Energy transition

BRIEFING NOTE

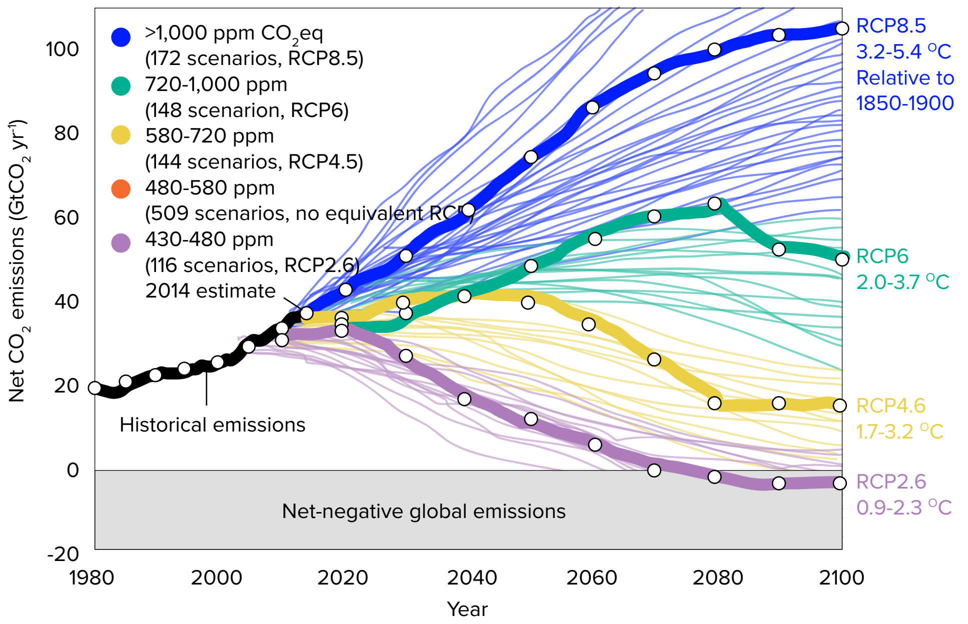
Summary

- The energy sector is the biggest source of anthropogenic greenhouse gas emissions globally.
- To meet the climate goals of the Paris Agreement, the reliance on fossil fuels needs to stop.
- The task of transitioning to cleaner energy sources is herculean, but feasible.
- The technology exists, costs have plummeted, and capacity is rapidly being expanded.
- Clean electricity will be the backbone of energy transition.
- Hydrogen and batteries will be important in both storing and distributing energy.
- Carbon capture technologies will be required to deal with remaining emissions from hard-to-abate sectors.

Scale of the challenge

- Limiting the global temperature rise to less than 2°C requires that:
  - Global emissions of greenhouse gases (GHGs) start falling immediately;
  - The decline be maintained until around 2070; and
  - Thereafter emissions become negative i.e. that greenhouse gases thereafter be removed from the atmosphere. (See Intergovernmental Panel on Climate Change scenario RCP2.6 in Figure 1 below).
- **The reality so far is not following the required path.** Although global fossil CO_2 emissions declined by about 7% year-on-year in 2020 (i.e., by around 2.4 $GtCO_2$ to 34 $GtCO_2$),[1] this performance was anomalous, being due to the dramatic fall in activity worldwide as a result of economic lockdowns in response to the global COVID-19 pandemic. Emissions are set to recover strongly in 2021.
  - To meet the targets outlined in the Paris Agreement, emissions need to fall by 1–2 $GtCO_2$ every year throughout the 2020s and beyond.[2]
  - The Climate Action Tracker calculates that, on current policies, the world is headed towards a **2.9°C warmer climate by the end of the century.**[3] The recently-upgraded net-zero commitments from the US, China, and the EU are noteworthy and, if implemented, stand to lower the trajectory of warming: but these pledges need to be backed up by action near-term.

Figure 1: IPCC Representative Concentration Pathways

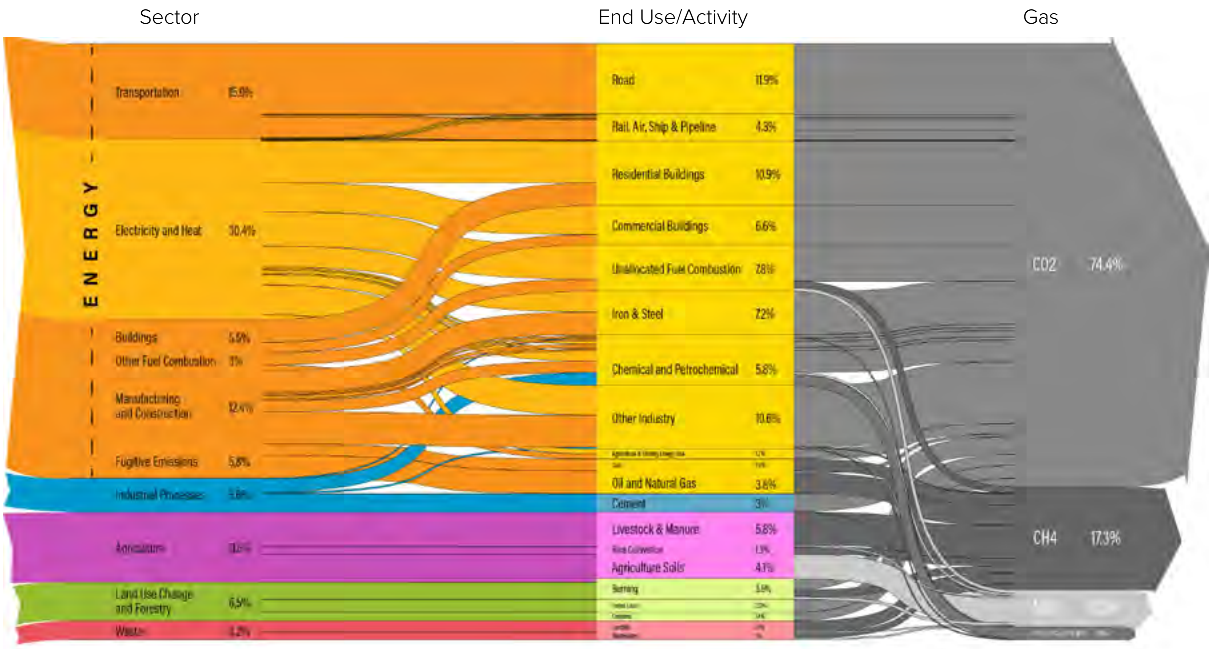


Source: IPCC

- **Geographically, GHG emissions are highly concentrated,** with the ten largest emitters accounting for over two-thirds of the global total.[4]
  - The challenge is particularly acute for the top three emitters, which collectively are responsible for nearly half of all global emissions: China (26% of the total), the US (13%), and the EU (8%).[5]
  - Moreover, the emissions from China and India are both set, on current trajectories, over the coming three decades.[6] to double
- As regards sectors, **the energy sector is by far the biggest source of anthropogenic GHG emissions globally,** accounting for about **three-quarters of total emissions** (Figure 2).[7]

Figure 2: Main emitters globally by sector, end use/activity, and gas

World Greenhouse Gas Emissions in 2016 Total: 49.4 GtCO2e



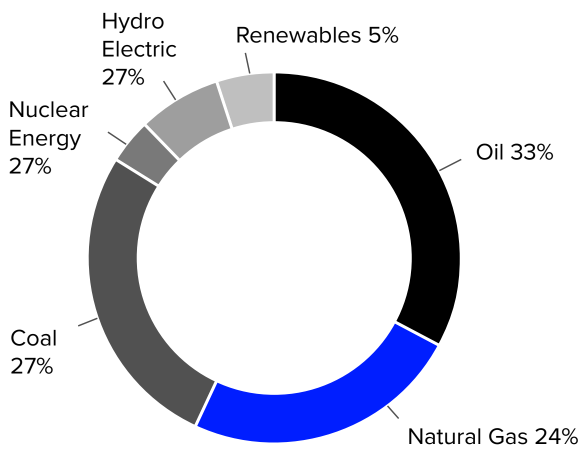
Source: World Resources Institute

Limiting global warming to less than 2°C is, therefore, critically linked to:

1. **How much energy is being used,** and crucially,
2. **How this energy is being generated.**

- In 2019, **fossil fuels accounted for 84% of all energy consumed globally** (Figure 3). **Only 16% came from carbon-neutral sources,** i.e. renewables (solar, wind, geothermal, biomass), hydro, and nuclear power. These relative proportions have to be broadly reversed by 2050 if the Paris targets are to be within reach.[8]
    - The phase-out of coal is a critical priority, with China alone accounting for about half of global production and consumption.[9]

Figure 3: Primary energy consumption by fuel, 2019



Source: http://www.bp.com/statisticalreview

Energy transition

Energy transition, i.e. shifting the global energy sector from fossil-based systems of energy production and consumption — including oil, natural gas, and coal — to renewable energy sources, notably wind and solar, implies **a profound transformation of the global energy system** and is **crucial to addressing the climate crisis.**

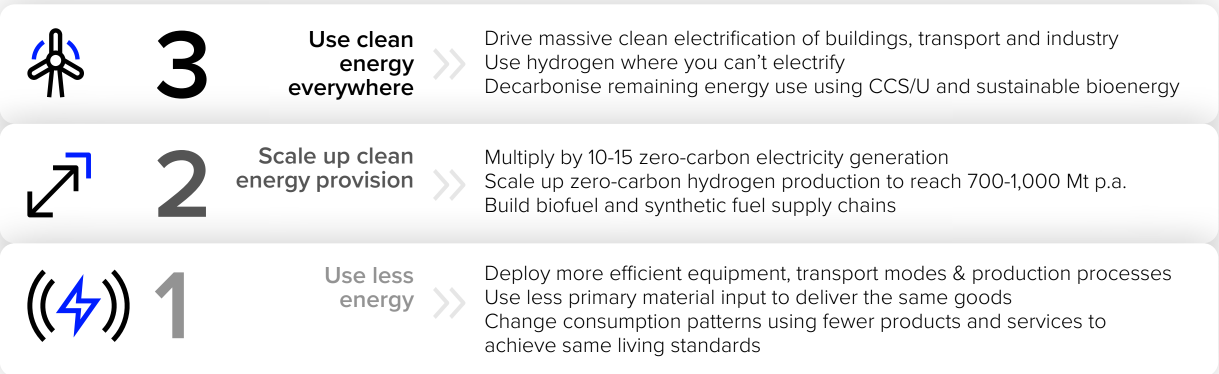
- Reaching net-zero emissions by mid-century is a formidable challenge; it is, however, **technically and economically feasible** – most of the technology already exists, the investment needed is manageable, and the minor loss to incomes in the aggregate would be far outweighed by benefits to health and biodiversity.
- **Clean electricity will be the backbone of energy transition, complemented by some sustainable biomass, and limited use of fossil fuels in hard-to-abate sectors, combined with carbon capture, utilisation and storage** (CCUS).
  - Both hydrogen and batteries will be important in the storage and transportation of renewable energy.
  - All this will involve a shift to new business models and consumption patterns, and will require a careful and fair management of the employment and income consequences.

The **three key steps** in transitioning to net-zero energy provision are summarised in Figure 4: [10]

1. Use less energy.
2. Scale up clean energy provision.
3. Use clean energy everywhere.

Figure 4: Summary of energy transition framework

3 steps to a net-zero-emissions economy



Source: Making-Mission-Possible-Executive-Summary-English.pdf (energy-transitions.org)

1. Use less energy

Reducing energy use through optimisation and/or lifestyle changes **will have to be the foundation for energy transition,** and will determine the final energy demand that needs to be met from sustainable sources.

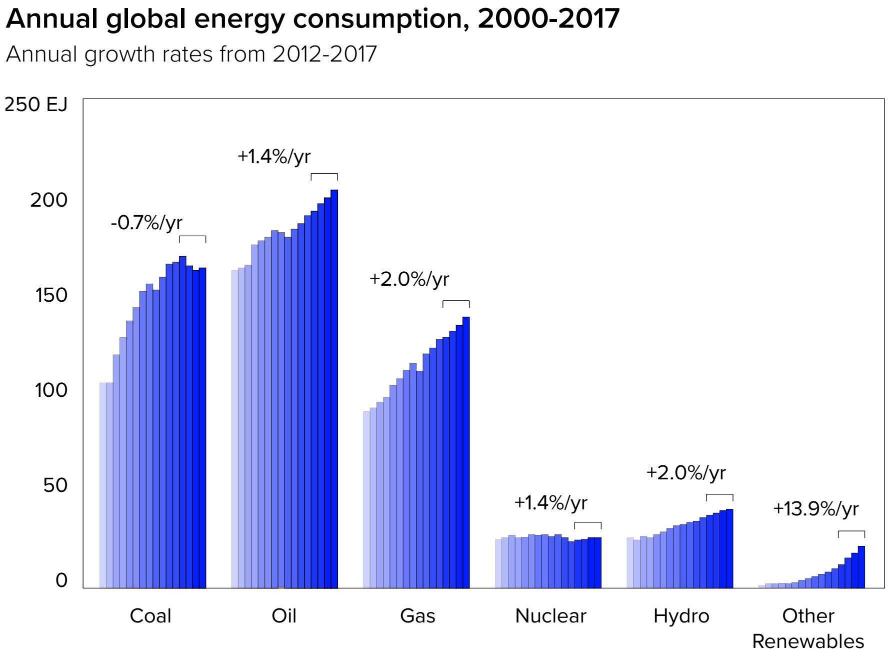
- In the IEA Sustainable Development Scenario, energy efficiency represents more than 40% of the emissions abatement needed by 2040.[11]

- **Energy efficiency** can be improved in many sectors (e.g., more fuel-efficient aircraft/cargo vessels, long-haul trucking; buildings, etc).
  - IEA analysis estimates that through using the technology already available, energy efficiency could be improved by more than 12% compared with global electricity consumption in 2018.[12]
  - In the transport sector, improvements of up 50% are in principle possible; while in industry, improvements of 10-20% could be achieved.[13]
- **Material efficiency advances** could be particularly important for the hard-to-abate sectors, including steel and cement, via product redesign, greater use of recycled inputs in a 'circular' economy, and the use of alternative materials.
- **Lifestyle changes** can offer incremental, but collectively significant, gains e.g. travelling less, and by train, or in electric cars; using heating and/or air conditioning less; eating less animal protein, etc.
- **Digital technologies** are proving constructive in transforming the energy landscape and creating invaluable efficiency solutions. Examples include:[14]
  - Enabling energy savings in many sectors, from construction to manufacturing (e.g., 3D printing, light-weighting).
  - Improving the monitoring of, and responses to, efficiency losses across sectors (e.g., industrial energy efficiency monitoring, automated alarms, load management in logistics).
  - Improving energy demand monitoring and management at the energy system level (e.g. increasing grid flexibility; limiting energy production and distribution losses; optimising building heating/cooling).
- Taken together, the potential to reduce energy needs, and thereby to reduce the costs of the energy transition, is significant: **energy demand could be up to 15% lower by mid-century than it is today without compromising improvements in living standards in developing economies**.[15]

2.Scale up clean energy provision and storage

- Decarbonisation requires a major shift from carbon-intensive fossil fuels to clean energy. The elimination of GHGs will have to involve primarily the **displacement of hydrocarbons by electricity, produced from renewable sources,** and used:
  - **Directly** as the energy source in most processes and end-use activities;
    or, where it cannot be direct, such as in some branches of transport or heavy industry,
  - **Indirectly,** whether via **hydrogen or batteries.**
- Renewable energy provision has been growing exponentially over the past decade, but its share is still much too low to offset the growth in fossil fuel energy consumption (Figure 5).

Figure 5: Annual global energy consumption, 2000-19



Source: Global Carbon Budget 2017 (globalcarbonproject.org)

- It is highly speculative to forecast the precise **global energy mix of the future,** but all feasible scenarios for a zero-carbon emissions economy involve:
  - A massively expanded role for **direct electricity** use (reaching **65-70% of final energy demand),** and
  - A significant expansion of the role of **hydrogen** (accounting for another 15-20% of the final energy demand (and itself perforce produced from renewable electricity).[16]

2.1. Direct electrification

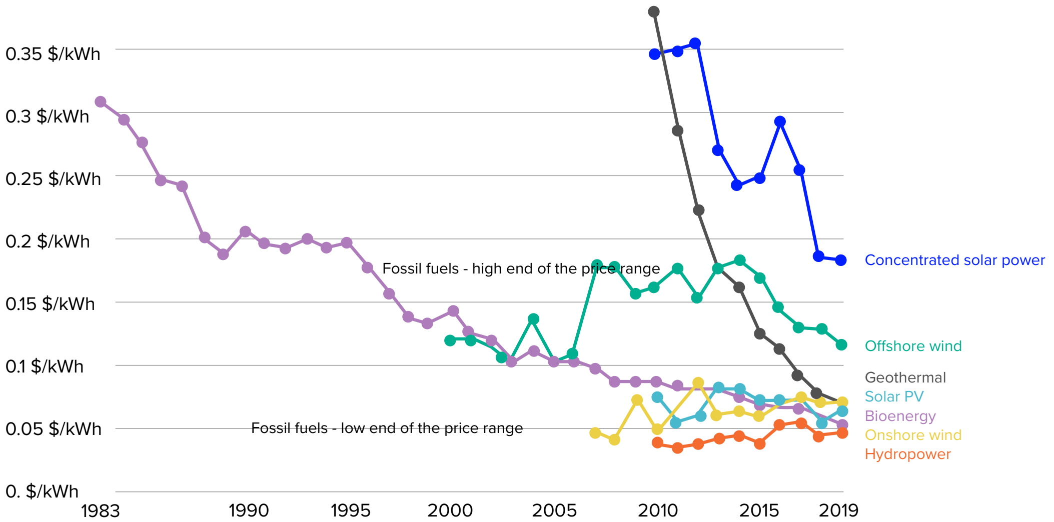
- **Direct electrification is the cheapest and most energy-efficient option in most applications,** so **scaling up zero-carbon electricity** (e.g., solar, wind, hydro, biofuels, nuclear) **provision is the most important priority.** Sustainably-sourced biomass-based energy will supplement this, but only to a limited extent.
- To make the required energy shift to zero-carbon energy sources, **annual global electricity supply will have to expand by a factor of 4 to 5**, to reach ~90-115,000 terawatt-hours (TWh), with all of this electricity produced in a zero-carbon fashion.[17]
  - For this to be feasible, renewable power investment will need to be scaled up markedly: some estimates suggest that over the coming 30 years the **average annual pace of wind and solar capacity increases will need to be about 5 to 6 times that achieved in 2019.**[18]
- With the expansion of capacity, the **costs of renewable energy have come down dramatically** (Figure 6). In many countries, renewable electricity costs are already below total costs of new coal or gas plants and in some cases below the marginal cost of existing thermal plants; and as renewable capacity costs continue to fall, their cost advantage will become increasingly significant.[19]
  - **Solar.** Solar PV module prices have fallen by around 90% since the end of 2009.[20] The world's best solar power schemes are now the "cheapest source of electricity in history", according to the International Energy Agency (IEA).[21]

- **Wind.** The cost of electricity from wind continues to fall, driven by declines in wind turbine prices – by 55-60% since 2010.[22] Deep ocean windfarms promise a breakthrough in tapping wind resources further offshore, where winds are both steadier and higher than those onshore. A small increase in wind speed produces disproportionately large increases in energy output.[23]
- **Hydro.** Hydropower has historically been the backbone of low-cost electricity in a number of countries and, where the requisite resources exist, it is often the cheapest way to generate electricity. But in general the best options have now been exploited, and the potential for cost reduction is small, generally limited to improvements in civil engineering techniques and processes.[24]
- **Nuclear.** As of the end of 2019, nuclear power reactors provided approximately 10% of the world's total electricity, and nearly 40% of its low-carbon electricity.[25] Next-generation nuclear aims to address the various safety, sustainability, efficiency, and cost issues that afflict older reactors, many of which are scheduled to be shut down in the coming years. But implementation is probably a decade away.
- **Biomass.** This can be used in a variety of applications, including industrial heat, chemical feedstock, flexible thermal power supply, and transport fuels. But its future use must reflect the limited potential supply of truly sustainable biomass. Biomass-based energy should, therefore, be seen only as a supplementary source.

Figure 6: Levelised cost of energy

Levelised cost of energy by technology, World

Levelised cost of energy (LCOE) estimates the average cost per unit of energy generated across the lifetime of a new power plant. It is measured in 2019 US$ per kilowatt-hour.



Source: Levelized cost of energy by technology, World (ourworldindata.org)

- Cost competitiveness is reflected in deployments in 2019, where **renewables accounted for 72% of new capacity additions worldwide.**[26]
- The crucial issue today is therefore no longer t**he cost of generating renewable electricity, but rather the cost of balancing supply and demand in systems with very high levels of variable renewable supply.** A mix of existing and new approaches, particularly in terms of storage – from batteries to hydrogen to compressed air – can help with day-to-day and seasonal load balancing.
- Technological advances are also set to improve the efficiency of **grid management.**
  - Decentralised or 'smart grids', i.e. localised energy networks based on the principle of bringing supply closer to demand, are being trialled, but are yet to have wider application.
- **Where direct electrification is not feasible, hydrogen fuel cells and/or batteries may provide a solution.**

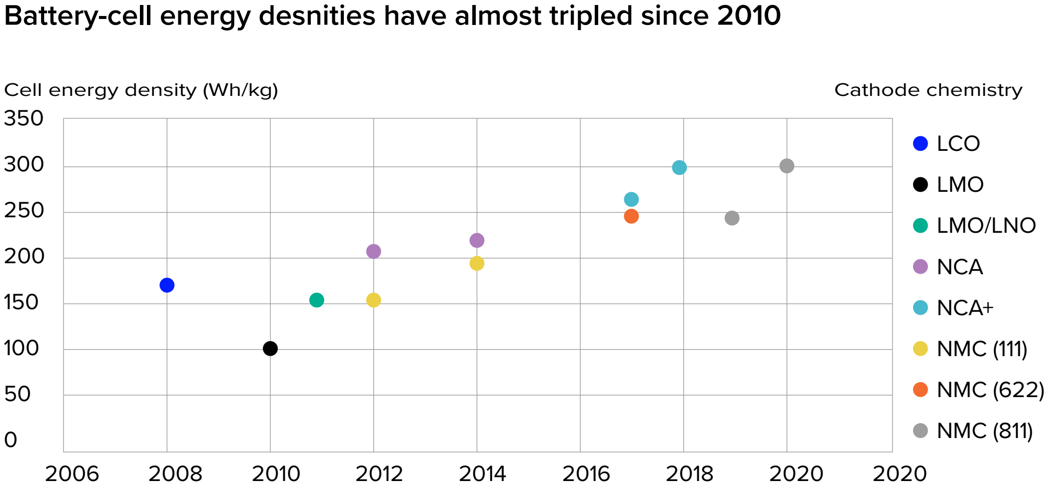
2.2. Hydrogen

- **Hydrogen (H_2),[27]** is an odourless, colourless, tasteless, combustible gas that occurs naturally. But to be useable in quantity it has to be manufactured, in either of three principal ways: electrolysis;[28] coal gasification;[29] or pyrolysis.[30]
  - **Green hydrogen',** i.e. produced with electricity from renewable sources, **currently represents only about 1% of total world production** of hydrogen.
  - **'Blue' and 'Grey'** hydrogen however are produced from, and using, hydrocarbons, and hence cannot be part of the long term energy solution.
- Hydrogen is an energy carrier whose energy density, storability, and suitability for high-heat applications make it superior to electricity in some specific applications.
  - It can also be used to produce hydrogen-based fuels (e.g., ammonia and synfuels).
- To meet the future demand for hydrogen, ammonia, and synfuels in end-use applications, **total annual hydrogen production will need to increase between 8- and 13-fold,** from about 60 million tonnes (Mt) today to 500 to 800 Mt by mid-century.[31]
- The key issue is that **'green' hydrogen is not cost competitive today** with fossil-based hydrogen, fossil fuels, and some renewables. Representative costs:
  - Renewable (green) hydrogen: 2.5-5.5 €/kg.[32]
  - Fossil-based hydrogen: around 1.5 €/kg in the EU, although this figure is highly dependent on the prices of natural gas, and excludes the cost of sequestering the CO_2 produced in the process.
  - Fossil-based hydrogen with CCUS sequestering: around 2 €/kg.
- With expanded future capacity and technological advances, **costs are however likely to fall.** A key driver for hydrogen cost competitiveness stands to be the size of the tax on emissions of carbon, together with the evolution of renewable energy, and electrolyser costs.
  - Electrolyser costs have already fallen by around 60% in the last ten years, and economies of scale are expected to lead to a further halving by 2030.[33] In regions where renewable electricity is cheap, electrolysers are expected to be able to compete with fossil-based hydrogen by 2030.

2.3. Batteries

- Thus the key issue is increasingly not the feasibility of generating cost-competitive renewable electricity, but rather **the issue of intermittency** (i.e., the sun doesn't always shine, the wind doesn't always blow).
- **Developing better and cheaper electricity storage is a major challenge.** According to the IEA, for the world to meet climate and sustainable energy goals, close to 10,000 gigawatt-hours of battery and other forms of energy storage will be required worldwide by 2040, i.e., 50 times the size of the current market.[34]
- Technical progress and mass production have led to a **significant drop in battery prices** in recent years: Lithium-ion batteries for electric vehicles, for example, have fallen by nearly **90% since 2010.**[35]
  - There is scope for more: Tesla has announced the feasibility of technological innovation that would cut its battery costs by more than half.[36]
- At the same time, **battery-cell energy densities have almost tripled** since 2010 (Figure 7).
- Finally, **demand management, e.g.**, via optimal timing of electric vehicle (EV) charging is also important.

Figure 7: Battery-cell energy densities



Source: BloombergNEF

3. Use clean energy everywhere

The above technologies would make it technically possible to reach net-zero emissions in most economic activities by mid-century, with the exception of agriculture and some particularly hard-to-abate sectors (notably steel, cement, long-haul aviation, and shipping).

- In many sectors, direct electrification will dominate, being the most efficient and cost-effective solution. In industry and buildings, however, a mix of solutions will most likely have to be used.
  - Sectoral energy shifts will also depend on the local availability of renewable resources and costs.

Road transport[37]

- Today, nearly all energy consumption of the transport sector consists of fossil fuels. Looking ahead, the main decarbonisation pathways are relatively clear:
  - **Battery electrification** is likely to dominate, particularly in the light-duty vehicle segment.
  - For medium and heavy-duty vehicles, decarbonisation will likely entail either battery-based electrification or use of **hydrogen** in fuel cell electric vehicles.

Aviation[38]

- That aircraft have to lift their fuel into the air and carry it with them puts a premium on energy/weight density.[39] There are currently no close substitutes for high-energy-density hydrocarbons.
  - **Hydrogen** could be part of the solution (particularly for short flights), but not in the near term.[40]
  - **Mixing aviation and biofuels** has also been suggested as a way to lower the sector's emissions, but the heavy demands on land use make it unsustainable at the scale required.[41]

Shipping[42]

- Like aviation, shipping is another 'hard-to-abate' sector, and many ships currently use particularly 'dirty' fossil fuels, notably heavy fuel oil.
  - **Many technical and operational efficiency measures,** such as slow steaming,

weather routing, contra-rotating propellers, and propulsion efficiency devices, can deliver more fuel savings than the cost of the required investment. Maximum deployment of currently-known technologies could almost wholly decarbonise maritime shipping by 2035. This reduction would be equivalent to eliminating the emissions of approximately 185 coal-fired power plants.[44]
- **Cleaner fuels.** Biofuels and liquefied natural Gas (LNG) have been proposed as alternative fuel sources. However, LNG delivers, at best, only up to a 10% reduction of GHGs compared with (the replaced) diesel fuel. Hydrogen is also being considered as a potential alternative.[45]
- There are also some promising developments of fairly large-scale wind-power use, including possibly supplementation from wind power.

Manufacturing

- Manufacturing is heavily reliant on hydrocarbons for motive power, heating, etc. Energy transition solutions include:
  - **Increased manufacturing and energy efficiency and accuracy** (e.g. automation, big data, etc) and expanded use of alternative materials (e.g., wood and wood-based solutions instead of steel, aluminium in construction)[46] to reduce final energy demand of the sector.
  - **Electrification** (with clean-energy sources) of manufacturing sub-sectors with low-and medium-temperature heat requirements (e.g., food, textiles).
    - Where electrification is more challenging – i.e. in **processes with high-temperature requirements** (notably iron, steel, cement, aluminium),[47] a combination of clean energy sources (particular hopes are placed on green hydrogen) and carbon capture is likely to be used to remove both energy-based emissions and emissions resulting from the chemical processes themselves. Electric arc furnace (EAF)-based production of steel – which uses steel scrap or direct reduced iron (DRI) as its main raw material – is a potential approach, but at present is not scalable.[48]

Buildings

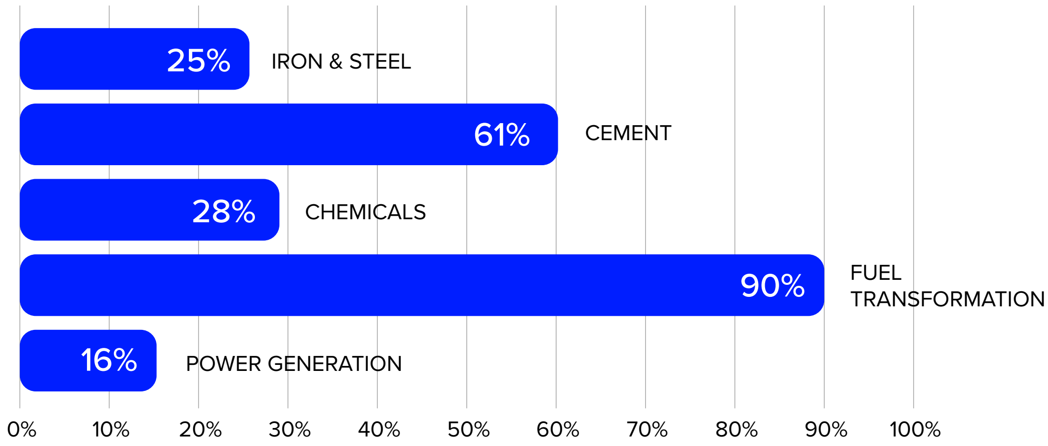
- Space heating/cooling and the heating of water are the primary contributors to emissions. Improving energy efficiency through retrofitting will need to be the first point of call. Meeting the goals of the Paris Agreement will require that buildings improve in energy intensity by 30-50% per square metre.[49]
  - **Heat pumps** using electricity from renewables will in many cases be the single most efficient technology for heating and cooling.[50] Heat pumps are already an established technology in many countries.
  - Blending (green) **hydrogen** into gas grids can offer alternative solutions. **Biogas** may be preferable to natural gas, but it produces carbon dioxide when burned, and so at best can be a transition technology.
  - **District heating** is feasible in densely populated areas, and waste heat is sometimes available from large-scale processes.

Carbon capture

To the extent that it is **not possible fully to decarbonise all activities,** it will be necessary also to implement **Carbon Capture Usage and Storage (CCUS)** technologies.[51] A 1.5oC to 2oC world cannot be achieved without some deployment of CCUS.

- The **26 CCUS projects already in operation** have the capacity to capture and permanently store only around 40 million tonnes of CO_2 per year[52] – a miniscule amount compared with the 34 giga tonnes of CO_2 emitted annually, and compared with what is needed to meet the IPCC targets.
- In the IEA's Sustainable Development Scenario, **the mass of CO_2 captured using CCUS rises to around 5.6 giga tonnes in 2050 – a more than 100-fold increase.** Its contribution is significant, accounting for between 16-90% of emissions reductions in various 'hard-to-abate' sectors (Figure 7).
    - The deployment of CCUS to date has been hampered by high costs, inadequate infrastructure, and inappropriate policy frameworks.
- Finally, by 2070 it will be necessary to have in place a technology or technologies that can remove GHGs directly from the atmosphere (so-called 'Direct Air Capture').
    - Such technology exists, but would need to be scaled up dramatically to make any meaningful difference.

Figure 7: Contribution of CCUS to sector CO_2 emissions reductions up to 2070



Source: Global-Status-of-CCS-Report-English.pdf (globalccsinstitute.com)

Note: Fuel transformation covers sectors such as refining, biofuels, and merchant hydrogen and ammonia production

Policy

For these changes to occur fast and efficiently, all economic agents must face **appropriate incentives** – a **carbon price plus regulations** – in all countries, including especially China and other large emitters.

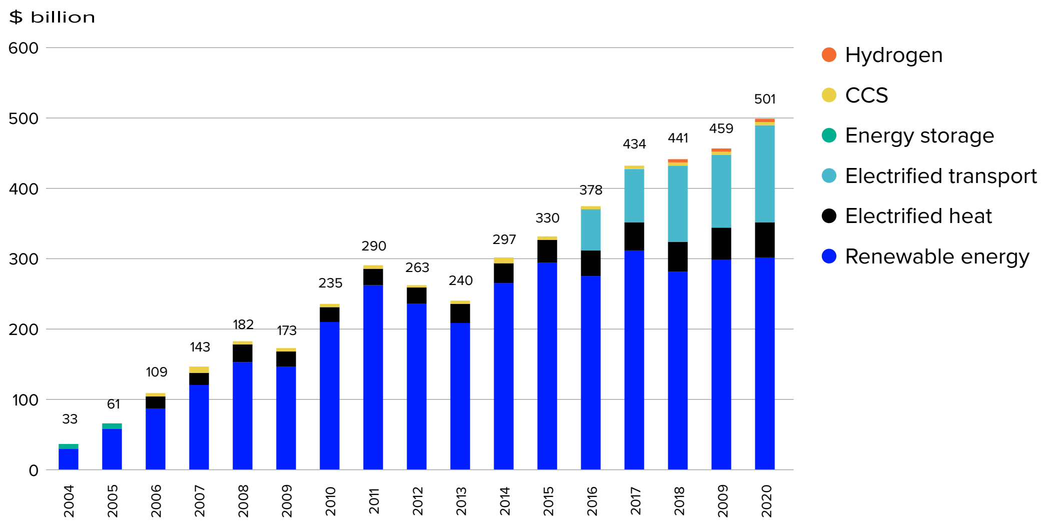
- **Removal of remaining fossil fuel subsidies, i**ntroduction of explicit **carbon pricing mechanisms,** and applying the **'polluter pays'** principle across all sectors should be the priority.
  - To avoid international competitiveness issues, **carbon border tax adjustments** are necessary.
  - For a fair global transition, the **developing countries would have to be compensated,** out of the tax receipts in the developed countries.
- In sectors, where carbon prices are likely to be insufficient to trigger a shift in investment and purchase decisions, governments should set up **standards and regulations** to determine explicit targets, increase market certainty, and thereby facilitate investments.[53] These could include:
  - GHG emissions standards, renewable energy or fuel mandates, and eventual bans on the most carbon-intensive products.
  - Net-zero building codes, energy performance ratings.
  - Minimum energy performance standards for industrial equipment, etc.
  - The **most effective approaches** tend to c**ombine carbon pricing, regulations, and incentives.**
- The right financial incentives can trigger very quick take-up, as shown by Norway where the majority of new cars sold are emissions-free.

Investment

Getting to a zero-carbon-emissions world requires a major transformation of how economies are powered. Accordingly, transitional costs will be unavoidable, and therefore will need to be accepted.

- The Energy Transitions Commission estimates that **the required additional annual investments will be around 1-1.5% of global GDP** (about US$1-2 trillion per year).[54]
  - This is affordable, especially at present given the unusually high level of savings globally and commensurate low interest rates.
- **Money is already moving in the right direction.** A new, broad measure of 'energy transition investment', compiled by BloombergNEF (BNEF), finds that globally a record sum of over $500 billion was committed to decarbonisation in 2020, up by 9% on the year – and this notwithstanding the economic disruption caused by the global pandemic (Figure 8).[55]
  - Total investment in energy transition has grown nearly 10-fold in the past 15-odd years.
  - BNEF's analysis finds that companies, governments, and households invested just over $300bn in new renewable energy capacity in 2020, up by 2% on the year (boosted by the biggest-ever build-out of solar projects and a $50bn surge for offshore wind). Nearly $140 billion was spent on electric vehicles and associated charging infrastructure, up by 28% and a new record.[56]

Figure 8: Global energy transition investment, 2004-20



Source: Energy Transition Investment Hit $500 Billion in 2020 – For First Time I BloombergNEF (bnef.com)

- Finally, and critically, **investment in mining the minerals and metals that are needed for batteries, solar panels, and wind turbines** (e.g. lithium, cobalt, copper, rare earth minerals) that are central to the energy transition **needs to accelerate significantly.**
    - For the Paris climate targets to be feasible with new clean technologies, **mineral demand is likely to quadruple by 2040.**[57]
    - Raw materials used in batteries are likely to see the biggest increase in demand, with the **demand for lithium set to grow by a factor of more than 40.**[58]
- At present, the lack of investment in new mines may well lead to prices of these commodities rising considerably further from their already elevated levels. Copper, for example, is already trading at close to record highs (Figure 9).

"Today, the data shows a looming mismatch between the world's strengthened climate ambitions and the availability of critical minerals that are essential to realising those ambitions." [59]

Figure 9: Copper price

Source: Macrobond

- Wider deployment of clean technologies is also likely to bring **new energy security challenges.**
  - China at present **dominates the rare earth industry** (used in the manufacturing of a wide range of high-technology products and defence systems), accounting for about **60% of global production,** well ahead of the US in second place at just over 15%.[60]
  - The rare earths, which are used in making magnets, e.g., neodymium, have seen sharp price rises in the past few months, driven principally by demand from the electric vehicle sector.

Useful sources

*Making-Mission-Possible-Full-Report.pdf (energy-transitions.org)

World Energy Transitions Outlook: 1.5OC Pathway (irena.org)

Global Carbon Budget 2017 (globalcarbonproject.org)

IEA – International Energy Agency

The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA

[1] https://www.carbonbrief.org/global-carbon-project-coronavirus-causes-record-fall-in-fossil-fuel-emissions-in-2020

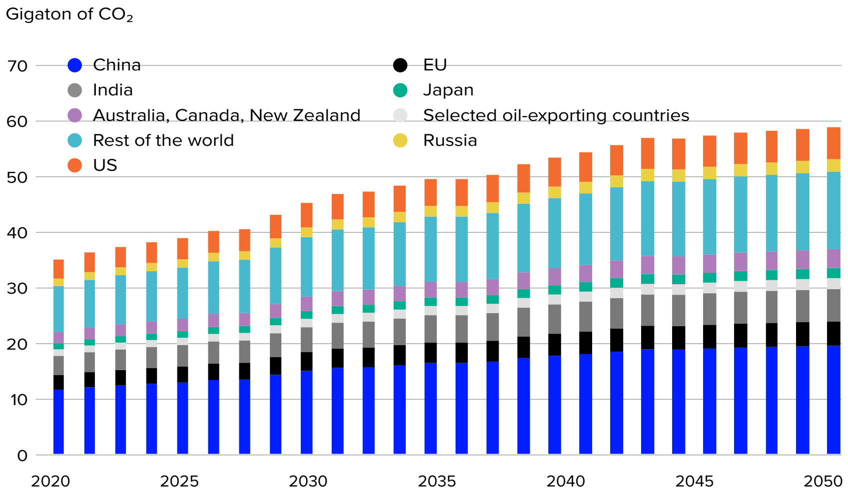
[2] https://www.nature.com/articles/s41558-021-01001-0

[3] https://climateactiontracker.org/publications/global-update-paris-agreement-turning-point/

[4] https://www.wri.org/blog/2020/02/greenhouse-gas-emissions-by-country-sector

[5] Ibid.

[6] Figure 1: Forecast global CO_2 emissions under business-as-usual scenario

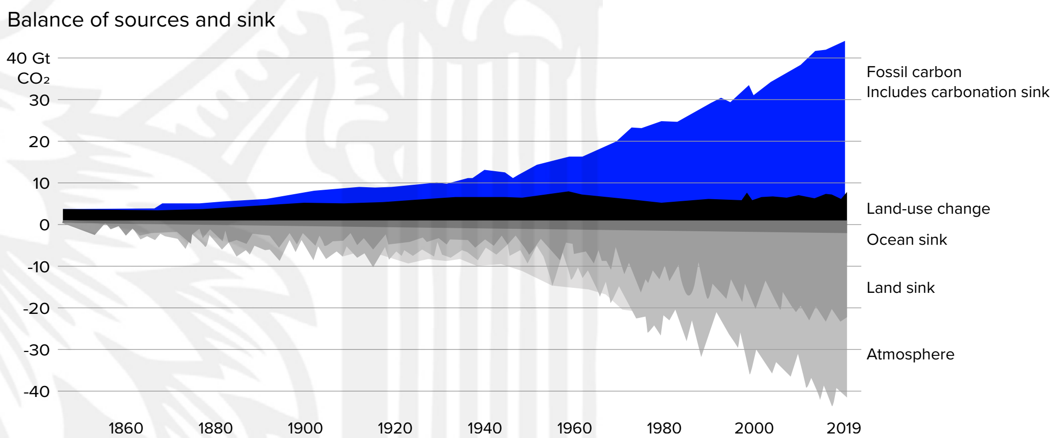


Source: IMF World Economic Outlook (October 2020)

Full link: https://www.imf.org/en/Publications/WEO/Issues/2020/09/30/world-economic-outlook-october-2020#Chapter%203

[7] For more, see https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors

Figure 2: Balance of CO_2 sources and sinks



Source: Global Carbon Budget 2017 (globalcarbonproject.org)

[8] The share of renewable energy in primary supply must grow to at least 74% in 2050 in the 1.5°C Scenario. This entails an eight-fold increase in the pace of renewable share growth, and a 2.5-fold increase in the rate of energy

intensity improvement. For more, see https://www.irena.org/

[9] Source: http://www.bp.com/statisticalreview

[10] This section draws importantly on the report by Energy Transitions Commission. Available at https://www.energy-transitions.org/wp-content/uploads/2020/09/Making-Mission-Possible-Executive-Summary-English.pdf

[11] How Energy Efficiency Will Power Net-Zero Climate Goals – Analysis - IEA

[12] Ibid.

[13] Energy Transitions Commission (2020).

[14] Ibid.

[15] Ibid.

[16] Ibid.

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[18] Ibid.

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[20] IRENA (2020). https://www.irena.org/costs/

[21] https://www.bbc.co.uk/news/science-environment-54723147?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20201102&utm_medium=email&utm_source=Revue%20Daily

[22] IRENA (2020). https://www.irena.org/costs/

[23] See Llewellyn Consulting (2019). Technologies series: Deep ocean windfarms. Available upon request.

[24] IRENA (2020). Hydropower. Available at: https://www.irena.org/costs/Power-Generation-Costs/Hydropower

[25] See BP (2020). BP Statistical Review of World Energy. Available at: < https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html >

[26] https://www.irena.org/costs/Power-Generation-Costs

[27] For more, see Sustainable Markets Initiative briefing note on Hydrogen, November, 2020.

[28] Electrolysis, which splits water (H_2O) into its constituent atoms, hydrogen and oxygen. When carried out using electricity generated from renewable sources, the result is termed ‘green’ hydrogen.

[29] Conversion of fossil fuels (hydrocarbons) by coal gasification and (mainly) methane reformation, into H_2 and CO_2. The resulting hydrogen is dubbed ’grey’, unless the resulting CO_2 is captured and stored, in which it is called ‘blue’. Nearly all (around 99%) of global hydrogen production (some 70m tonnes) is currently by this method.

[30] Pyrolysis, whereby natural gas is passed through a molten alkali or metal, producing carbon black as a by-product. This ‘turquoise hydrogen’ process can be powered by clean energy.

[31] Energy Transitions Commission (2020).

[32] https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

[33] Ibid.

[34] European Patent Office and the International Energy Agency (2020). Innovation in batteries and electricity storage. Available at: https://www.epo.org/news-events/news/2020/20200922.html

[35] Ibid.

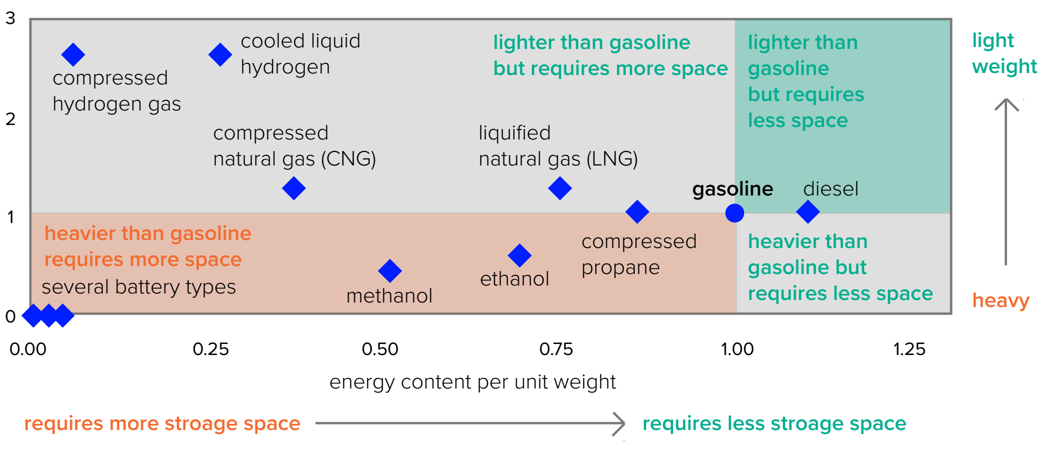
[36] Financial Times (2020). Tesla outlines ambition to halve cost of batteries. Available at: https://www.ft.com/content/184acb43-b99a-4312-9318-04aa142cc4c1

[37] For more, see Sustainable Markets Initiative briefing note on Hydrogen (November, 2020) and Trucking (March, 2021)

[38] For more, see Sustainable Markets Initiative briefing note on Aviation, February, 2020.

[39] Figure 3: Energy-density comparison

Energy density comparison of several transportation fuels (indexed to gasoline = 1)
energy content per unit weight



Source: EIA

Full link: https://www.eia.gov/todayinenergy/detail.php?id=9991

[40] Hydrogen, with its low energy/weight density, is feasible only for short flights. Moreover, it is dangerous, being highly flammable, and costs are high (Fossil fuel-based hydrogen costs about $1/kg, while the European offshore wind farm can technically produce it at $6/kg – given its energy content, the equivalent energy amount of hydrocarbon price would be $270 per barrel oil.) As with all use of hydrogen, development of ‘green hydrogen’ as a fuel depends on the growth of carbon-free electricity.
Hydrogen’s involvement is likely to be focused on shorter distances and liquid fuels rather than fuel cells, and that only in the medium to long term (2030-2050). For a detailed report on the impact of hydrogen on the aviation industry see, McKinsey & Company for the Clean Sky 2 JU, and Fuel Cells and Hydrogen 2 JU, 2020. Hydrogen-powered aviation. European Commission, [online] Available at: <https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf> [Accessed 2 November 2020]. The future of hydrogen powered flight is generally seen as utilising hydrogen in liquid fuels however, smaller aircraft have demonstrated the possibility of hydrogen fuel cell powered flight. See, ZeroAvia, 2020. ZeroAvia Completes World First Hydrogen-Electric Passenger Plane Flight. Zero Avia [online] Available at: <https://www.zeroavia.com/press-release-25-09-2020> [Accessed 2 November 2020].

[41] NASA has determined that a mixture of 50% aviation/biofuel mix can cut air pollution caused by air traffic by 50–70%. However: biofuels emit CO_2 when burned; and to be produced at scale they would make heavy demands on land use e.g., to meet current demand for aviation with plant-based biofuels, arable land approximately the size of Australia would be required.

[42] For more, see Sustainable Markets Initiative briefing note on Shipping by Llewellyn Consulting, November, 2020.

[43] https://ec.europa.eu/clima/policies/transport/shipping_en

[44] https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport.pdf

[45] Much of the existing hydrogen infrastructure is concentrated around ports, potentially lowering the barriers to entry for hydrogen-fuelled shipping and hydrogen transport. Energy density remains an issue, however. For more, see IEA. Available at: https://www.iea.org/reports/the-future-of-hydrogen

[46] For more, see Sustainable Markets Initiative briefing note on Wood-based solutions by Llewellyn Consulting, January, 2020.

[47] For more, see Sustainable Markets Initiative briefing note on Steel (December 2020) and Cement (March 2021) by Llewellyn Consulting

[48] This process maximises secondary flows and recycling by melting more scrap in EAFs. However, it requires the cost-efficient supply of renewable electricity as well as a sufficient supply of high-quality steel scrap. For more see, McKinsey (2020). Decarbonization challenge for steel. Available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel

All major European iron and steel players are currently building, or already testing, hydrogen-based steel production processes, either using hydrogen as a replacement for pulverized coal injection (PCI) or using hydrogen-based direct reduction. Sweden’s SSAB has built a pilot DRI plant that will start trials using ‘green’ hydrogen next year. The technology holds promise – with the hydrogen-based direct reduction, the majority of CO_2 emissions from iron production are eliminated – but the technology is far from scalable at present. For more, see Financial Times (2020). Europe leads the way in the ‘greening’ of steel output. Available at: https://www.ft.com/content/b07c8a83-4b0c-4f96-8ff0-789c51b6e46b

[49] https://www.iea.org/commentaries/how-energy-efficiency-will-power-net-zero-climate-goals

[50] Leonardo Energy (2020). Heat Pumps - Integrating Technologies to Decarbonise Heating and Cooling. Available at: https://help.leonardo-energy.org/hc/en-us/articles/360013224459-Heat-Pumps-Integrating-Technologies-to-Decarbonise-Heating-and-Cooling

[51] For more see Sustainable Markets Initiative briefing note on Carbon Capture and Storage by Llewellyn Consulting, March, 2020.

[52] https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf

[53] Energy Transitions Commission (2020).

[54] Ibid.

[55] https://about.bnef.com/blog/energy-transition-investment-hit-500-billion-in-2020-for-first-time/

[56] Ibid.

[57] The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA

[58] Ibid.

[59] Dr Fatih Birol, International Energy Agency (IEA) Executive Director

[50] http://www.tribune242.com/news/2021/may/03/are-rare-earths-next-big-thing/

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