 28, 2016b, p. 22; Shearer, Ghio, Myllyvirta, Yu, & Nace, 2016, p. 31). The term 'captive' can also describe heat and power generated from industrial by-products: for example, in the pulp and paper industry, captive heat and power are generated from wood shavings and bark on site (International Energy Agency, 2017, p. 203).

Using captive power gives a company control over its energy costs, reducing its exposure to fluctuations in energy and fuel prices on the open market (International Energy Agency, 2017, p. 173). Captive power is also more reliable than electrical grid power in developing countries, and can allow energy-intensive industries to develop without placing a power burden on the grid or having to wait for extension of the grid to an industrial site (PwC, 2016b). On the other hand, using captive power instead of the national electrical grid deprives the grid of investment and undermines the economies of scale that large-scale grids can offer. In China, concerns have been raised that captive coal operations are not covered by the same regulations as public power plants, and may be built without permits and without meeting legal emissions standards (Shearer et al., 2016, pp. 31–32).

In this report, approaches to reducing the use of coal, including captive coal, are covered in the sections on the steel and cement industries and electrical generation. However, businesses that have access to captive coal may find switching to lower-carbon energy sources less attractive than other businesses do.

## 5. Shipping

Shipping is the most energy-efficient and least carbon-intensive way to move freight (Balcombe et al., 2019, p. 72; Energy Transitions Commission, 2018b, p. 75; Wan, el Makhoulfi, Chen, & Tang, 2018, p. 428). Shipping is very important to developing countries, which are major exporters of raw materials, and are importers and exporters of finished and semi-finished goods: in 2018, ports in developing countries loaded 54% and unloaded 42% of all seaborne cargo in the world (UNCTAD, 2019, pp. 6–8).

Most of the fuel used in shipping is heavy fuel oil, 'a high-carbon, high-sulphur residual substance left over from the process of refining crude oil' (Englert & Losos, 2020). Globally, international shipping is currently responsible for 3.1% of global CO<sub>2</sub> emissions and 13% of sulphur oxides (Balcombe et al., 2019, p. 74), and emissions could increase by 2.5 times from 2012 to 2050 due to increasing global freight volumes (Wan et al., 2018, p. 428). Emissions from shipping have been largely unregulated until recently, and major shipping nations and the shipping industry have been slow and reluctant to introduce measures aimed at reducing emissions (Balcombe et al., 2019, p. 73; Wan et al., 2018, p. 428).

The shipping industry is likely to be one of the most expensive sectors to decarbonise (Energy Transitions Commission, 2018b, p. 85). Change takes place slowly, partly because of the high cost and relatively long life of ships (the average age of the merchant fleet is 21 years) and port infrastructure (Energy Transitions Commission, 2018b, p. 18; UNCTAD, 2019, p. 30). Adopting new, unproven technologies in shipping is expensive and the industry tends to be conservative and risk-averse (Balcombe et al., 2019, p. 80; Wan et al., 2018, p. 432). The industry is also fragmented, with complex contracting structures and conflicting incentives which make it difficult to coordinate decarbonisation efforts (Energy Transitions Commission, 2018b, pp. 76, 132),

**Energy efficiency** measures including improved hull shapes and materials, larger ships, various means for reducing hull drag, more efficient on-board electrical systems, better propulsion systems, waste heat recovery systems, logistics improvements, and optimising routing, speed, and sailing practices such as ship trim, could in principle deliver significant efficiency improvements (Balcombe et al., 2019, pp. 80–81; Energy Transitions Commission, 2018b, p. 76; Wan et al., 2018, pp. 430–433). In particular, **slow steaming**, which simply means sailing more slowly, is the most promising emission-reduction strategy (Wan et al., 2018, p. 430). The resulting longer journey times may mean that more ships are required to maintain total transport capacity, but a 10% reduction in speeds could reduce total average emissions by 19% (Balcombe et al., 2019, p. 80). Slow steaming reduces fuel costs, but longer journeys increase costs for labour, insurance, and other time-related expenses, and reduce ship utilisation (Balcombe et al., 2019, p. 80; Wan et al., 2018, p. 430).

**Liquefied natural gas** (LNG) has been used as a fuel for more than 40 years as a fuel by vessels that transport LNG as their cargo. Engines can be retrofitted to burn LNG, but the cost of this can be in the millions of dollars and reduces cargo-carrying capacity (Wan et al., 2018, p. 430). This reduces pollution in the form of nitrogen oxides, sulphur oxides, particulates, and CO<sub>2</sub>, but releases methane, which is a greenhouse gas, so that the net reduction in greenhouse gases is only 9% to 12%. Widespread transitioning to LNG fuel would also require extensive investment in fuelling infrastructure at ports, at considerable cost (Balcombe et al., 2019, pp. 75–77; Energy Transitions Commission, 2018b, p. 87; Wan et al., 2018, p. 480).

A variety of **biofuels** derived from agricultural products can potentially serve as alternative fuels. These would require only minor alterations to engines and would be largely compatible with existing fuelling infrastructure. However, they are expensive, potentially increasing a ship's voyage cost by up to 120% (Energy Transitions Commission, 2018b, p. 84). They are not expected to become cost-competitive with fuel oil or diesel, and large-scale production would lead to competition with other agricultural crops for scarce land and water resources (Balcombe et al., 2019, pp. 77–78). **Methanol**, which can be produced from natural gas, waste CO<sub>2</sub>, or biomass, is in use in seven ships as of 2018, but is more expensive than fossil fuels or LNG and there is no net climate benefit if it is produced from natural gas (Balcombe et al., 2019, p. 78). **Ammonia** is clean-burning, but only achieves a net benefit if it is produced using low-carbon electricity. Existing engines can be modified to use ammonia, but significant new fuelling

infrastructure at ports would be required. No commercial deployments have yet taken place, and it is forecast that the cost could add 50% to 120% to the cost of a ship's voyage, depending on the cost of producing the ammonia (Balcombe et al., 2019, p. 79; Energy Transitions Commission, 2018b, pp. 84–86).

**Hydrogen fuel cells** produce electricity with no greenhouse gas emissions at source, but the net benefit depends greatly on how the hydrogen is produced. The technology is not fully mature but fuel cells for shipping are being tested in 23 projects as of 2017, including at least two commercial-scale trials (Balcombe et al., 2019, p. 78).

**Batteries** will likely play a role in river, coastal, and short-distance shipping, and passenger and car ferry traffic, but the size and weight of batteries makes them infeasible and uneconomical for longer journeys in the foreseeable future (Energy Transitions Commission, 2018b, pp. 80–82).

**Wind assistance** is being tested in forms ranging from traditional sails to new types of kites, rotors, and turbines. It is being used to supplement to conventional engines rather than as the sole source of propulsion (except on heritage craft), and estimates of fuel savings vary widely. These deployments are experimental and cost-effectiveness has not yet been established (Balcombe et al., 2019, pp. 79–80).

**Solar power** is used on some ships for supplementary power for onboard systems, but not for main propulsion. Corrosion of solar panels in the saltwater environment has been reported as a problem. It is in an experimental stage and cost-effectiveness has not been determined (Balcombe et al., 2019, p. 80).

Some approaches to **carbon capture** and other exhaust gas treatment have been proposed but these are experimental and likely to be energy-intensive and expensive (Balcombe et al., 2019, p. 81).

## 6. Road freight

Road freight transport is a key contributor to economic development and integration, the dominant mode of transport in many regions of the world, and often the only available mode of freight transport for landlocked developing countries (Tanase, Kunaka, Paustian, & Philipp, 2016, pp. 1, 4). Road freight traffic is expected to grow significantly in developing countries; in Africa, for example, the amount of freight carried by road is expected to quadruple between 2015 and 2050 (Mulholland, Teter, Cazzola, McDonald, & Ó Gallachóir, 2018, p. 687). Globally, medium and heavy freight trucks (gross vehicle weights of 3.5 tonnes and up) are responsible for 24% of greenhouse gas emissions from transport (International Energy Agency, 2017, p. 240).

The trucking industry is decentralised and informal, dominated by small enterprises and individual owner-operators. In many developing countries, the sector is poorly regulated, few operators have formal commercial legal status, associations representing and coordinating operators are small and lack influence, drivers tend to be poorly trained, and many vehicles are obsolete or poorly maintained (Tanase et al., 2016, pp. viii, 7–8). While these features enable the sector to be flexible, and create economic opportunities due to relatively moderate barriers to entry (Tanase et al., 2016, pp. 5–7), they also make the sector difficult to engage with and influence for the purposes of decarbonisation.

**Electric vehicles:** Globally, the Energy Transitions Commission argues that electric vehicles 'will almost certainly eventually dominate' (2018b, p. 18) because they are significantly more efficient than internal combustion engines. Electric trucks are likely to become cost-competitive with

diesel or gasoline vehicles during the 2020s and cheaper than diesel in the 2030s, first being used for lighter loads and shorter trips and gradually extending to larger loads and longer trips. Battery technology is likely to dominate short- and medium-distance trucking, while hydrogen fuel cells may play a role in long-distance trucking, depending on the cost of hydrogen (Energy Transitions Commission, 2018b, pp. 18, 79, 84; Mulholland et al., 2018, p. 687). The critical challenge, however – especially in a developing country context – is to ensure rapid enough development of electric charging infrastructure and/or hydrogen refuelling stations (Energy Transitions Commission, 2018b, p. 86). In addition, zero-carbon electricity generation capacity will also be required (see section 8 below) (Energy Transitions Commission, 2018b, p. 136).

**Other fuels:** Truck engines can be designed, or in some cases modified, to use fuels such as compressed or liquid natural gas, methane from biomass or waste decomposition, biodiesel, or vegetable oil, possibly blended with conventional diesel, in order to reduce CO<sub>2</sub> emissions (Mulholland et al., 2018, p. 685). However, although using methane derived from organic waste leads to a net reduction in CO<sub>2</sub> compared with diesel, natural gas-powered and dual-fuel vehicles do not produce significantly less CO<sub>2</sub> emissions (International Energy Agency, 2017, p. 246; Robinson, 2017; Transport & Environment, 2018, p. 26). The economic competitiveness of these alternative fuels is uncertain, and fuels produced from agricultural products raise concerns about competing for scarce land and water resources with other crops (Mulholland et al., 2018, p. 685). The Energy Transitions Commission argues that globally, ‘biofuels and biogas probably will not have a significant, long-term, cost-effective role’ (Energy Transitions Commission, 2018b, p. 120), although other authors suggest that low-carbon biofuels could have a role as a ‘bridge’ from current fossil-fuel infrastructure to future low-carbon fuel infrastructure’ (Mulholland et al., 2018, p. 687).

**Shift traffic to rail or ship:** Emissions from road freight transport could be reduced by diverting freight to rail or ship, but this option is only available where the alternative modes exist and infrastructure is good quality (Energy Transitions Commission, 2018b, p. 74).

**Energy efficiency:** Globally, technical improvements to engine and drivetrain efficiencies, vehicle aerodynamics, and tyre design, as well as training drivers, limiting vehicle speeds, and reducing vehicle weights and loads, can increase energy efficiency and reduce carbon emissions (Energy Transitions Commission, 2018b, p. 76; Mulholland et al., 2018, p. 684). In a developing-country context, however, individual operators may lack the resources to upgrade their vehicles without assistance.

**Freight system optimisation:** Globally, freight systems can in principle be made more energy efficient through logistical improvements such as optimising routing, platooning vehicles, and various approaches to increasing vehicle utilisation (Mulholland et al., 2018, pp. 684–686). However, these measures require close collaboration among truck operators and significant changes to logistics systems, which would be difficult in a fragmented industry dominated by individual owner-operators (Energy Transitions Commission, 2018b, p. 74; Mulholland et al., 2018, p. 684).

## 7. Railway electrification

Rail transport is already far more energy-efficient than road and air transport, and comparable to shipping (International Energy Agency, 2019b, pp. 47–48). Railways consume 2% of transport energy use worldwide while transporting 8% of passenger traffic and 7% of freight (measured by passenger-kilometres and tonne-kilometres) (International Energy Agency, 2019b, p. 47). Shifting additional freight and passenger traffic from road and air to rail could reduce CO<sub>2</sub>

emissions from the transport sector by up to 20% (Energy Transitions Commission, 2018b, pp. 18, 74).

Most modern trains use diesel-electric power, in which the locomotive (or, in some passenger trains, each powered car) uses a diesel-powered generator to feed electric motors that drive the train's wheels. Electrified railways use electric power that is generated centrally and supplied to trains through overhead lines or third rails. Trains that can operate using both overhead electric power and conventional diesel-electric power are an established technology, and have the flexibility to travel over both electrified and non-electrified track. Trains that can switch between overhead electric lines and battery operation for short distances (up to 40 km) have been developed but are not yet commercially available, and hydrogen-powered trains are in experiment and testing stages (International Energy Agency, 2019b, p. 83).

**Overhead line electrification** has very high capital costs, and is normally undertaken only where track utilisation is very high, where high-speed passenger service is required, or in urban light rail passenger systems. Overhead line electrification is cost-competitive with conventional diesel-electric operation where train frequencies are above six trains per hour for passenger traffic, or over two trains per hour for freight traffic (International Energy Agency, 2019b, p. 84). For the purposes of decarbonisation, electrification would depend on the capacity to generate sufficient reliable low-carbon electricity (see section 8 below).

**Battery and hydrogen fuel technologies** are not currently ready for large-scale deployment. They could become cost-competitive for passenger trains if improvements to range and cost can be made, but it appears unlikely that these technologies will become cost-competitive for heavy freight transport (International Energy Agency, 2019b, pp. 84–85).

## 8. Electricity generation: electrical grids

Centralised electrical grids benefit from economies of scale, can supply the large quantities and high voltages needed by some commercial and industrial applications, are an established technology with tested business models and well-known institutional requirements, can integrate large amounts of electricity generated by renewable resources, and provide electricity at a lower retail price than other approaches to electrification (Morrissey, 2017, pp. 7, 26–27). 'All countries that have significantly increased their electrification rates in recent years', including China, Vietnam, the Philippines, and South Africa, have done so by expanding electrical grids (Morrissey, 2017, pp. 26–27).

Non-carbon-emitting sources of electricity such as solar and wind power have decreased in price to the point where 'cost is no longer the primary constraint to deploying renewables' (Avila, Carvallo, Shaw, & Kammen, 2017, p. 38). In Brazil, India, and South Africa, for example, the cost of electricity generated from solar PV and wind power systems is quite competitive with natural gas, with solar PV costs ranging from US\$47 to \$168/MWh, wind ranging from US\$32 to \$96/MWh, and combined cycle gas turbines ranging from \$70 to \$106/MWh (Lazard, 2019, p. 9). In sub-Saharan Africa, solar power is growing so rapidly that investment in solar PV is expected to exceed investment in hydropower in 2019 (International Energy Agency, 2019a, p. 33).

One of the principal challenges to grid expansion is the large up-front cost of extending the grid, especially in areas of low population density and where poverty means that power consumption will be low (Morrissey, 2017, p. 27). Institutional weaknesses such as poor regulation and management have also restricted grid development, damaged performance, and inhibited investment (Avila et al., 2017, pp. 32–33; Morrissey, 2017, p. 28). Thus, electrical grids are

poorly developed in many low-income countries. For example, sub-Saharan Africa's electrical grid has a generation capacity of 0.1 kW per capita, compared with 1 to 3 kW per capita in wealthy countries (Avila et al., 2017, p. 29).

The other main challenge is ensuring that electrical grids can cope with the intermittency and variability of solar and wind, and can rapidly change the amount of power being generated to match varying levels of demand (Avila et al., 2017, p. 38; Davis et al., 2018, p. 6). This requires a flexible and adaptive system with remote monitoring and control technologies, the ability to balance generation and consumption over large geographic areas and through regional cooperation and power sharing arrangements, and investment in 'load-following' electricity generation or storage capacity that is only used a small percentage of the time (Avila et al., 2017, p. 38; Davis et al., 2018, p. 6). Advanced monitoring and control systems are being retrofitted to existing power grids in wealthy countries, but developing countries may be able to leapfrog this challenge when designing and deploying new infrastructure (Avila et al., 2017, p. 38). Load-following generation capacity is often provided by natural gas, other fossil fuels, or hydroelectricity, and is responsible for approximately 12% of global fossil-fuel and CO<sub>2</sub> emissions (Davis et al., 2018, p. 5). The Energy Transitions Commission forecasts that it will be possible to provide reliable electricity at a price competitive with fossil fuels by the early 2030s using a mix of wind and solar, batteries, hydro, and biomass or fossil fuels with carbon capture (Energy Transitions Commission, 2018b, p. 47).

**Natural gas** power plants can change their power output rapidly and are well-suited to complementing intermittent wind and solar power generation in an electrical grid equipped with suitable sensing and control technologies without the need for additional storage (Avila et al., 2017, p. 47) and are a well-established technology. Similar power plants operating on biomass or synthetic gas, with carbon capture and storage, could in principle provide load-following capacity with greatly reduced CO<sub>2</sub> emissions, but the capital cost of carbon capture and storage is high (Davis et al., 2018, p. 6).

**Hydropower** is a well-established electrical power generation technology, where geography provides suitable conditions. Hydropower makes up 16% of electricity generation in Africa, and more than half of electricity generation in sub-Saharan Africa, but there is a great deal of untapped potential – a study by the International Energy Agency examining 12 countries found sufficient capacity to produce more than eight times as much electricity from hydropower as all of Africa currently produces (International Energy Agency, 2019a, pp. 56, 132). There is, however, also a long-term risk that droughts and increased variability in rainfall due to climate change could reduce the performance and reliability of hydropower dams (Avila et al., 2017, p. 38). For example, in 2019, Ethiopia, Kenya, South Africa, Zambia and Zimbabwe all experienced electricity price hikes, outages, or rationing as a result of low water levels in hydropower systems (International Energy Agency, 2019a, p. 63).

**Dual fuel operation:** Some electricity generation plants are designed to be able to operate using more than one fuel, for example being able to switch between gas and oil, or gas and coal. Dual-fuel power plants offer flexibility in case the availability of one of the fuels is insecure, the preferred fuel is not yet available but is expected to become available in the future, or fuel prices change significantly, depending on local circumstances, and can be a step in transitioning from one fuel to another (Faquiri, 2016; U.S. Energy Information Administration, 2019; Wärtsilä, n.d.). For example, a new power plant to be constructed in 2019-2020 in Cambodia will operate on heavy fuel oil initially with the ability to switch to liquefied natural gas when the local gas distribution infrastructure is complete (Akella, 2019), while a power plant to be constructed in

Nigeria in 2019-2020 will use natural gas as its primary fuel with the ability to switch to oil as a backup (Power Engineering, 2019).

**Nuclear** power plants can vary their output to follow demand, but are normally operated at a constant high output because their high capital cost makes it important to maximise revenue (Davis et al., 2018, p. 6). South Africa is currently the only country in Africa using nuclear power (6% of generating capacity in 2018) and nuclear power is not likely to be deployed elsewhere in Africa in the near future (International Energy Agency, 2019a, pp. 125, 142).

**Batteries** are widely used for short-term and relatively low-capacity storage, but currently available technologies have prohibitively high capital costs for grid-scale applications that store large quantities of energy and cycle infrequently. The cost of storing electricity using current lithium-ion battery technology can be between 4 and 14 times as expensive as generating it, although new technologies are being investigated, such as batteries using sulphur, that may have the potential to bring down costs in future (Davis et al., 2018, p. 6).

**Pumped-hydro storage:** Water can be pumped from one reservoir uphill into a second reservoir for later release through a hydroelectric generator. This is a cost-effective and technologically mature option for storing large quantities of energy with high round-trip efficiency (>80%). Capital costs are substantial, but the cost of the generated electricity is competitive. Such systems are only feasible where geography provides suitably-located reservoirs and sufficient water is available. There can also be social and environmental opposition, and timing of water release can be affected by other considerations such as flood protection and agricultural needs (Avila et al., 2017, pp. 46–47; Davis et al., 2018, p. 6).

**Compressed air storage:** Electricity can be stored by compressing air in underground rock formations, underwater containers, or above-ground pressure vessels. When power is required, the compressed air is released through a turbine, recovering 75% or more of the energy stored (Davis et al., 2018, p. 6). The cost of such systems is comparable to an equivalent gas-powered generating plant where geography permits (Avila et al., 2017, p. 47).

**Thermal storage** systems store energy in large masses of material such as water tanks, bricks, or molten salt, or they may use other chemical transformations. They tend to have low energy densities, low efficiency, and high costs. 'Thermal storage is well suited to within-day shifting of heating and cooling loads, but not to longer-term or larger-scale electricity generation' (Davis et al., 2018, p. 7).

**Flywheel storage** uses a massive wheel, spinning the wheel faster to store energy and slowing it to release energy (Avila et al., 2017, p. 47). This technique is fairly novel, and was used for the first time in a grid-connected system in 2014 in Canada although it has been used on a smaller scale (off-grid) in other circumstances, including a micro-grid in Marsabit, Kenya (Kenning, 2015).

**Chemical storage** of energy in gas or liquid fuels includes is a flexible but currently low-efficiency method of storage. Hydrogen, in particular, can be created through electrolysis and converted back to electricity in fuel cells or burned in gas turbines. Fuel cells are 40-50% efficient but usually rely on expensive materials as catalysts, although various substitutes are being explored. Commercial-scale systems for creating and then burning hydrogen produce a round-trip efficiency of 30% or more (Davis et al., 2018, p. 6).

**Energy efficiency and demand management** techniques may be able to play a role in reducing grid capacity requirements and improving reliability of supply. Consumers may, for example, be incentivised to operate power-consuming equipment at different times of day to match generating

capacity, such as aiming to coincide operations with peak solar generating capacity or reduce power consumption when generating capacity is low (Avila et al., 2017, p. 46; Davis et al., 2018, p. 7).

**Carbon capture** technologies under development may have a role in other industries, but due to dramatic reductions in the cost of renewables in the past decade, it seems unlikely that carbon capture will have a large role in the power sector (Energy Transitions Commission, 2018b, p. 26).

## 9. Electricity generation: back-up generation and mini-grids

Backup generators provide power in areas where no main grid connection is available or where grid power is unreliable. Most backup generators are used by businesses; most households cannot afford them (International Energy Agency, 2019a, vols. 63, 265). Backup generators are fuelled by diesel oil, heavy fuel oil, or petrol and are relatively low-capacity (a few kilowatts) but are so widespread and so frequently necessary in Africa (for example, in Nigeria 85% of firms have one) that they account for approximately 8% of total electricity generation (International Energy Agency, 2019a, pp. 63, 265). Backup generators are noisy, contribute significantly to emissions of CO<sub>2</sub> and other pollutants, and pose significant risks of fire, respiratory illnesses, and carbon monoxide poisoning (Avila et al., 2017, p. 32; International Energy Agency, 2019a, p. 63). They are inefficient and expensive, with the power they generate costing about three times the price of electricity from the grid (Avila et al., 2017, p. 31).

Mini-grids<sup>3</sup> are small-scale power generation and distribution systems located close to the point of consumption, and can be either independent of a centralised electricity grid or coupled to it. These systems are able to reach poor and remote populations relatively quickly and cheaply, typically use renewable energy sources and have low carbon emissions, and typically bypass national utilities, creating opportunities for private sector operators (Avila et al., 2017, p. 51; Morrissey, 2017, pp. 23–31). Although they are relatively small scale, they can generate sufficient electricity for commercial and industrial applications, and are modular so they can be expanded as demand for electricity increases (Morrissey, 2017, p. 31). Although they are usually stand-alone systems independent from the electricity grid, they can also be used by grid-connected consumers to compensate for problems with grid supply (Morrissey, 2017, pp. 30–31). Mini-grids are typically privately owned and operated, with investment from sources including donors, private investors, or government sources, although some are operated by public utilities or use hybrid operating models (Avila et al., 2017, p. 54).

Mini-grids most often use solar PV as their energy source, but they may incorporate wind or small-scale hydropower where conditions allow (Morrissey, 2017, pp. 30–31). Renewable sources are increasingly affordable for use due to rapid construction timelines, falling prices of solar and wind technologies, improving battery storage technologies, and ICTs that support remote operation, billing and customer services, and mobile phone payment systems (Avila et al., 2017, p. 54). To cope with intermittency, they are often built as hybrid systems incorporating natural gas, biogas, or diesel generation (Avila et al., 2017, p. 52; Morrissey, 2017, pp. 30–31)

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<sup>3</sup> Various authors use terms such as mini-, micro-, or nano-grids to describe systems of various sizes; the term 'mini-grid' is used here for all such small-scale electricity generation and distribution systems.

although 'expert advice has begun to suggest eschewing hybrid systems in favour of purely PV generation, despite the increased costs' (Morrissey, 2017, p. 37).

The initial capital cost for a mini-grid is significantly lower than for extending the main electrical grid, but is still a large investment for small entrepreneurs in many developing countries. Mini-grids require storage in the form of batteries, which are expensive, they cannot take advantage of economies of scale, maintenance costs can be high in remote locations, and their successful operation requires significant economic, financial, and technical skills (Morrissey, 2017, pp. 31–32). Thus, the retail cost of electricity from mini-grids is higher than that from the grid (Avila et al., 2017, p. 54; Morrissey, 2017, p. 33). Costs can be reduced by keeping the system small at first and expanding incrementally, integrating residential and commercial demand, and finding a so-called 'anchor tenant' consumer that can provide a relatively secure level demand (Morrissey p. 35-36).

The main challenge facing mini-grids is high regulatory uncertainty about their role in relation to the central grid, if and when the central grid is expanded. Investors would be more willing to invest if mini-grids were assured of eventually being able to connect to the central grid and serve a role within it, which would require a long-term regulatory framework for mini-grids (Avila et al., 2017, p. 55). Other challenges include a lack of installers, technicians, and trainers, and the fact that mini-grids are a relatively new technology operating in a risky business environment with unknown consumer characteristics, weak institutional arrangements, non-supportive regulatory and policy frameworks, and limited access to finance (Morrissey, 2017, p. 34).

**Solar home systems** are smaller-scale approaches to supplying electricity to individual households, typically in remote areas, that are too dispersed to be connected through mini-grids. They have limited capacity, sufficient only for lighting, ICTs, entertainment, and cooling, and electricity from solar home systems is more expensive than electricity from the grid or mini-grids (Morrissey, 2017, p. 7).

**Solar appliances and pico-solar systems** are even smaller PV systems that can supply power for minimal-load applications (up to 10 watts) like lighting and mobile phone charging. They offer a replacement for light sources such as kerosene lamps and candles (Avila et al., 2017, pp. 52–53). The cost of all of these systems has dropped over the past decade due to decreases in manufacturing and materials costs for PV panels, and the utility of low-power solar panels has increased due to improvements in energy-efficient appliances and light bulbs, particularly light-emitting diodes (LEDs) (Avila et al., 2017, p. 53). Mobile phone banking has also facilitated instalment payments and pay-as-you-go business models (Avila et al., 2017, p. 53).

The table below summarises the strengths and challenges of generating and distributing electricity via centralised electrical grids, mini-grids, or local off-grid systems.

**See: Strengths and challenges of four approaches to electricity generation and distribution**, Source: Morrissey, 2017, p. 30, <https://s3.amazonaws.com/oxfam-us/www/static/media/files/oxfam-RAEL-energySSA-pt2.pdf>

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