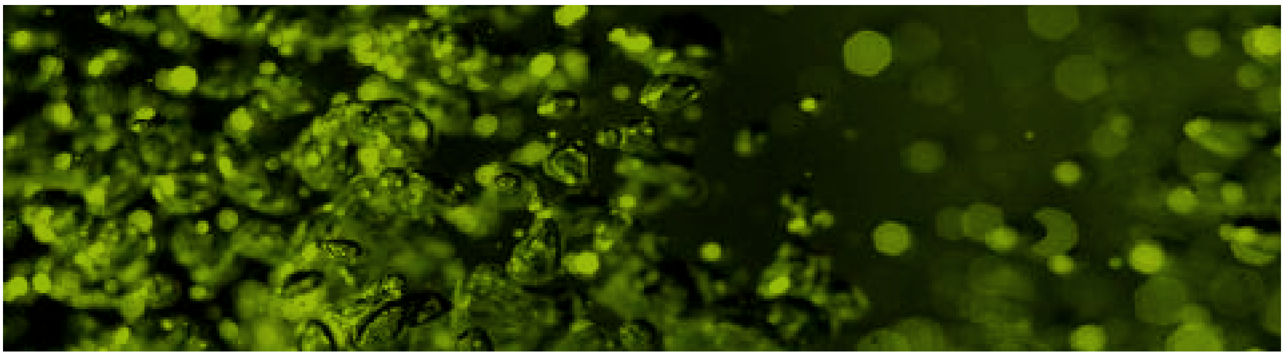
## 1.1. DIFFERENT **SHADES** OF HYDROGEN

Hydrogen can be produced with multiple processes and energy sources; a colour code nomenclature is becoming commonly used to facilitate discussion (Figure 1.2). But policy makers should design policy using an objective measure of impact based on life-cycle greenhouse gas (GHG) emissions, especially since there might be cases that do not fully fall under one colour (*e.g.* mixed hydrogen sources, electrolysis with grid electricity) (see Section 2.3).


**FIGURE 1.2** Selected shades of hydrogen

| Color | GREY HYDROGEN | BLUE HYDROGEN | TURQUOISE HYDROGEN* | GREEN HYDROGEN |
|---|---|---|---|---|
| Process | SMR or gasification | SMR or gasification with carbon capture (85-95%) | Pyrolysis | Electrolysis |
| Source | Methane or coal | Methane or coal | Methane | Renewable electricity |

*Note: SMR = steam methane reforming.*
** Turquoise hydrogen is an emerging decarbonisation option.*



**GREY HYDROGEN**

**GREY HYDROGEN**[1] is produced with fossil fuels (i.e. hydrogen produced from methane using steam methane reforming (SMR) or coal gasification). The use of grey hydrogen entails substantial $CO_2$ emissions, which makes these hydrogen technologies unsuitable for a route toward net-zero emissions.

**BLUE HYDROGEN**

During early stages of the energy transition, the use of **BLUE HYDROGEN** (i.e. grey hydrogen with carbon capture and storage [CCS]) could facilitate the growth of a hydrogen market. Around three-quarters of hydrogen is currently produced from natural gas. Retrofitting with CCS would allow the continued use of existing assets while still achieving lower GHG emissions. This is an option is to produce hydrogen with lower GHG emissions while reducing pressure on the renewable energy capacity installation rate to produce green hydrogen. Notably, industrial processes like steel production may require a continuous flow of hydrogen; blue hydrogen could be an initial solution while green hydrogen ramps up production and storage capacity to meet the continuous flow requirement.

However, blue hydrogen has limitations that have so far restricted its deployment: it uses finite resources, is exposed to fossil fuel price fluctuations, and does not support the goals of energy security. Moreover, blue hydrogen faces social acceptance issues, as it is associated with additional costs for $CO_2$ transport and storage and requires monitoring of stored $CO_2$. In addition, CCS capture efficiencies are expected to reach 85-95% at best,[2] which means that 5-15% of the $CO_2$ will still be emitted. And these high capture rates have yet to be achieved.

In sum, the carbon emissions from hydrogen generation could be reduced by CCS but not eliminated. Moreover, these processes use methane, which brings leakages upstream, and methane is a much more potent GHG per molecule than $CO_2$. This means that while blue hydrogen could reduce $CO_2$ emissions, it does not meet the requirements of a net-zero future. For these reasons, blue hydrogen should be seen only as a short-term transition to facilitate the uptake of green hydrogen on the path to net-zero emissions.

**TURQUOISE HYDROGEN**

**TURQUOISE HYDROGEN** combines the use of natural gas as feedstock with no $CO_2$ production. Through the process of pyrolysis, the carbon in the methane becomes solid carbon black. A market for carbon black already exists, which provides an additional revenue stream. Carbon black can be more easily stored than gaseous $CO_2$. At the moment, turquoise hydrogen is still at the pilot stage. (Philibert, 2020; Monolith, 2020).

**GREEN HYDROGEN**

Among the different shades of hydrogen, **GREEN HYDROGEN** – meaning hydrogen produced from renewable energy – is the most suitable one for a fully sustainable energy transition. The most established technology options for producing green hydrogen is water electrolysis fuelled by renewable electricity. This technology is the focus of this report. Other renewables-based solutions to produce hydrogen exist.[3] However, except for SMR with biogases, these are not mature technologies at commercial scale yet (IRENA, 2018). Green hydrogen production through electrolysis is consistent with the net-zero route, allows the exploitation of synergies from sector coupling, thus decreasing technology costs and providing flexibility to the power system. Low VRE costs and technological improvement are decreasing the cost of production of green hydrogen. For these reasons, green hydrogen from water electrolysis has been gaining increased interest.

1 Sometimes referred to as black or brown hydrogen.

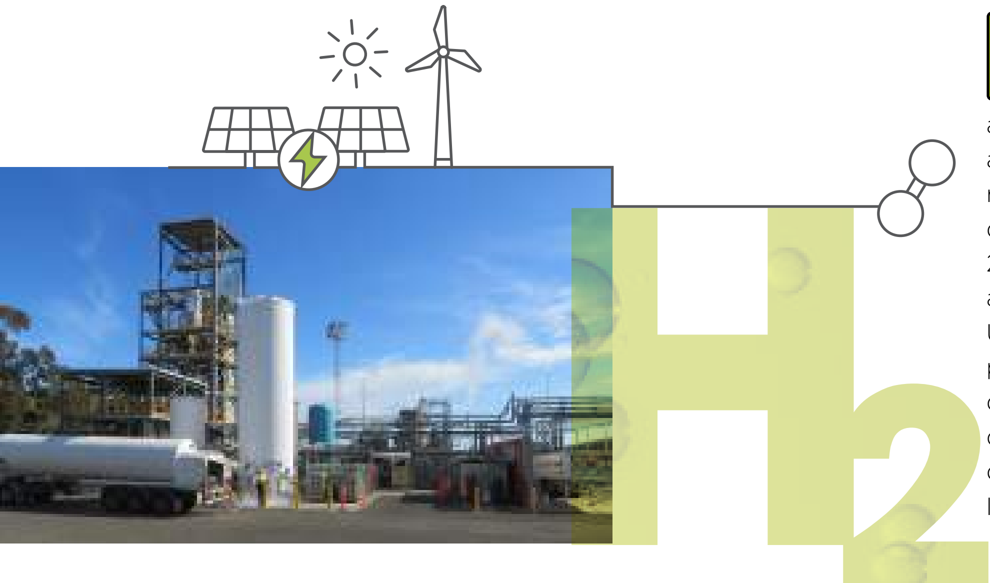
2 An alternative route to SMR could be a process called autothermal reforming, for which it is estimated that a possible capture rate up to 94.5% of the $CO_2$ emitted is possible (H-Vision, 2019).

3 For example, biomass gasification and pyrolysis, thermochemical water splitting, photocatalysis, supercritical water gasification of biomass, combined dark fermentation and anaerobic digestion.

## 1.2. DRIVERS OF THE NEW WAVE OF GREEN HYDROGEN

There have been several waves of interest in hydrogen in the past. These were mostly driven by oil price shocks, concerns about peak oil demand or air pollution, and research on alternative fuels. Hydrogen can contribute to energy security by providing another energy carrier with different supply chains, producers and markets; this can diversify the energy mix and improve the resilience of the system. Hydrogen can also reduce air pollution when used in fuel cells, with no emissions other than water. It can promote economic growth and job creation given the large investment needed to develop it as an energy carrier from an industrial feedstock.

As a result, more and more energy scenarios are giving green hydrogen a prominent role, albeit with significantly different volumes of penetration (see Box 1.1). The new wave of interest is focused on delivering low-carbon solutions and additional benefits that only green hydrogen can provide. The drivers for green hydrogen include:



**1.** **Low variable renewable energy (VRE) electricity costs.** The major cost driver for green hydrogen is the cost of electricity. The price of electricity procured from solar PV and onshore wind plants has decreased substantially in the last decade. In 2018, solar energy was contracted at a global average price of 56 USD/MWh, compared with 250 in 2018. Onshore wind prices also fell during that period, from 75 USD/MWh in 2010 to 48 in 2018 (IRENA, 2019b). New record-low prices were marked in 2019 and 2020 around the world: solar PV was contracted at USD 13.12/MWh in Portugal (Morais, 2020) and USD 13.5/MWh in the United Arab Emirates (Abu Dhabi) (Shumkov, 2020); onshore wind was contracted at USD 21.3/MWh in Saudi Arabia (Masdar, 2019) while in Brazil, prices ranged between USD 20.5 and 21.5/MWh (BNEF, 2019). With the continuously decreasing costs of solar photovoltaic and wind electricity, the production of green hydrogen is increasingly economically attractive.

**2.** **Technologies ready to scale up.** Many of the components in the hydrogen value chain have already been deployed on a small scale and are ready for commercialisation, now requiring investment to scale up. The capital cost of electrolysis has fallen by 60% since 2010 (Hydrogen Council, 2020), resulting in a decrease of hydrogen cost from a range of USD 10-15/kg to as low as USD 4-6/kg in that period. Many strategies exist to bring down costs further and support a wider adoption of hydrogen (IRENA, forthcoming). The cost of fuel cells[4] for vehicles has decreased by at least 70% since 2006 (US DOE, 2017).

4 Fuel cells use the same principles as an electrolyser, but in the opposite direction, for converting hydrogen and oxygen into water in a process that produces electricity. Fuel cells can be used for stationary applications (*e.g.* centralised power generation) or distributed applications (*e.g.* fuel cell electric vehicles). Fuel cells can also convert other reactants, such as hydrocarbons, ethers or alcohols.

While some technologies have not been demonstrated at scale yet (such as ammonia-fuelled ships) (IRENA, 2020b), scaling up green hydrogen could make those pathways more attractive as production costs decrease.

**3.** **Benefits for the power system.** As the share of VRE rapidly increases in various markets around the world, the power system will need more flexibility. The electrolysers used to produce green hydrogen can be designed as flexible resources that can quickly ramp up or down to compensate for fluctuations in VRE production, by reacting to electricity prices (Eichman, Harrison and Peters, 2014). Green hydrogen can be stored for long periods, and can be used in periods when VRE is not available for power generation with stationary fuel cells or hydrogen-ready gas turbines. Flexible resources can reduce VRE curtailment, stabilise wholesale market prices and reduce the hours with zero or below zero electricity prices (or negative price), which increases the investment recovery for renewable generators and facilitates their expansion. Finally, hydrogen is suitable for long-term, seasonal energy storage, complementing pumped-storage hydropower plants. Green hydrogen thus supports the integration of higher shares of VRE into the grid, increasing system efficiency and cost-effectiveness.

**4.** **Government objectives for net-zero energy systems.** By mid-2020, seven countries had already adopted net-zero GHG emission targets in legislation, and 15 others had proposed similar legislation or policy documents. In total, more than 120 countries have announced net-zero emissions goals (WEF, 2020). Among them is the People's Republic of China (hereafter "China"), the largest GHG emitter, which recently pledged to cut its net carbon emissions to zero within 40 years. While these net-zero commitments have still to be transformed into practical actions, they will require cutting emissions in the "hard-to-abate" sectors where green hydrogen can play an important role.

**5.** **Broader use of hydrogen.** Previous waves of interest in hydrogen were focused mainly on expanding its use in fuel cell electric vehicles (FCEVs). In contrast, the new interest covers many possible green hydrogen uses across the entire economy, including the additional conversion of hydrogen to other energy carriers and products, such as ammonia, methanol and synthetic liquids. These uses can increase the future demand for hydrogen and can take advantage of possible synergies to decrease costs in the green hydrogen value chain. Green hydrogen can, in fact, improve industrial competitiveness, not only for the countries that establish technology leadership in its deployment, but also by providing an opportunity for existing industries to have a role in a low-carbon future. Countries with large renewable resources could derive major economic benefits by becoming net exporters of green hydrogen in a global green hydrogen economy.

**6.** **Interest of multiple stakeholders.** As a result of all the above points, interest in hydrogen is now widespread in both public and private institutions. These include energy utilities, steel makers, chemical companies, port authorities, car and aircraft manufacturers, shipowners and airlines, multiple jurisdictions and countries aiming to use their renewable resources for export or to use hydrogen to improve their own energy security. These many players have also created partnerships and ongoing initiatives to foster collaboration and co ordination of efforts.[6]

**However, green hydrogen still faces barriers.**

5 System flexibility is here defined as the ability of the power system to match generation and demand at any timescale.

6 The Hydrogen Council is an example of a private initiative. Launched in 2017, it has 92 member companies (by October 2020). The Hydrogen Initiative under the Clean Energy Ministerial is an example of a public initiative, where nine countries and the European Union are collaborating to advance hydrogen. The Fuel Cell and Hydrogen Joint Undertaking is an example of private-public partnership in the European Union.

## Box 1.1 Roles for green hydrogen in different energy transition scenarios

The role given to green hydrogen in existing regional and global energy transition scenarios differs greatly due to a number of factors.

First, not all scenarios aim for the same GHG reduction target. The more ambitious the GHG reduction target, the greater is the amount of green hydrogen expected in the system. For low levels of decarbonisation, renewable power and electrification might be enough. But with deeper decarbonisation targets, green hydrogen would play a larger role in the future energy mix.

Second, not all scenarios rely on the same set of enabling policies. The removal of fossil fuel subsidies, for example, would increase the space for carbon-free solutions.

Third, the technology options available vary between scenarios. Scenarios that give greater weight to the social, political and sustainability challenges of nuclear, carbon capture, use and storage, and bioenergy anticipate limited contributions from those technologies to the energy transition, and thus require greater green hydrogen use.

Fourth, the more end uses for green hydrogen included in a scenario, the higher the hydrogen use will be. Scenarios that cover all hydrogen applications and downstream conversion to other energy carriers and products provide more flexibility in ways to achieve decarbonisation. More hydrogen pathways also help create larger economies of scale and faster deployment, leading to a virtuous circle of increasing both demand and supply.

Finally, cost assumptions, typically input data including capital and operating costs (Quarton et al., 2019) differ between scenarios. Those with the highest ambitions for hydrogen deployment are those with the most optimistic assumptions for cost reduction.

For all these reasons, the role of green hydrogen varies widely between scenarios. However, as more and more scenarios are being developed to reach zero or net-zero emissions, green hydrogen is more prominently present in scenarios and public discourse.

# 1.3. **BARRIERS** TO THE UPTAKE OF GREEN HYDROGEN

Green hydrogen faces barriers that prevent its full contribution to the energy transformation. Barriers include those that apply to all shades of hydrogen, such as the lack of dedicated infrastructure (*e.g.* transport and storage infrastructure), and those mainly related to the production stage of electrolysis, faced only by green hydrogen (*e.g.* energy losses, lack of value recognition, challenges ensuring sustainability and high production costs).

1. **HIGH PRODUCTION COSTS** Green hydrogen produced using electricity from an average VRE plant in 2019 would be two to three times more expensive than grey hydrogen (see Box 1.2). In addition, adopting green hydrogen technologies for end uses can be expensive. Vehicles with fuel cells and hydrogen tanks cost at least 1.5 to 2 times more than their fossil fuel counterparts (NREL, 2020). Similarly, synthetic fuels for aviation are today, even at the best sites in the world, up to eight times more expensive than fossil jet fuel (IRENA, 2019a). Box 1.2 provides examples of the production and transport costs of green hydrogen.

2. **LACK OF DEDICATED INFRASTRUCTURE.** Hydrogen has to date been produced close to where it is used, with limited dedicated transport infrastructure. There are only about 5 000 kilometres (km) of hydrogen transmission pipelines around the world (Hydrogen Analysis Resource Center, 2016), compared with more than 3 million km for natural gas. There are 470 hydrogen refuelling stations around the world (AFC TCP, 2020), compared with more than 200 000 gasoline and diesel refuelling stations in the United States and the European Union. Natural gas infrastructure could be repurposed for hydrogen (IRENA, IEA and REN21, forthcoming), but not all regions of the world have existing infrastructure. Conversely, synthetic fuels made from green hydrogen may be able to use existing infrastructure, though it might need to be expanded.

3. **ENERGY LOSSES.** Green hydrogen incurs significant energy losses at each stage of the value chain. About 30-35% of the energy used to produce hydrogen through electrolysis is lost (IRENA, forthcoming). In addition, the conversion of hydrogen to other carriers (such as ammonia) can result in 13-25% energy loss, and transporting hydrogen requires additional energy inputs, which are typically equivalent to 10-12% of the energy of the hydrogen itself (BNEF, 2020; Staffell *et al.*, 2018; Ikäheimo *et al.*, 2017). Using hydrogen in fuel cells can lead to an additional 40–50% energy loss. The total energy loss will depend on the final use of hydrogen. The higher the energy losses, the more renewable electricity capacity is needed to produce green hydrogen. The key issue, however, is not the total capacity needed, since global renewable potential is in orders of magnitude higher than the hydrogen demand, and green hydrogen developers are likely to first select areas with abundant renewable energy resources. The key issue is whether the annual pace of development of the solar and wind potential will be fast enough to meet the needs for both the electrification of end-uses and the development of a global supply chain in green hydrogen, and the cost that this additional capacity will entail.

4. **LACK OF VALUE RECOGNITION.** There is no green hydrogen market, no green steel, no green shipping fuel and basically no valuation of the lower GHG emissions that green hydrogen can deliver. Hydrogen is not even counted in official energy statistics of total final energy consumption, and there are no internationally recognised ways of differentiating green from grey hydrogen. At the same time, the lack of targets or incentives to promote the use of green products inhibits many of the possible downstream uses for green hydrogen. This limits the demand for green hydrogen.


5. **NEED TO ENSURE SUSTAINABILITY.** Electricity can be supplied from a renewable energy plant directly connected to the electrolyser, from the grid, or from a mix of the two. Using only electricity from a renewable energy plant ensures that the hydrogen is "green" in any given moment. Grid-connected electrolysers can produce for more hours, reducing the cost of hydrogen. However, grid electricity may include electricity produced from fossil fuel plants, so any $CO_2$ emissions associated with that electricity will have to be considered when evaluating the sustainability of hydrogen. As a result, for producers of hydrogen from electrolysis, the amount of fossil fuel-generated electricity can become a barrier, in particular if the relative carbon emissions are measured based on national emission factors. Box 1.3 discusses how to ensure that grid-connected electrolysers deliver hydrogen with minimum emissions.

## Box 1.2 Key cost components for green hydrogen

Green hydrogen competes both with fossil fuels and with other shades of hydrogen. It is important, therefore, to understand the factors that determine the cost of green hydrogen.

The production cost of green hydrogen depends on the investment cost of the electrolysers, their capacity factor,[7] which is a measure of how much the electrolyser is actually used, and the cost of electricity produced from renewable energy.

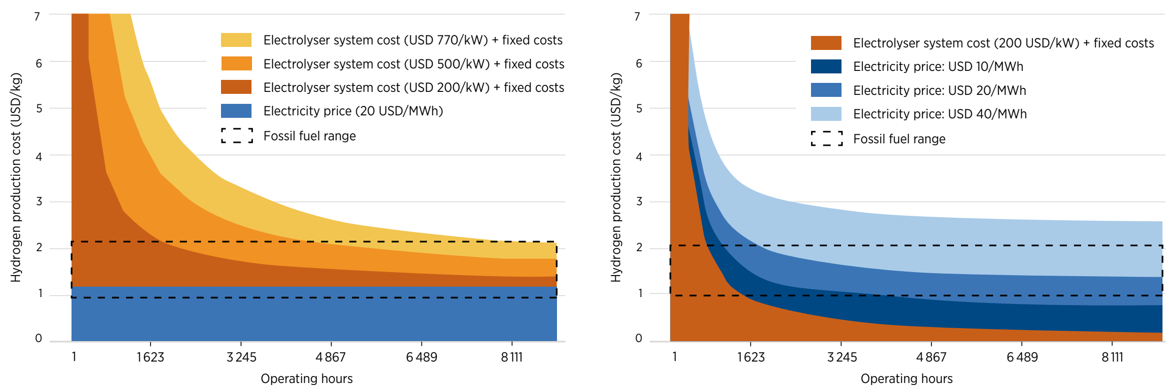
By 2020, the investment cost for an alkaline electrolyser is about USD 750-800 per kilowatt (kW). If the capacity factor of the green hydrogen facility is low, such as below 10% (fewer than 876 full load hours per year), those investment costs are distributed among few units of hydrogen, translating into hydrogen costs of USD 5-6/kg or higher, even when the electrolyser is operating with zero-priced electricity. In comparison, the cost of grey hydrogen is about USD 1-2/kg of hydrogen (considering a price range of natural gas of around USD 1.9 – 5.5 per gigajoule [GJ]). If load factors are higher, however, investment costs make a smaller contribution to the per-kg green hydrogen cost. Therefore, as the facility load factor increases, the electrolyser investment cost contribution to the final hydrogen production cost per kg drops and the electricity price becomes a more relevant cost component.

At a given price of electricity, the electricity component in hydrogen's final cost depends on the efficiency of the process. For example, with an electrolyser efficiency of 0.65 and electricity price of USD 20 per megawatt hour (MWh), the electricity component of the total cost would go up to USD 30/MWh of hydrogen, equivalent to USD 1/kg.[8]

Given today's relatively high electrolyser costs, low-cost electricity is needed (in the order of USD 20/MWh) to produce green hydrogen at prices comparable with grey hydrogen (see Figure 1.3). The objective of green hydrogen producers is now to reduce these costs, using different strategies (IRENA, forthcoming). Once electrolysers costs have fallen, it will be possible to use higher-cost renewable electricity to produce cost-competitive green hydrogen.

Transporting hydrogen generates additional costs. Transport costs are a function of the volume transported, the distance and the energy carrier. At low volumes, the cost of transporting compressed hydrogen 1 000 km in a truck is around USD 3.5/kg. For large volumes, shipping green ammonia is the lowest-cost option and adds only USD 0.15/kg of hydrogen (without considering conversion costs, i.e. cracking). Similar low costs can be achieved using large pipelines (around 2 000 tonnes per day) over short distances (BNEF, 2020). Hydrogen transport by pipeline can be one-tenth of the cost of transporting the same energy as electricity (Vermeulen, 2017).

**FIGURE 1.3** Hydrogen production cost depending on electrolyser system cost, electricity price and operating hours




*Notes: Efficiency = 65% (lower heating value). Fixed operational cost = 3% of the capital costs. Lifetime = 20 years. Interest rate = 8.0%. Fossil fuel range: grey hydrogen, considering fuel costs of USD 1.9–5.5/GJ for coal and natural gas.*

*Source: IRENA, forthcoming.*

7 The capacity factor can span between 0 and 100% and represents the average full load hours of use of the electrolyser as a percentage of the total number of hours in a year (8 760). For example, a capacity factor of 50% indicates an average use of 4 380 hours.

8 1 kg of hydrogen contains around 33.33 kilowatt hours (kWh).