The crucial difference between hydrogen and electricity is that hydrogen is a chemical energy carrier, composed of molecules and not only electrons. This distinction underpins all the reasons why hydrogen might outcompete electricity in some situations (and vice versa). Chemical energy is attractive because it can be stored and transported in a stable way, as is done today with oil, coal, biomass and natural gas.[4] Molecules can be stored for long periods, transported across the sea in ships, burned to produce high temperatures, and used in existing infrastructure and business models designed around fossil fuels. Because of its molecular nature, hydrogen can also be combined with other elements such as carbon and nitrogen to make hydrogen-based fuels that are easier to handle, and can be used as feedstock in industry, helping to reduce emissions.

Without hydrogen a decarbonised energy system based on electricity would be much more flow-based. Flow-based energy systems must match demand and supply in real time, across wide distances, and can be vulnerable to disruptions of supply. Chemical energy can add a stock-based element to an energy economy and thus contribute significantly to energy system resilience.

All energy carriers, including fossil fuels, encounter efficiency losses each time they are produced, converted or used. In the case of hydrogen, these losses can accumulate across different steps in the value chain. After converting electricity to hydrogen, shipping it and storing it, then converting it back to electricity in a fuel cell, the delivered energy can be below 30% of what was in the initial electricity input. This makes hydrogen more "expensive" than electricity or the natural gas used to produce it. It also makes a case for minimising the number of conversions between energy carriers in any value chain.

That said, in the absence of constraints to energy supply, and as long as CO_2 emissions are valued, efficiency can be largely a matter of economics, to be considered at the level of the whole value chain. This is important as hydrogen can be used with much higher efficiency in certain applications and has the potential to be produced without greenhouse gas emissions. For example, a hydrogen fuel cell in a vehicle is around 60% efficient, whereas a gasoline internal combustion engine is around 20% efficient, and a modern coal-fired power plant is around 45% efficient, with electricity power line losses accounting for a further 10% or more.

What is the difference between hydrogen and hydrogen-based fuels and feedstocks?

Hydrogen can be used in its pure form as an energy carrier or as an industrial raw material. It can also be combined with other inputs to produce what are referred to as hydrogen-based fuels and feedstocks. Hydrogen-based fuels and feedstocks can be produced using hydrogen from any source, whether electricity, biomass or fossil fuels, and can readily be used in applications such as engines, turbines and chemical processes. They include such derivative products as synthetic methane, synthetic liquid fuels and methanol, all of which require carbon alongside hydrogen. They also include ammonia, which can be used as a chemical feedstock or potentially as a fuel, and which is made by combining hydrogen with nitrogen.

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[4] Batteries also store chemical energy, but not in the bonds of molecules that can be stored in bulk. In batteries, the chemical energy is a build-up of ions and electrons on cathodes and anodes in specially prepared combinations of chemicals; often these are complex chemicals with poor stability. The chemical energy in batteries degrades more quickly over time.

Chapter 2: Producing hydrogen and hydrogen-based products

②

- **Around 70 Mt of dedicated hydrogen are produced today, 76% from natural gas and almost all the rest (23%) from coal.** Annual hydrogen production consumes around 205 billion m^3 of natural gas (6% of global natural gas use) and 107 Mt of coal (2% of global coal use), with coal use concentrated in the People's Republic of China ("China"). As a consequence, global hydrogen production today is responsible for 830 $MtCO_2$/yr – corresponding to the annual CO_2 emissions of Indonesia and the United Kingdom combined.

- **Electrolysis currently accounts for 2% of global hydrogen production, but there is significant scope for electrolysis to provide more low-carbon hydrogen.** Surplus electricity from variable renewables has low costs, but the number of hours during which this surplus occurs is generally low. Falling costs mean that dedicated renewables for hydrogen production in regions with excellent resource conditions could, however, now become a reliable low-cost hydrogen source. If all current dedicated hydrogen production were produced through water electrolysis (using water and electricity to create hydrogen), this would result in an annual electricity demand of 3 600 TWh – more than the annual electricity generation of the European Union. Water requirements would be 617 million m^3, or 1.3% of the water consumption of the global energy sector today; this is roughly twice the current water consumption for hydrogen from natural gas.

- **There are huge regional variations in hydrogen production costs today, and their future economics depend on factors that will continue to vary regionally, including prices for fossil fuels, electricity and carbon.** Natural gas without CCUS is currently the most economic option for hydrogen production in most parts of the world, with costs being as low as USD 1/kgH_2 in the Middle East. Among low-carbon options, electrolysis requires electricity prices of USD 10–40/MWh and full load hours of 3 000–6 000 to become cost-competitive with natural gas with CCUS (depending on local gas prices). Regions with good renewable resources or nuclear power plants may find electrolysis an attractive option, especially if they currently depend on relatively high cost natural gas imports.

- **Conversion of hydrogen into other hydrogen-based fuels could be attractive where few other low-carbon alternatives are available, but is not economic at current prices.** The conversion of hydrogen to ammonia benefits from existing infrastructure and demand; it also does not need carbon as an input. For synthetic liquid fuels from electrolytic hydrogen, however, electricity costs of USD 20/MWh translate into costs of USD 60–70/bbl without taking account of any capital expenditure or CO_2 feedstock costs. For synthetic methane the equivalent figure is USD 10–12/MBtu. Carbon pricing or equivalent policies would be needed to reduce the cost gap between synthetic hydrocarbons and fossil fuels.

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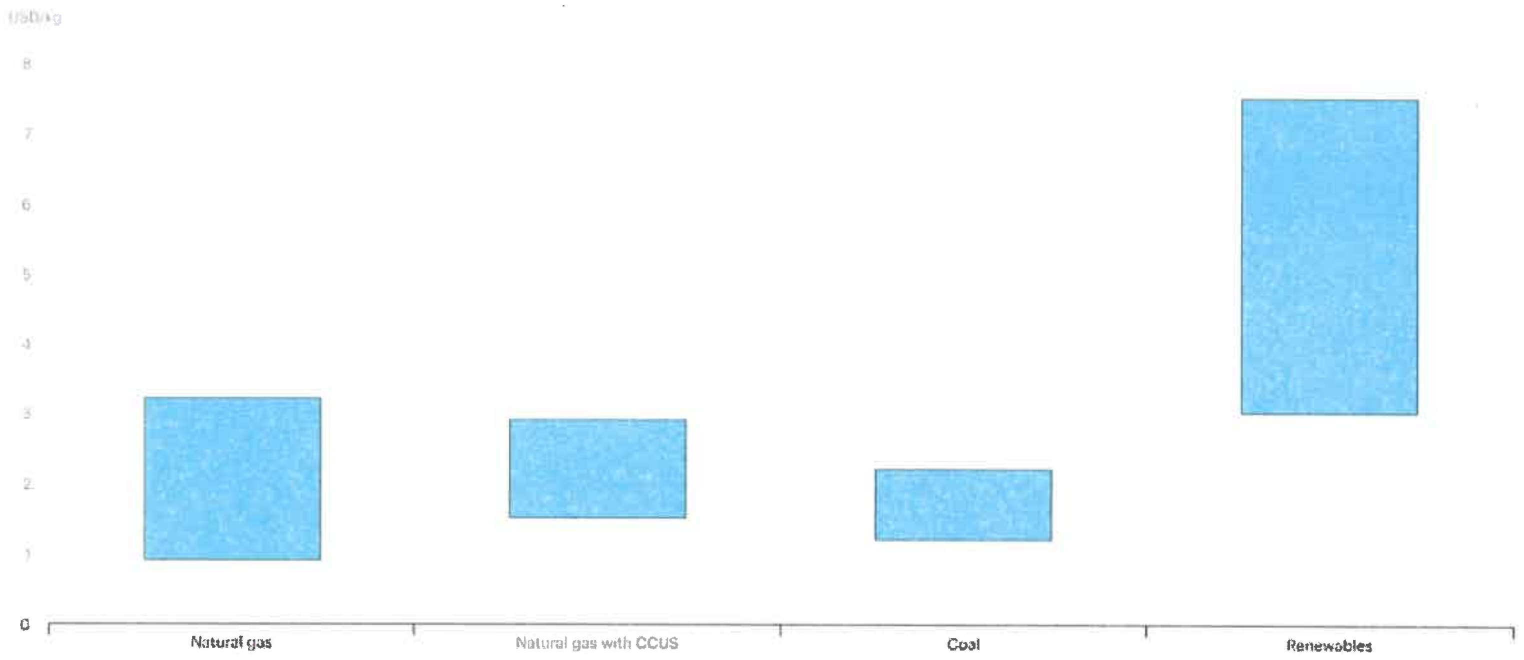
Keeping an eye on costs

Dedicated electricity generation from renewables or nuclear power offers an alternative to the use of grid electricity for hydrogen production.

With declining costs for renewable electricity, in particular from solar PV and wind, interest is growing in electrolytic hydrogen and there have been several demonstration projects in recent years. Producing all of today's dedicated hydrogen output from electricity would result in an electricity demand of 3 600 TWh, more than the total annual electricity generation of the European Union.

Hydrogen production costs by production source, 2018

Open



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④a

The need to mobilise all low-carbon energy technologies

Fundamentally, there is no sustainable level of emissions if the 2°C scenario is to be realised. Constrained by the world's carbon budget, carbon emissions must peak within the next few years and go to zero by 2100 (or sooner). This will require policy changes around the world as well as massive investments in innovation, infrastructure, and deployment of non-emitting energy resources. More specifically, electricity grids must be decarbonised; vehicle fleets must be electrified or transitioned to non-emitting fuels; and a range of industrial sectors (e.g. off-grid mining, buildings, chemicals, iron and steel, cement, oil and gas) must be transformed as well.

Whatever else might be said about the efforts undertaken thus far, they are on track to far exceed the targets arising from the 2°C scenario. It is clear that a shift in direction will be required if countries' stated objectives are to be met.

As highlighted by NEA studies such as *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*, countries face unique and distinct options and challenges in their efforts to achieve optimum energy portfolios (NEA, 2019). There is no commonly applicable solution for all countries. The best energy mix and energy strategy depends on, inter alia, a country's natural endowments, state of economic development, technological capabilities, human capital, stability, legal and regulatory frameworks, as well as culture, values, and priorities.

Many countries are committing to reach net zero emissions by 2050. It has yet to be seen, however, whether countries have the technologies and political will to achieve this ambitious target of net zero by 2050. It is clear that a serious effort to do so would require massive investments in and deployment of all non-emitting energy solutions, including renewable energy, nuclear energy, and carbon capture, utilisation and storage (CCUS), in addition to energy storage, energy efficiency, and demand-side management, among other measures.

There is no "silver bullet", no perfect solution to the complex and urgent challenge of climate change mitigation. All non-emitting energy options offer benefits but face limitations and challenges.

While hydroelectricity and nuclear energy currently account for approximately 16% and 10% of the world's electricity supply, respectively, variable renewables (e.g. wind and solar) are the fastest growing segment of the clean energy market. Hydroelectricity is expected to continue to play an important role in providing baseload power; however, it is not a solution in many parts of the world that lack hydro potential. In theory, other non-emitting technologies, such as variable renewables, nuclear power, and CCUS, can be transferred and deployed in most jurisdictions around the world. In practice, the effectiveness and efficiency of variable renewable technologies (e.g. wind and solar) also varies by jurisdiction, but has great potential in many energy poor parts of the world (e.g. near to the equator for solar potential). Embarking nuclear nations face some barriers to entry, including the need to implement effective regulatory frameworks as nuclear is a strictly controlled sector; however, engagement with the international community – through the International Atomic Energy Agency (IAEA) with its milestones approach or bilaterally with experienced nuclear nations for capacity building – can facilitate successful outcomes.

Variable renewables generally benefit from strong public confidence in many parts of the world; however, the sun does not always shine and the wind does not always blow, and the variable (and often unpredictable) nature of these forms of power generation can create systems level challenges and grid instability, that translate into higher systems costs. Higher levels of variable renewables could be deployed more aggressively if they could be coupled with adequate energy storage capacities, dispatchable power, and baseload power. Storage and batteries, however, are not yet available at the scale that would be required to replace fossil energy with variable renewables and achieve zero global emissions by 2050.

Despite the massive capacity additions of variable renewables (mainly wind and solar power) over the last two decades, the relative share of fossil fuels in the electricity generation mix has barely changed (see Figure 3 below). In fact, the surge in variable renewable generation has primarily served to compensate for the decline of nuclear power output. In absolute terms, electricity generation from fossil fuels has also increased globally, driven in large part by increasing electricity demand in non-OECD countries.

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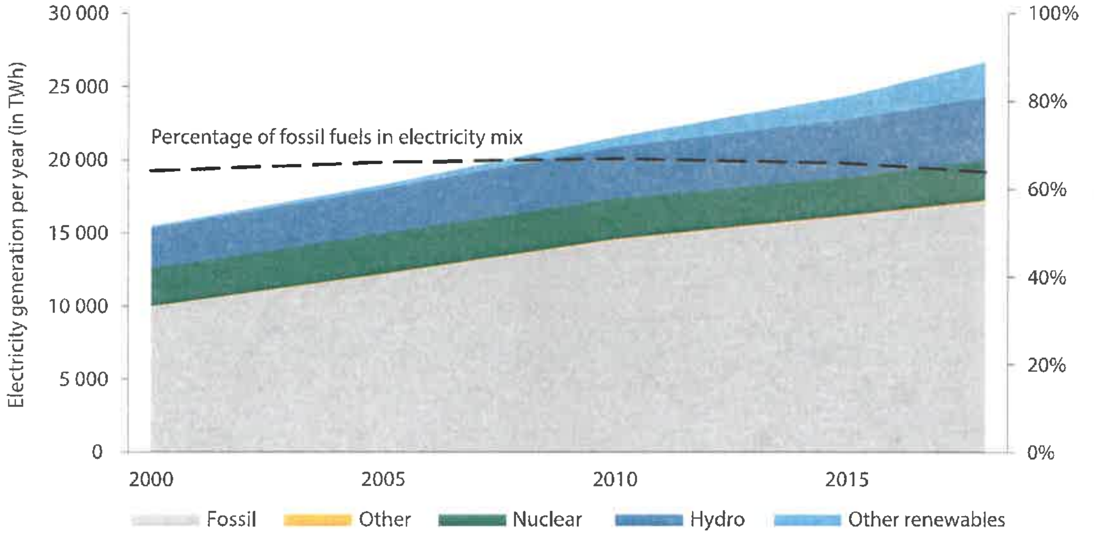
As a result, global carbon emissions are far from being on track with the Paris Agreement. After two years of consecutive increases, carbon emission flattened at 33 gigatonnes of carbon dioxide in 2019. In 2020, carbon dioxide emissions experienced a major fall of 5% mainly due to a major global economic downturn during the COVID-19 pandemic. The fall in emissions in 2020 was not based on any structural changes in emission patterns. Accordingly, driven by post COVID-19 economic recovery, carbon emissions are expected to increase by 5% in 2021, regressing to levels prior to the pandemic (IEA, 2021b).

Figure 3. **Growth in electricity generation (2000-2018)**



Source: IEA (2021a).

CCUS may have a role to play, not only in reaching net zero emissions, but in exceeding this target to reach net negative emissions. There are several potential scenarios that could unfold, with countries taking steps to reach net zero emissions by 2050. In some possible scenarios, if countries do not reach peak emissions early enough, the world could exceed its carbon budget even if it reaches net zero by 2050. In this scenario, CCUS would be required to extract carbon from the atmosphere after it has been emitted (a model that is often referred to as negative emissions), reversing and mitigating some of the worst effects of climate change.

There is considerable uncertainty however in the readiness of CCUS technologies. CCUS technology readiness levels are low, with several projects presently ongoing to demonstrate the viability and scalability of CCUS. The IEA (2021c) has identified CCUS as one of the three key uncertainties in the pathway to net zero by 2050, along with behavioural changes and bioenergy.

Natural gas, as the least carbon intensive fossil fuel, may be a good fit in many jurisdictions in the short term, for gradually decarbonising the global energy mix; however, in order to go to zero emissions by 2100, natural gas will likely also need to be phased out (unless it can be paired with CCUS). Breakthroughs in renewables, energy storage, energy efficiency, as well as CCUS are needed. Equally importantly, however, the IEA anticipates that, in order to achieve the 2°C scenario, global installed nuclear energy capacity will need to double by 2050. This will require significant investments in life extension and refurbishment of existing nuclear reactors, as well as new builds of existing large-scale nuclear power technologies, as well as investments in small modular reactors (SMRs) and Generation IV technologies.

All credible models show that nuclear energy has an important role to play in global climate change mitigation efforts. In its 2019 report on nuclear energy – its first report on nuclear energy in over 20 years – the IEA found that nuclear has an important role to play in global efforts to meet Paris Agreement targets (IEA, 2019). Nuclear power plant retirements would significantly constrain