POLICY RESEARCH WORKING PAPER

Hydrogen coming of age? A policy framework for Cyprus

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Summary

1. Hydrogen is an energy vector projected to play a significant role in decarbonisation efforts globally, mostly in sectors that cannot easily use direct electrification (such as heavy goods road transport, shipping & aviation, and high-T industry). At present hydrogen is used in the refining and fertiliser industries, produced using fossil fuels.
2. The EU has already published its own roadmap for hydrogen in July 2020 (where it proposed 40MW of new electrolyser capacity to be installed until 2030) and has followed up with even more ambitious targets for using hydrogen in various end sectors via the updated Renewable Energy Directive (RED) III, part of the proposed legislative package called 'Fit-for-55' of July 2021.
3. Producing hydrogen from renewable electricity (called 'green' hydrogen) is the preferred method for decarbonising the end sectors where it will be used, but it remains considerably more expensive than what is produced via traditional, fossil-fuel based methods ('grey' hydrogen). Combining these with Carbon Capture and Storage (CCS) leads to 'blue' hydrogen, the emissions-saving potential of which is questionable, and Cyprus may not have suitable sites for long-term storage of CO_2.
4. Storing hydrogen is a very attractive proposition, but compression and/or liquefaction is necessary due to hydrogen's very low density. Long-term storage of H_2 to serve as seasonal balance to Cyprus' electricity grid is contingent to storing cheaply, effectively and in large quantities, with the best option being geological formations such as salt caverns. Cyprus' potential for this is unknown, but the potential of H_2 as a seasonal energy storage medium can have significantly positive impact on the versatility and resilience of its energy system, as well as its ability to absorb renewables.
5. Transporting hydrogen in NG pipelines is a technically feasible possibility in low blending ratios (up to around 15%); transporting pure hydrogen in pipelines can take place either in a dedicated network, or after retrofitting exiting NG pipes (an easier and cheaper option). Green hydrogen used this way can reduce the emissions of end uses of Natural Gas.
6. Hydrogen's role in passenger cars is questionable; upfront vehicle costs are high, refuelling stations are expensive, and carbon-free electricity is better used directly in electric cars rather than via the green hydrogen – fuel cell route. For heavier vehicles (buses and heavy goods trucks) there is a case for deploying a fleet for larger volumes/distances, with the counterarguments being the short driving distances in Cyprus and the falling costs of electromobility even in these vehicle segments.
7. There is no clear usage case for H_2 in the domestic sector, given Cyprus' demand for cooling, and the advantages offered by direct electrification of the sector via heat pumps.
8. Industry, aviation, and shipping are potentially important future end users. Cyprus could very well prepare and invest in industrial clusters that will include port and airport facilities to prepare for the switch.
9. The possibility to produce synthetic or e-fuels via green hydrogen should be a priority. This could be relevant to the aviation and possibly the maritime industries, backed by proper demonstration/pilot projects and the related technoeconomic studies.
10. Overall, hydrogen can play an important role in decarbonising the economy of Cyprus, with uses in areas harder to electrify directly. A robust decarbonisation plan and a H_2 deployment roadmap are necessary to evaluate its true potential.

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1 Background

The Paris Agreement signed in 2015 aimed to limit the rise in average global temperature to well below 2 °C in this century, as compared to pre-industrial levels. How this will be achieved varies widely amongst countries, but there is a general convergence towards pledges for net-zero Greenhouse Gas (GHG) emissions from the word's major economies. The European Union has the much-publicised pledge to net zero by 2050, underpinned by its 'European Green Deal' set of measures and tools. The US has a similar goal in the same time frame, while China has pledged net zero for 2060 and India for 2070. In the run-up to the 26th Conference of the Parties to the UN Framework Convention on Climate Change (COP 26), a growing number of countries have announced targets to achieve net zero GHG emissions over the next decades. In turn, more than 100 companies that consume large volumes of energy or produce energy-consuming goods have followed suit (International Energy Agency 2021).

There is mounting evidence in numerous recent decarbonisation studies undertaken at a global, region or national scale that hydrogen will most probably play an important role in the energy system of the future (e.g., IEA 2021; IRENA 2020a; Piebalgs et al. 2020; Project Drawdown 2020; SolarPower Europe and LUT University 2020; Wilson et al. 2020; McKinsey & Co. 2021; Williams et al. 2021). Hydrogen is an energy vector that has attracted considerable attention in this setting, an attention that – for the EU at least – has culminated in the publishing of the Hydrogen Strategy by the European Commission in July 2020 (European Commission 2020a). The Commission introduced several targets within its Fit-for-55 legislative package and updated its hydrogen strategy in late 2021 to emphasise use in steel and cement (among other sectors).

Ever since then, several countries have also made tentative steps in charting their own national strategies, chiefly among which the one from Germany (German Federal Ministry for Economic Affairs and Energy 2020), Spain (Spanish Ministry for the Ecological Transition and the Demographic challenge 2020), the Netherlands (Ministerie van Economische Zaken en Klimaat 2020), Norway (Norwegian Ministry of Petroleum and Energy and Norwegian Ministry of Climate and Environment 2020) and France (S&P Global Market Intelligence 2020). All these documents reserve a significant role for 'Green Hydrogen', produced via the electrolysis of water using electricity produced by renewables, or, in the case of France, also by nuclear power. The number of countries with roadmaps for hydrogen is growing by the day; while in 2017 only Japan had a hydrogen roadmap, today over 30 countries have developed or are preparing such strategies (IRENA 2022), and numerous companies are seeking to tap into hydrogen business opportunities (International Energy Agency 2021).

The underlying reason is that emissions-free hydrogen can overcome many of the hurdles that clean electricity itself cannot at present do very effectively – predominantly in industries using high-grade heat, in freight transport, in shipping and in aviation. It can also complement and safeguard an electricity network by providing non-intermittent energy storage, by taking advantage of existing natural gas network infrastructures. A major incentive to promote hydrogen lies in the uncertain future for fossil fuel companies (mining, extraction, exploration, transportation, and utilities), as they fear their assets becoming stranded if rapid electrification of the transportation and domestic heating sectors takes place.

There are still several drawbacks with the use of hydrogen. These include several efficiency penalties in the various transformation stages in which hydrogen provides useful end products, its flammability and general difficulty in handling, the extremely low liquefaction point, the very low density, the need for highly fortified containers to prevent leakages, the embrittlement of containers and pipelines, and, as of present, its high cost. Added to this discussion should be the feasibility and desirability of Carbon Capture and Storage (CCS) as an option if hydrogen utilises existing hydrocarbon reserves (a route for hydrogen production called 'blue' hydrogen).

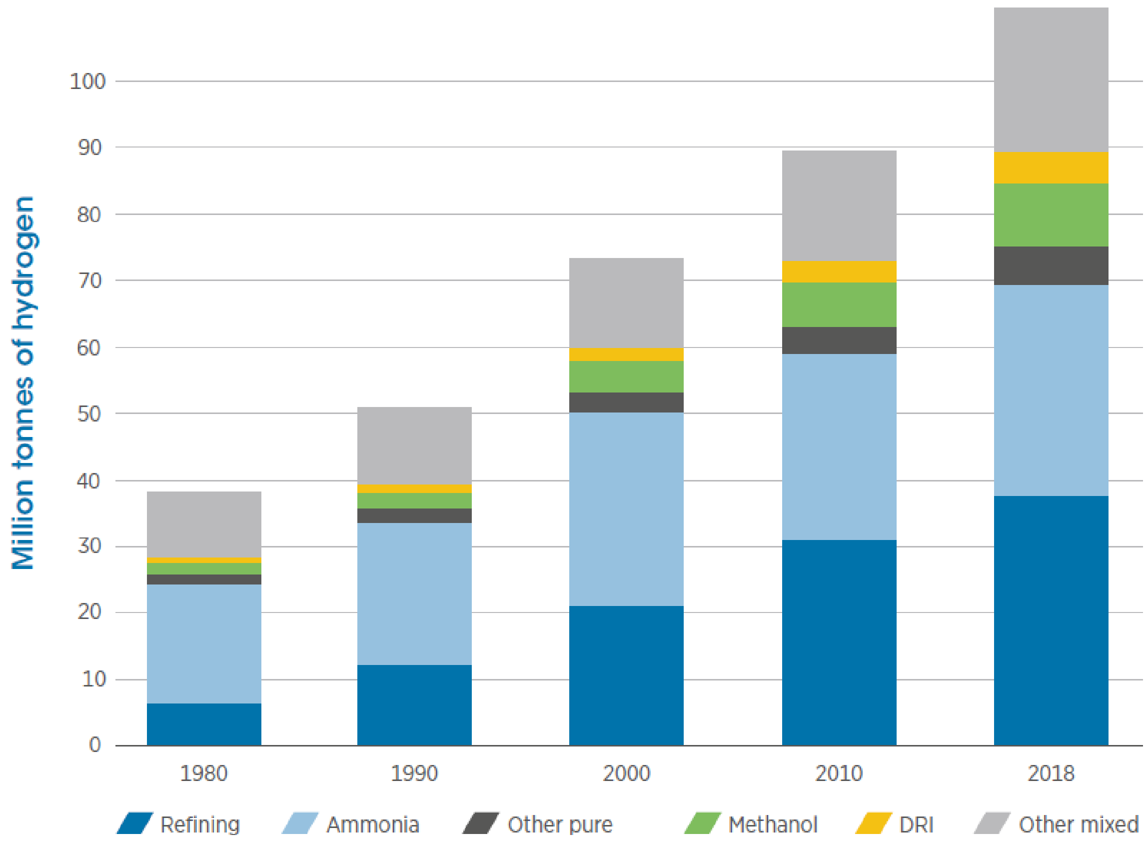


Figure 1: Current global demand for hydrogen. Source: (IEA, 2019)

The attention for the technology largely bets on the things it promises to do, rather than what it does already. Most of the hydrogen currently produced comes from fossil fuels such as natural gas and coal, creating emissions equivalent to 110 times the overall emission from Cyprus — about 830 million tonnes of carbon dioxide annually — mainly as an input to the petrochemical, fertiliser and liquid fuel sectors (IEA 2019a), while demand is in refining and ammonia production for the most part (Figure 1).

The European Commission (2020b, 2020a) supports hydrogen production based entirely on renewable electricity, but in May 2021 Europe has also backed Low Carbon Hydrogen, that includes 'blue' hydrogen using CCS/CCUS solutions (Kurmayer 2021). These plans however may be hard to realise, with carbon storage sites hard to come by, and - at least in Europe – concentrated in depleted hydrocarbons reservoirs in the North Sea. Even if storing CO_2 at those sites proves effective and cheap, which is still debateable, it would leave countries far from these locations with no real immediate option for storage[1]. Right now Europe is responsible for 10% of the global hydrogen production (Terlouw and Peters 2019) but these numbers will have to be markedly ramped up if the projected demand for hydrogen are realised.

[1] Facilities - Global CCS Institute (co2re.co)

With the publication of the Fit-for-55 package in July 2021, the European Commission proposed an extensive set of legislation for achieving the European Union's (EU's) target of reducing greenhouse gas (GHG) emissions by 55% by 2030. As part of the package, a revised and more ambitious Renewable Energy Directive (RED) II was proposed. In this directive, the EU's new target share of renewable energy sources is proposed to increase from at least 32% to 40% by 2030. The proposal also contains a set of new sub-targets for 2030 and extended requirements for renewable fuels of non-biological origin (RFNBOs, including renewable hydrogen and its derivatives), aimed at achieving Europe's ambitious climate targets. The requirements for counting RFNBOs as renewables are being extended from transport to other end-use sectors.

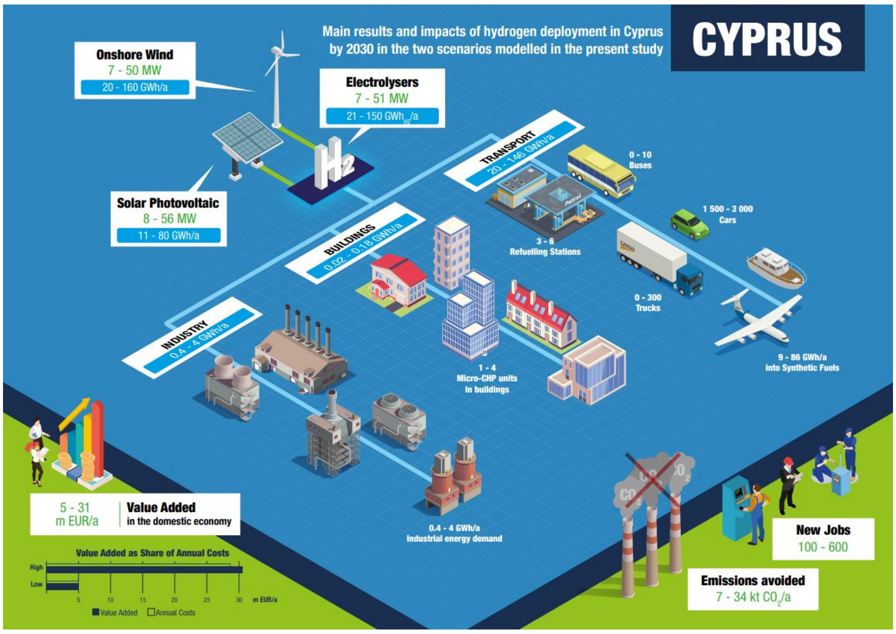


Figure 2: Hydrogen deployment in Cyprus according to Fuel Cells and Hydrogen JU (2020)

Two new targets are proposed for industry: Firstly, the Commission proposes a new indicative 1.1% annual increase in the share of RES used in industry. Second, a binding 2030 target for renewable fuels of non-biological origin (essentially renewable hydrogen) is proposed on Member States for 50% of the hydrogen used as feedstock or as an energy vector in industry.

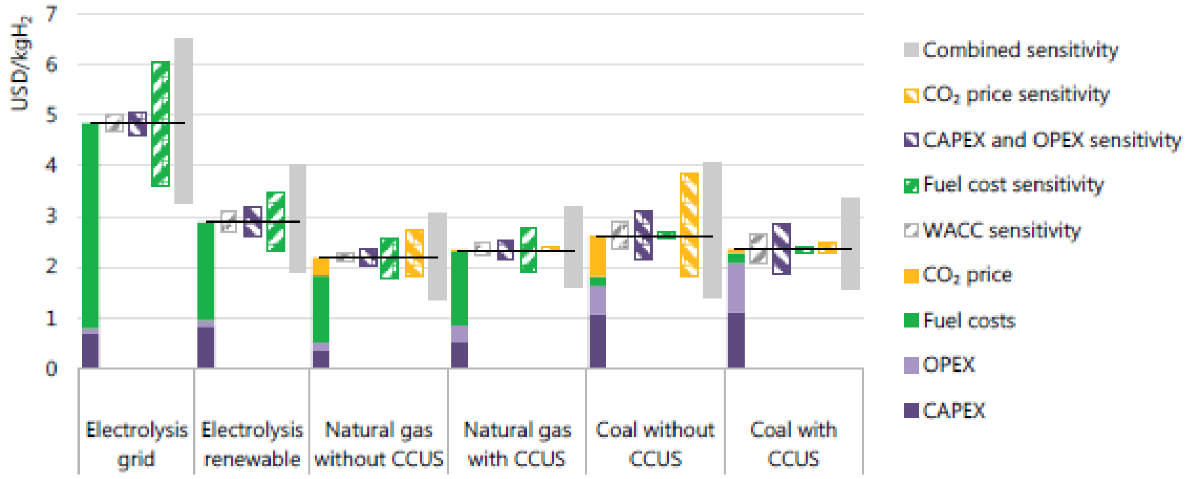
In transport a reformed, more ambitious, and still binding target is proposed: Member States are obliged to reduce the greenhouse gas intensity of fuels by 13% by 2030, but the methodology to calculate this target is not technology-neutral - only the use of renewable fuels or electricity will count. The use of low-carbon fuels based on blue hydrogen (see par. 2.3) would not therefore count towards this 13% target. A new sub-target for renewable hydrogen is established (at 2.6% for 2030) (Jones and Piebalgs 2021).

Implications for Cyprus:

1. Cyprus should act fast and settle on a hydrogen deployment roadmap with adequate consultation from all stakeholders, supported by modelling and calculations considering the particularities of its island nature. Island and isolated energy systems exhibit distinct characteristics compared to continental, interconnected grids. Cyprus remains the only energy isolated EU country.
2. The Fit-for-55 package is expected to increase the pressure for the use of hydrogen in all EU member states because of extended requirements for renewable fuels of non-biological origin (RFNBOs, including renewable hydrogen and its derivatives), aimed at achieving Europe's ambitious climate targets. The requirements for counting RFNBOs as renewables are being extended from transport to other end-use sectors. **Without some pilot installations close to potential end use points (see sec. 5), Cyprus is losing valuable time and needs to act fast**.

2 Production

An overall comparison of hydrogen production cost from each technology is presented in Figure 3 showing the average and best-case supply costs of hydrogen from renewables and fossil fuels. Producing hydrogen from renewables (green hydrogen) could potentially be a cheap option, however this only applies in specific situations. In the best-case option for green hydrogen, it can be produced from wind at 23 USD/MWh assuming an electrolyser with a 200 USD/kW and total production cost of some 1.7 USD/ kgH_2, while the overall cheapest option is producing hydrogen using natural gas in steam methane reformers (SMR) with CCS at 3 USD/MM Btu, which would have a production cost of some 1.5 USD/kgH_2. The most expensive option of hydrogen production is from photovoltaics with a production of some 6.8 USD/kgH_2.



Notes: WACC = weighted average cost of capital. Assumptions refer to Europe in 2030. Renewable electricity price = USD 40/MWh at 4 000 full load hours at best locations; sensitivity analysis based on +/-30% variation in CAPEX, OPEX and fuel costs; +/-3% change in default WACC of 8% and a variation in default CO_2 price of USD 40/tCO_2 to USD 0/tCO_2 and USD 100/tCO_2. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Figure 3. Hydrogen production cost from different technologies 2030 (IEA 2019b)

The most established technology used for producing green hydrogen is water electrolysis via renewable electricity. Using green electricity in electrolysers however is tied to significant efficiency penalties: Approximately half of the energy is lost in the various stages of production (30% alone is lost in breaking the water chemical bond), **and a strong case can be made that electricity would be better used directly in several applications**. Yet, from a cost point of view, price parity for green hydrogen is expected by the end of the decade in renewable energy-rich areas of the world (Sheppard, Hume, and Thomas 2021).

2.1 Electrolyser types

Electrolysis requires an electricity source, electrodes, and a conductive electrolyte. There are three mature types of electrolysers in use today:

1. Alkaline Electrolysers (AEL)
2. Polymer electrolyte membrane (PEM) and
3. Solid oxide electrolysers (SOEC)

Alkaline electrolysers are considered well advanced and can generate renewable hydrogen at substantial rates, with an operation efficiency ranging between 62 and 82%, and production capacity from 1 to 760 Nm^3/h. Some 9 litres of water are required to produce 1kg H_2. Oxygen is also produced as a by-product (8 kg) which could be used in other sectors (e.g., industry).

Electrolysis can take also place in an acid medium, a process known as Proton Exchange Membrane (PEM) or Solid Polymer Electrolyte (SPE) which does not require any electrolytic liquid. PEMs operate at a temperature of 80 °C and 15 bar pressures, with a specific energy demand between 4.5 and 7 kWh/Nm^3H_2. The production capacity ranges between 0.06 and 30 Nm^3/h, and their efficiency between 67 and 82%. Despite some advantages PEM electrolysers have, such as reduced corrosion of electrodes compared to AEL, they have a higher investment cost due to the membranes and noble metals of electrodes. Solid oxide electrolysers (SOE) operate at higher temperatures (600 – 1000 °C) which allows for higher efficiencies compared to AEL and PEM methods. SOEs require a heat source for high temperature electrolysis, such as nuclear heat, solar thermal or geothermal systems. However, finding thermally stable and waterproof materials is a barrier. Currently SOEs are considered the least advanced electrolysis method, and have not yet been commercialised at scale (Braga et al. 2017; IEA 2019b).

2.2 Electrolyser costs

Several technical and economic factors affect the production costs from water electrolysis. Today, CAPEX is between 500 and 1,400 USD/kW_e for AELs, between 1,000 and 1,800 USD/ kW_e for PEMs, and estimated between 2,800 and 5,600 USD/ kW_e for SOEs. Electrolyser stack has the largest share of CAPEX, 50% for AELs and 60% for PEMs.

In the case of increased share of renewables in the electricity mix, surplus electricity may be available at a low cost, which could allow for producing hydrogen and storing it for later use. However, in the case of low availability of surplus electricity (i.e., a low capacity factor), the electrolyser economics look less favourable.

Christensen has recently (2020) assessed the costs of electrolysers in the US and Europe under various scenarios of deployment (grid connection, dedicated renewable production and grid connection but using only renewable curtailed generation) and found that costs are generally higher than usually quoted in the literature due to the Balance-of-Plant costs that are usually omitted (e.g. compressors, localised storage etc.), and that they range from around $13/kg in Europe today down to $7.7 in 2050 for grid connected H_2, and $19 today to $/kg in 2050 for dedicated production. These numbers are substantially larger than what we get today from Natural Gas, even if using CCS.

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
Operating pressure (bar)	1–30			30–80			1		
Operating temperature (°C)	60–80			50–80			650 – 1 000		
Stack lifetime (operating hours)	60 000 – 90 000	90 000 – 100 000	100 000 – 150 000	30 000 – 90 000	60 000 – 90 000	100 000 – 150 000	10 000 – 30 000	40 000 – 60 000	75 000 – 100 00
Load range (%, relative to nominal load)	10–110			0–160			20–100		
Plant footprint (m^2/kW_e)	0.095			0.048					
CAPEX (USD/kW_e)	500 – 1400	400 – 850	200 – 700	1 100 – 1 800	650 – 1 500	200 – 900	2 800 – 5 600	800 – 2 800	500 – 1 000

Notes: LHV = lower heating value; m^2/kW_e = square metre per kilowatt electrical. No projections made for future operating pressure and temperature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

Sources: Buttler and Spliethoff (2018), "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: a review"; Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), *The Future Cost of Electricity-Based Synthetic Fuels*; NOW (2018), *Studie IndWEDe Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme*; Schmidt et al. (2017), "Future cost and performance of water electrolysis: An expert elicitation study"; FCH JU (2014), *Development of Water Electrolysis in the European Union, Final Report*; Element Energy (2018), "Hydrogen supply chain evidence base".

Figure 4. Techno-economic characteristics of electrolysers (IEA 2019b)

Cyprus Focus: Electrolysis

- There is no doubt that localised production of green H_2 will be required for decarbonising hard to abate sectors. There is a strong probability of increased costs in the long run, but these will have to be mitigated by energy efficiency and the fact that Cyprus is endowed with great solar potential – which reinforces the argument on localised production.
- Electrolyser infrastructures are getting larger. While in 2020 the largest system in operation was 25MW, there are several >100MW under construction and a few >1GW. This will be crucial in bringing costs down and standardising the technology, that Cyprus can then tap in using its – mainly – solar potential.

2.3 Other production methods

Grey hydrogen (sometimes called black or brown) refers to the production from fossil fuels and entails substantial CO_2 emissions and is not suitable as a path towards decarbonisation (IRENA 2020b). Currently, the primary source of hydrogen is natural gas in the diesel purification, ammonia and methanol industries utilising steam methane reformers (SMR). SMR happens in two steps, one taking place at high temperatures (steam reforming) in which the fuel is converted into a gaseous mixture after reacting with steam, and the second step occurring in lower temperatures in a shift reactor, in which the CO which is part of the synthesis gas reacts with H_2O to produce CO_2 and H_2 (Braga et al. 2017).

Some 75% of the annual global hydrogen production (70 Mt H_2) are attributed to natural gas production, 23% is attributed to coal, and the remaining 2% accounts to oil and non-renewable electricity. **It is expected that SMR will retain its dominant status as the main technology for hydrogen production in the short and medium term due to its advantageous economics and the large number of units that are currently in operation** (IEA 2019b)**.** The cost of production from natural gas (excluding CCUS) is now in the range of 1-2 USD/kgH_2, contingent on the local cost of fuels that have the largest share of production costs – excluding hydrogen production from coal.

Cyprus Focus: Grey hydrogen production

1. The imminent availability of NG in Cyprus (the relevant infrastructure will be ready by mid-2023 as per the latest reports) presents a rather tempting proposition of using it to produce grey hydrogen from a cost point of view, even though it does not offer any distinct advantage domestically over existing technologies if it is not emission-free.
2. In fact, relying on SMRs for large scale H_2 production without CCS, will result in **more emissions compared to the direct use of fossil fuels** due to conversion efficiency losses.

Blue hydrogen is technically grey hydrogen coupled with CCS. It is expected to play a role in the early stages of energy transition and could help hydrogen market grow. CCS offers potentially a lower-emission pathway for using hydrogen and can alleviate the pressure on the capacity of renewables required to generate green hydrogen.

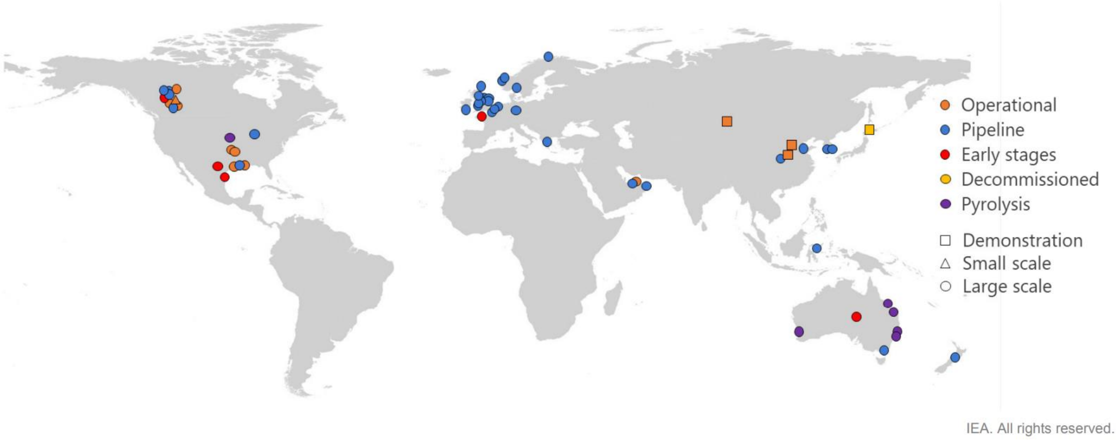


Figure 5: Projects for producing hydrogen from fossil fuels with CCUS, operational or under development. Source: IEA (2021)

Blue hydrogen production consists of five steps: (a) production, (b) CCS, (c) hydrogen transport, (d) daily and seasonal storage, and (e) industrial applications. Capturing CO_2 takes place after the water-gas-shift reactor or after the hydrogen separation step, but CO_2 can also be found in the flue gas of SMR which can be captured, albeit harder given the large share of nitrogen. It is generally expected that blue hydrogen will play a role in the short-term horizon and will be replaced by green hydrogen (van Cappellen, Croezen, and Rooijers 2018), but exporting nations that base their economies on the use and export of fossil fuels consider CCS a central option for their decarbonisation plans.

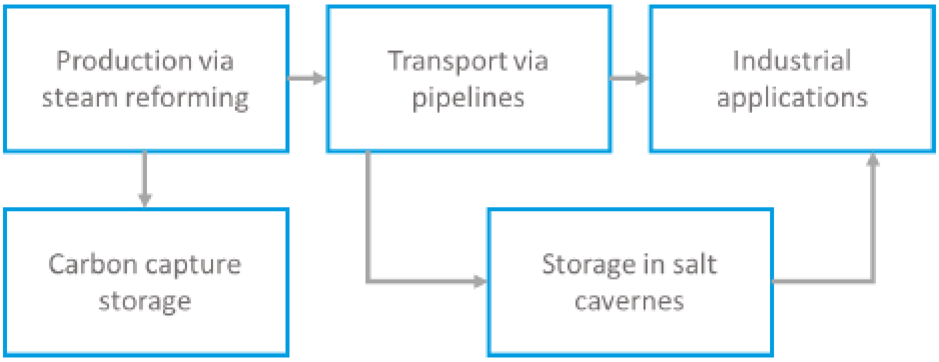


Figure 6. Blue hydrogen process diagram (van Cappellen, et al. 2018)

Blue hydrogen must therefore be seen with scepticism: its deployment is contingent to fluctuations of fossil fuel prices, the continuous reliance on economies built around extraction and use of fossil fuels, the potential lack of social acceptance, the relatively low capturing efficiency (right now in the mid-50%, expected to rise and reach 85-95%) and the elevated costs. Overall, carbon emissions from blue hydrogen production can be driven down substantially, but not eliminated.

Cyprus Focus: Blue hydrogen

1. CCS remains off-track for large scale deployment, but several projects across the world will certainly accelerate maturity. It is not certain yet that the level of capture will be adequate to address plans for net zero emissions, and the process is heavily linked to methane leakages if connected to CCS on the power side
2. Cyprus potential to store CO_2 in geological formations is still unknown.

There are other production methods, of note is “turquoise” hydrogen, referring to the process of producing hydrogen from natural gas via pyrolysis, that does not result in CO_2 emissions. In this process the carbon content of methane is transformed into carbon black, a solid that’s far easier to store than CO_2. This also provides an additional potential revenue stream due to an already existing – but presently rather small - market. Nevertheless, turquoise hydrogen is still at a pilot stage (IRENA 2020b), even though it is quickly gaining attention (e.g., see Conti et al. 2021).

3 Storage, Transportation & Power generation

3.1 Storage of Hydrogen

Despite the large energy content of hydrogen (33 kWh/kg compared to 12 kWh/kg of petrol and diesel), large volume is required to store it, and **hence the energy density of liquid or compressed H_2 at practical pressures is significantly less than traditional fuel sources**. Therefore, developing hydrogen storage technologies is a major requirement for hydrogen powered energy systems. A large amount of hydrogen storage options is required to maintain the hydrogen value chain, considering the short- or long-term needs. It must not be forgotten that storing hydrogen is rather inefficient process, with only around 50% round-trip efficiency – far worse than batteries (Leibreich, 2020).

3.1.1 In cylinders

The most common method of hydrogen storage is compressing it into steel gas cylinders at a high pressure (700 bar). There are several challenges using this approach such as the weight of the cylinder which limits the capability of transport, or the heat transfer process during compressing (composite degradation), and the high cost (about 500 – 600 USD/kgH_2). **This process would require much more space to store the equivalent amount of energy compared to gasoline**.

3.1.2 Underground

Underground storage in aquifers (depleted deposits of natural gas and oil) or salt caverns are considered as the main options for large-scale hydrogen storage in medium and long term. Approximately 75% of the underground storage is in depleted deposits, with salt caverns taking great interest lately due to their stability and imperviousness of their walls of salt caverns. Salt cavern storage could have a volume range between 100,000 and 1,000,000 m^3 at maximum 200 bar. There are some technical challenges though such as tightness of boreholes and the transfer capacity of the surface installation, and environmental limitations in terms of sustainable development should be considered.

3.1.3 Liquefaction/compression

Another method of hydrogen storage is by liquefaction at very low temperatures (around 20 – 21 ^oK) and the volumetric density can reach 70.8 kg/m^3 but storing hydrogen in liquid form is time and energy consuming **as there are losses inherent in the process that can reach 45% of the energy content of the H_2 itself**. Currently this method is not commercialised at scale, while the low volumetric density would also increase transportation costs.

3.1.4 In hydrides

Solid hydrogen is another option in which hydrogen is combined with solid materials via absorption and adsorption. In absorption hydrogen is stored into the bulk of the material to form chemical compounds, out of which hydrides have gained interest due to their high storage capacity (e.g., palladium can store 900 times its own volume). Storing hydrogen in hydrides has several benefits, such as the suitability for long-term storage given the decoupling of energy and power rating, the ability to be directly coupled to electrolysers as it can be operated at a low pressures, safety and slow kinetic rate, and the high volumetric storage density (Yue et al. 2021; IEA 2019b; Abdin et al. 2020) but their commercial application is still unproven.

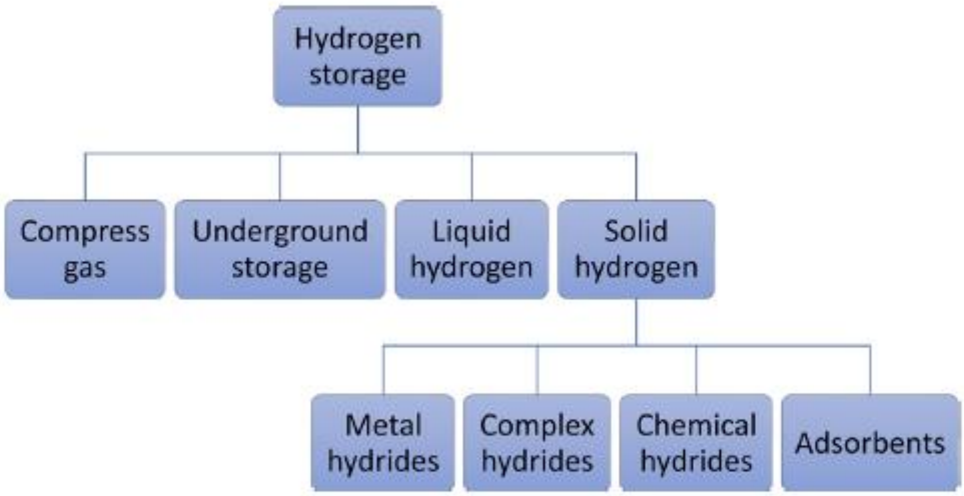


Figure 7. Hydrogen storage technologies (Yue et al. 2021)

3.2 Transportation

Hydrogen can be transported in various ways, depending on several factors such as the distance to be covered and the medium of storage. The EU Agency for the Cooperation of Energy Regulators (ACER) has recently completed a meta-study summarising the findings of several individual studies that investigated transporting H_2. The main conclusion is that

> *For smaller volumes and distances (less than 10 tonnes of hydrogen per day and less than ~ 200 km), transportation of hydrogen by trucks seems to be the most cost-effective option, in compressed form for short distances, and in liquid form for small volumes over longer distances (hundreds of km). For volumes exceeding 10 tonnes/per day, pipelines appear to the lowest-cost transportation option in most cases: distribution pipelines are preferred for local networks, while transmission pipelines with a capacity beyond 100 tonnes per day are more suitable to carry large volumes over longer distances. Shipping hydrogen carriers (ammonia) seems to be more economic for intercontinental distances of thousands of km, requiring high capacities (>100 t/day)* (ACER 2021).

Specifically for transportation via pipeline, hydrogen could be blended into the existing natural gas infrastructure and take advantage of the pipeline network. This is relevant for Cyprus that plans to build a transmission pipeline network from the Vassiliko area to the main consumers. At the moment this blending can be safely done up to about 15% p/v (Melaina, Antonia, and Penev 2013), but higher concentrations will require the repurposing of existing pipelines to combat steel embrittlement and issues with hydrogen compression. This is however easier and cheaper than building a dedicated hydrogen pipeline network: The ACER report states that '***the capital cost per km of refurbished hydrogen pipelines would amount to ~33% of the cost of newly built hydrogen pipelines***' (ACER 2021).

3.3 In Power Generation and Grid Services

Hydrogen can potentially have a major role in the future power systems covering needs for seasonal storage and system balancing, by offering services such as energy time shift, and balancing demand and supply through storing excess electricity generated by renewables released when required, e.g., using stationary fuel cells. **Compared to other options, such as batteries, hydrogen has a much higher storage duration which can be even up to months, whereas batteries can only be used for hourly or weekly storage.** Also, it can have a much higher scale in terms of capacity, reaching MWh or even TWh. Trinomics states that *"Cyprus could assess the potential contribution of deploying hydrogen in the frame of security of energy supply and to address the challenge of balancing electricity supply and demand in a system with a high share of variable renewable energy"* (Fuel Cells and Hydrogen JU 2020).

Hydrogen can also offer ancillary services to the grid via fuel cells and electrolysers, such as congestion mitigation, reduction of negative price incidences, frequency control, voltage control and black start. Transmission and distribution line congestion might occur in power systems and hydrogen storage – like other types of energy storage – can be used to mitigate it. While other types of energy storage might offer these services, **hydrogen has the major benefit of a low response time (seconds) which makes it very attractive** (Yue et al. 2021).

As mentioned, hydrogen can be used directly for combustion, **but right now the industry of Hydrogen-Fuelled Gas Turbines (HFGTs) is at a nascent stage of development** (Hernandez and Gençer 2021). The authors state that '*certain existing natural gas-fired gas turbines can operate with a blend of hydrogen and natural gas, but there are very few that can fuelled exclusively with hydrogen. This is primarily because the flame length of hydrogen is much longer than natural gas – this longer flame length leads to the production of NOx, a local air pollutant*'.

Cyprus Focus: Hydrogen storage, transportation and use in the power sector

1. Large-scale storage of H_2 in quantities required to serve large end uses (e.g., in industry), serving as a balancing agent for the electricity grid, or providing seasonal storage services **cannot be achieved just by storing it in pressurised containers**. Storing in salt caverns, depleted hydrocarbon reservoirs or aquifers is an option that needs to be **explored carefully in coordination with national authorities (e.g., the Cyprus Geological Survey Department)**
2. The pipeline transmission network for H_2 does not yet exist, but it can be based on NG pipes after repurposing. If there are ways to design NG pipelines now that will anticipate this conversion and reduce complexion and repurposing costs in the future, **they should be investigated as soon as possible**.
3. While fuel cells are an established method of converting H_2 to electricity, they remain an expensive solution for large-scale electricity production. **Combustion in existing Gas infrastructure should be included in the planning, but the technology does not yet exist**.

4 End uses

4.1 Road transport

Hydrogen passenger vehicles garnered a lot of attention a few decades ago when the engineering advances in fuel cells made the use of compressed hydrogen onboard vehicles a possibility. Fuel cell (FC) cars became commercially available in 2014 but only around 26,000 hydrogen FC passenger cars were sold by the year 2020 since their sales first began (IEA, 2020b). The market penetration of these vehicles has not been very deep mainly because as a source of work, fuel cells, turbines and engines are only 60% efficient (considerably less than electric motors), they are quite more complex than battery electric vehicles, and building a hydrogen refuelling station is also very costly[2].

For these reasons there are still fewer than 20,000 heavily subsidised hydrogen fuel cell (H_2FC) vehicles on the roads globally, served by around 400 almost exclusively publicly funded hydrogen filling stations (Leibreich 2020). **There are a few commercial passenger cars in the market today, albeit restricted to Japanese and Korean automakers (Toyota, Hyundai, and Honda), spurred on by domestic hydrogen support policies**. Hydrogen vehicles of this size exhibit low round-trip efficiencies, essentially restricted by physics, since there are several unavoidable steps between the energy source and motive energy at the wheels: Any renewable energy that acts as a feedstock (typically solar or wind) must be converted to electricity to drive the electrolyser, then compressed (or liquefied), transported, stored, reconverted to gaseous form, converted back to electricity through the on-board fuel cell, and finally converted to mechanical energy through an electric motor. **The final energy at the wheels is around 30% of what was generated**.

FCEVs (Fuel Cell Electric Vehicles) have an advantage as the size and range demand of vehicles increase. The inherent disadvantage of Electric Vehicles (EVs) is that the long ranges (>400km on a single charge), and powering heavier, less aerodynamic vehicles requires a proportionally larger battery pack that adds significant weight and requires longer charging times. FCEVs scale better: Hydrogen itself is extremely light, and larger compression tanks and fuel cells do not add weight at the same rate as EVs. This is why FCEV buses and heavy-duty long haul vehicles are a more attractive proposition than using batteries, even though fuel cell requirements for such vehicles are more stringent than passenger cars, and hence costs are higher (IEA 2019a).

In the light of the above, **the deployment of a hydrogen-powered bus fleet** (see section below) **may be a viable option in Cyprus, especially if the primary goal is sector decarbonisation**. These could operate in 'star' configuration, with a central hub offering refuelling. The case of long-haul trucking is less clear since the distances trucks cover on Cypriot roads are usually small – urban centres are less than 150km away from the country's ports and airports.

Increasing renewable targets in transport could have an impact on elevated hydrogen penetration (see section 5). The European Green Deal calls for a 90% reduction in greenhouse gas emissions from transport, for the EU to become a climate-neutral economy by 2050, while also working towards a zero-pollution ambition (European Commission 2020c).

Table 1: Cyprus' outlook for FCEV road vehicles

[2] Costs at $5 million for a station that can fill up to 25 buses a day at 6-to-10 minutes per bus. Source: https://h2stationmaps.com/costs-and-financing

Current status	Demand perspectives	Future deployment outlook
Non-existent penetration of either light duty or heavier FCEV vehicles	Depending on national strategy, **low** to **moderate**	For passenger vehicles: **Low**. The distances in Cyprus negate the largest potential advantage of FCEVs For heavy duty trucks and buses: **Medium**. This will depend on policies for deployment of fleets and the availability of refuelling stations.

4.1.1 Hydrogen-powered public transportation vehicles

Public transportation in Cyprus is served only by buses and therefore only those are discussed in this subsection. Hydrogen fuel cell (HFC) buses have been developed and trialled in Europe for more than a decade through various prototype vehicles or demonstration projects to test large fleets in the field. A key challenge of the commercialisation of HFC buses relates to the high ownership costs, as well as the high hydrogen infrastructure costs. The production costs for 12-metre hydrogen fuel cell busses are still much higher than standard diesel and electric buses. As in 2017, the purchase cost for a hydrogen fuel cell bus was around €1m, while the cost for a battery-electric (BE) bus was around €450k, and the cost of a standard diesel bus was around €250k. (Logan, Nelson, and Hastings 2020; Shell and Wuppertal Institut 2017). These costs are expected to fall as the annual production numbers increase.

Pre-commercial demonstration projects in place currently in Europe, such as the Joint Initiative for hydrogen Vehicles across Europe (JIVE) and JIVE 2 project, will pave the way to commercialisation by addressing the issues of high upfront vehicle costs, which together with infrastructure are the main barriers for the adoption of HFC buses. The overall objective of these initiatives is to unlock economies of scale through the large-scale deployment of vehicles and infrastructure in different cities in Europe. Thus, by the end of the projects, the costs for the HFC buses are reduced enough so they are commercially viable for the bus operators to include them in their fleet without the need for a subsidy aiming at a maximum price of €625k for a standard (12-metre) HFC bus thanks to economies of scale (Faltenbacher et al. 2018; Fuel Cell Electric Buses 2017). The overall price of FC buses is expected to fall to around €325k by the year 2030 as the cost of the components of the FC powertrains such as the fuel cells, hydrogen tank and battery, drop significantly (Monitor Deloitte 2021). However, as those buses have not been manufactured yet in large-volume series, it is difficult to estimate the related costs precisely.

The advances of the HFC buses over the BE buses is that they perform like traditional diesel buses. The current range of the HFC buses, up to 450km, is sufficient to cover the expected daily mileages of long-range bus segments and they can be refuelled in less than 10 minutes (Ballard power 2021). The refuelling stations are likely to be in or close to the bus depot, eliminating the need for roadside charging infrastructure.

Although there are a variety of factors that influence the choice of technology, such as the cost of acquiring buses and operating them[3], refuelling time and vehicle range, the total cost of ownership (TCO) is ultimately what matters the most to bus fleet operators. Cost analysis available in the literature shows that fuel cell technologies are ideal for the decarbonisation of long-range bus segments. In bus segments with short ranges, BEVs becomes the most competitive low carbon

[3] Operational costs include vehicle maintenance and fuel cost which depends on the production, transmission costs, as well as the infrastructure cost for refuel or charging.

alternative (Hydrogen Council 2020, Kim et al. 2021, Hyundai Motor Group TECH 2020), accounting for the fact that the average daily mileage of buses in Cyprus is around 150km.

4.1.2 Purchase of hydrogen-powered HGVs

In contrast to HFC buses, hydrogen-powered heavy-good vehicles (HGVs) have begun on-road demonstrations in the last couple of years but are still low in production levels to enable a commercial market. A detailed survey on trial and demonstration projects with HGVs is available by Ruf *et al.* (2020b). Currently, due to low prototype production volumes, the production cost for HFC HGVs is high. Successful commercialisation and market integration of HFC HGVs will depend on lowering their TCO and dealing with the lack of sufficient refuelling infrastructure for HFC HGVs. Likewise, BE HGVs face limitations regarding the charging time requirements as well as the battery weight and price, which constraint their range and payload. Nevertheless, BE HGV progress benefits from industry experience in smaller vehicle segments such as passenger cars and light-duty vehicles which have a head start of several years over HFC powertrains (Shell and Wuppertal Institut 2017, Ruf et al. 2020a). Therefore, the technological readiness of BE HGVs is higher compared to HFC HGVs, with the former being at a pre-series stage demonstrated in operational environments, while the latter being at a prototype stage demonstrated in relevant environments (Ruf *et al.* 2020b).

Currently, there is very limited field data on zero-emission powertrains for HGVs, i.e., BEV and HFC. There is big uncertainty around predicted performance and cost developments of the vehicles, which are mainly based on assumptions and limited data from the prototypes or small-scale demo phases. Therefore, industry knowledge needs to be verified in first demonstrations and early commercial deployments.

Several studies comparing the TCO of the alternative powertrains have shown that the most economical solution for zero-emission HGVs is the electric powertrain since the vehicle purchase cost, as well as the infrastructure cost for fuel cells is significantly higher compared to the alternative electric powertrains (ESC and APC 2019; ETI 2017; Plötz et al. 2018; Transport & Environment 2021). However, some studies have shown that fuel cell vehicles might be more cost-competitive compared to electric HGVs with a battery range of 800km (Kühnel, Hacker, and Görz 2018; Mottschall 2019). Due to the current uncertainties regarding the development of technology costs, energy prices and regulatory framework around the decarbonisation of HGVs, no clear preference between fuel cells and battery electric powertrains can be taken as it regards the purchase cost of the vehicle.

According to the data used in a recent project by the UK Energy Systems Catapult (ESC), on average rigid HGVs cover 242km daily and articulated HGVs 412km daily Freight (ESC and APC 2019). Since articulated HGVs cover longer distances compared to rigid HGVs, as expected, the powertrain costs of the former will be higher compared to the latter due to bigger batteries and bigger hydrogen fuel tanks. In 2025 CAPEX of an average rigid electric HGV and an average rigid fuel cell HGV is projected to be around €100k and €207k respectively while the cost for a baseline diesel powertrain is expected to be around €78k. In 2025 the CAPEX of an average electric articulated HGV and an average articulated fuel cell HGVs is projected to be around €163k and €255k respectively, while the cost for a baseline diesel articulated powertrain is expected to be €82k. Since the body and the trailer of a vehicle are independent of the powertrain, the difference in the HGV cost is attributed to the powertrain. The study reached the conclusion that, based on today’s assumptions, expected market developments and the foreseeable technology cost reductions, **battery electric long-haul trucks and those using an overhead catenary infrastructure are likely going to be the most cost-effective pathway to replace the vast majority of today's diesel-powered vehicle fleet**

and, eventually, reach zero well-to-wheel road freight greenhouse gas (GHG) emissions by 2050.

In Cyprus, the distances HGVs cover are much less than what HGVs cover in other European countries. So, the rigid HGV categories in the UK might be more comparable to the HGV categories in Cyprus. Based on the data mentioned above, the fuel cell HGV in 2025 is expected to be 107% more expensive than the electric powertrain.

Cyprus Focus: Hydrogen-powered Road Transport

1. Hydrogen-powered passenger cars will need **very generous backing if they are to compete against BEVs**. Not only are there fewer vehicles to choose from, their higher upfront costs and the very high capital costs of hydrogen refuelling stations make their deep penetration unlikely. Their advantage on range and refuelling times are partially negated by the short distances in Cyprus and the fast-charging capabilities of DC chargers to be rolled out in certain locations across the country.
2. There is a case to be made for both HFC buses and heavy-good vehicles. The total cost of ownership for both these categories is declining and combined with falling costs of key equipment (predominantly the power train), would make for a compelling option for a decarbonised fleet, **but due to the short distances and falling costs of BEVs, the choice is less clear than for passenger vehicles.**

4.2 Aviation

Hydrogen for use in aircraft has long been touted as one of the possible technologies to decarbonise the aviation sector. Recent publications in the general public press (Hollinger 2021; The Economist 2020) point to the fact that there is a lot of activity both from start-ups and from mainstream manufacturers of airplanes (e.g. Airbus 2020) for a future that heavily relies on green hydrogen. **The economics however are not favourable at the moment: assuming advances in propulsion technology, higher compression containers and solution of issues of storage of liquid H_2 onboard, a switch to hydrogen would result in price increases in the range of 10-60% per passenger, depending on size of aircraft** (Fuel Cells and Hydrogen JU and Clean Sky 2 JU 2020). Yet, it is believed that 2030 may be the cut-off point where the use of liquified H_2 in pressurised cryogenic tanks can become economical, but only for short-haul flights (i.e., covering distances under 1,500 km).

Decarbonisation of the sector must address the long-haul flights, which account for over 80% of its emissions. The European Commission in its recent transport vision document (European Commission 2020c), envisages large commercial hydrogen planes to be ready by 2035.

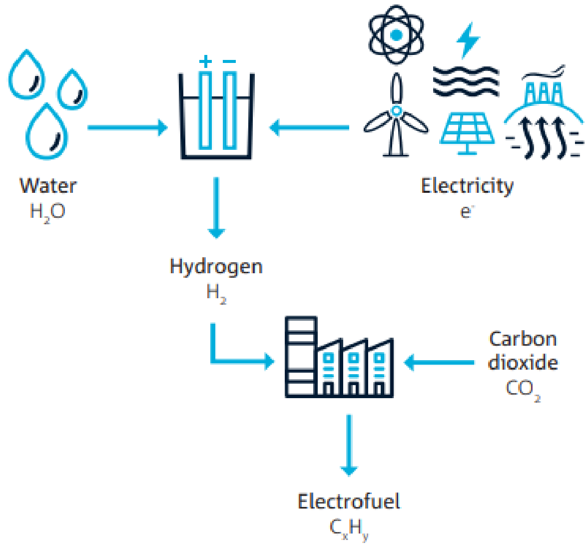


Figure 8: Electrofuels production principle. Source: Bruce et al. (2020)

The industry is not relying only on pure hydrogen using cryogenic tanks for propelling aircraft. A dominant trend in the attempts to decarbonise the aviation sector is the use of synthetic fuels (also called 'electrofuels'), that are derived from the **reaction of green hydrogen with CO_2, either from waste gas or from direct air capture** as recently reported by Boeing and CSIRO (Bruce et al. 2020). It is argued by several industries of the sector that the cost of these fuels remains high (in the order of 8 times that of kerosene), but these will eventually fall and be de-risked after 2030, settling at a level of around 1.5-2 times that of conventional fuels. It is thus more prudent, according to them, to adopt a staggered blending of these fuels with traditional jet fuel until their complete adoption by 2050. These scenarios are favourable to the aviation industry as it stands now, since few changes will need to happen in aircraft, engine, and airport design (Ueckerdt et al. 2021).

For Cyprus, flights that serve the usual destinations departing the island are mostly travelling towards Europe, mainly Greece, Russia, and the UK. In the case of Greece, the major urban centres (Athens for the most part, but also Thessaloniki) are within the 1,500km range, as are the numerous holiday destinations in the Aegean and Ionian seas. The UK that traditionally has business, education and family ties with Cyprus is well outside this range and cannot be served by such planes in the short and medium term. Russian destinations on the northern shores of the Black Sea are a possibility, other destinations (including Moscow) are outside this range.

A different approach to the use of hydrogen in aviation is the establishment of a refuelling hub in Cyprus for hydrogen planes that will link flights between Europe and the Middle East. Increased research activity in the area has been happening in the last few years, mostly in the re-design of airports for the safe and effective utilisation of hydrogen in airport facilities (incl. refuelling of aircraft), the upstream H_2 value chain (storage, transportation, distribution), and the decarbonisation of peripheral airport systems using green hydrogen (e.g., aircraft ground service equipment, logistics equipment, etc.). One solution that is mentioned is the use of the Natural Gas pipeline network for transportation, and this could be an area of investigation for Cyprus, should this network be built within the 2020s. Facilities for green hydrogen production could be located close to the airport to minimise these associated costs.

Table 2: Cyprus' outlook for hydrogen uses in aviation

Status	Demand perspectives	Future deployment outlook
No aircraft using **H_2** in existence (either using pure hydrogen or electrofuels)	Depending on where industry is heading, most probably **very low** in the short term, **low to medium** in the long term. Aviation is industry-	For H_2 power aircraft: **Low**. Technology is still immature, but after 2030 there may be a market for the short-haul segment. For electrofuels: **Low to medium**. The long-term prospect of these is

	driven, final customers have little influence on demand	under scrutiny (at least in Europe), as they cannot fully decarbonise the sector
H_2 facilities in airports	**Low** in the short term, potentially **high** in the long term	**Non-existent** now, **medium** to **high** after 20335 if Cyprus manages to position itself as a refuelling stopover hub using locally produced green hydrogen.

Cyprus Focus: Hydrogen in Aviation

1. Cyprus' total reliance on air transport for travelling will probably result in significant price rises of air fares (esp. under the proposals of Fit-for-55). Direct use of H_2 in aircraft is now a distant possibility since the technology is not ready, but the emergence of e-fuels based on hydrogen **has a significant chance to dramatically reduce emissions, while keeping cost rises relatively modest**. Cyprus should investigate the possibility of **investing in infrastructures to produce e-fuels near airports and establish itself as a hub of green aviation**.

4.3 Shipping and maritime

Hydrogen fuel cells have been demonstrated on several coastal and short-distance vessels since the early 2000s. None are yet commercially available, but the commercial operation of fuel cell ferries has tentatively begun in 2021 in the United States and Norway. Most hydrogen-fuelled vessels currently under demonstration or planned for deployment in the next few years are passenger ships, ferries, roll-on/roll-off ships and tugboats, typically with fuel cell power ratings of 600 kW to 3 MW. A recent EU partnership aims to build a hydrogen ferry with 23 MW of fuel cell power. Past and ongoing projects span both gaseous and liquid onboard hydrogen storage (International Energy Agency 2021).

Due to the low volumetric density of hydrogen (whether in gaseous or liquid form), direct use of hydrogen will be limited to short- and medium-range vessels, especially those with high power requirements that cannot be met through battery electrification. A recent study by the International Council on Clean Transportation (ICCT) (Mao et al. 2020) found that 99% of shipping voyages made on a popular China-US route can be made with hydrogen by replacing only 5% of cargo capacity with space for liquified H_2; The same could be achieved by adding one more refuelling stop to the route.

Green ammonia can be used in internal combustion engines to eliminate vessel CO_2 emissions. Major industry stakeholders have announced plans to make 100% ammonia-fuelled maritime engines available as early as 2023 and to offer ammonia retrofit packages for existing vessels from 2025. Ammonia has almost twice as much energy as liquid hydrogen by weight and nine times the energy density of lithium-ion batteries, but storage and handling are tricky – it's also highly toxic and is associated with serious nitrous oxide (N2O) emissions.

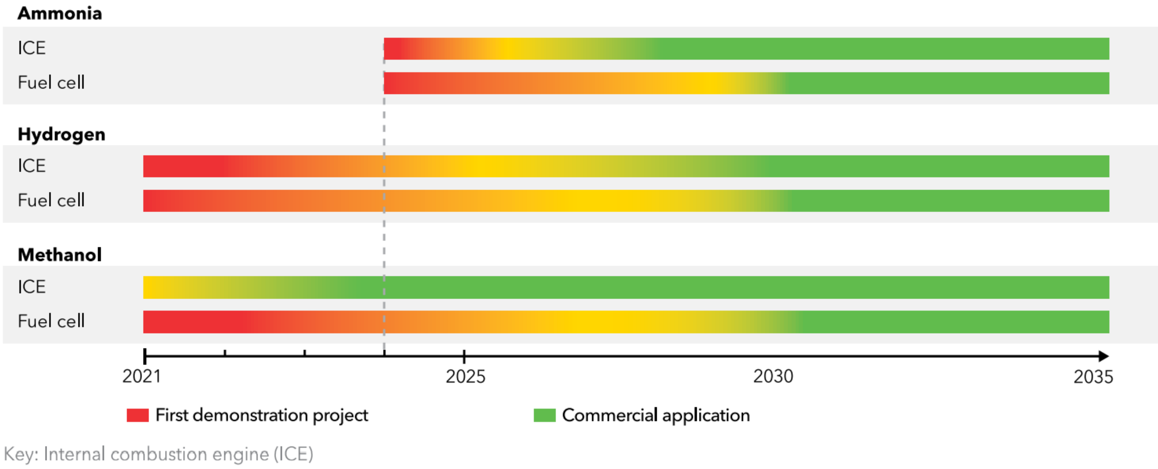


Figure 9: Estimated timeline for expected availability of alternative maritime fuel technologies. Source:(DNV 2021)

Methanol has also been demonstrated as a fuel for the maritime sector and is relatively more mature than hydrogen and ammonia. Given its compatibility with existing maritime engines, methanol could be a near-term solution to reduce shipping emissions, but ultimately ammonia offers deeper decarbonisation potential (IRENA 2019).

Cyprus Focus: Hydrogen in Shipping

1. The recent IEA's report on the Future of Hydrogen (IEA, 2019) identifies ports and coastal industrial hubs as opportune places to support the near-term scale-up of low carbon hydrogen production and use. The shift from fossil-based to low-carbon hydrogen by industries in these clusters would boost hydrogen fuel demand by ships and trucks serving the ports as well as by nearby industrial facilities, which would drive down costs. Cyprus should investigate this option and draft a plan of creating such hubs (see sec. 5).
2. Cyprus should **work with local centres of knowledge on maritime issues**, since shipping is a very crucial sector of the economy and draft a plan for the gradual introduction of hydrogen in ports and refuelling facilities (either in ammonia, methanol or pure compressed/liquified hydrogen). It should keep an eye on developments worldwide.

4.4 Industry

One of the main levers of promotion for hydrogen is its suitability to gradually replace all processes that require high temperatures, which are currently supplied by fossil fuels: Production of steel, production of cement, and various applications within the chemical industry, as well as the production of synthetic fuels is at the forefront of the discussion. All these are usually grouped under the 'Power-To-X' name, where the power is supplied by renewable electricity to produce green hydrogen, and then used via different routes to serve various industries (Figure 10).

Steel is a particularly interesting case since it is responsible for almost 9% of global GHG emissions (almost 5 times those from aviation), and urgently needs to decarbonise. A cleaner way to achieve this is to separate the oxygen from iron ore to make Direct Reduced Iron (DRI) as an intermediate step when using hydrogen (Pfeifer 2021), but the high-quality ore deposits required are rare (Sheppard et al. 2021). Such a case for Cyprus would have to revolve around importing iron ore of sufficient quality and producing steel locally, but **since there is no direct demand on the island, transporting the ore as an import and then exporting the finalised product makes the proposition financially untenable, assuming a new steel mill would be built**. In addition, the amount of renewable electricity required would be very large.

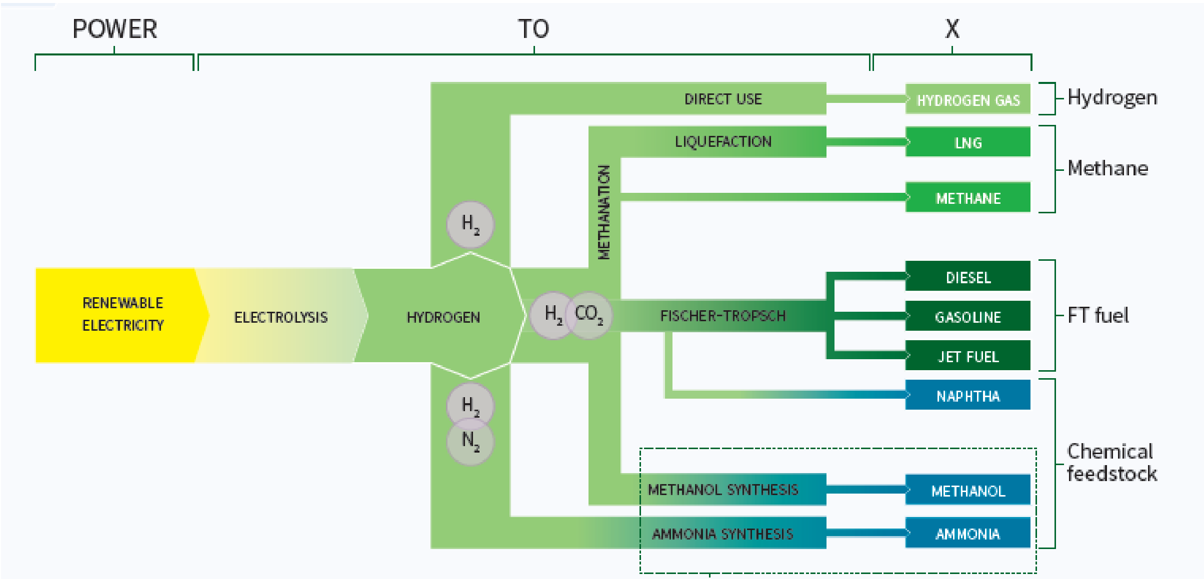


Figure 10: Simplified Power-To-X schematic. Source: LUT University (2020)

This is however a scenario that may not be entirely unrealistic, but many things would have to line up for it to succeed: First, Cyprus would have to establish itself as an economical steel exporting hub to countries of the region. As of 2021, countries with sufficiently large industrial base of the region include Israel, Turkey, and Egypt. All of these would be hard markets to reach, for different reasons each. Secondly, there would need to very generous governmental support that would need to also include the whole value chain of steel production – supporting the building of a steel mill, subsidising the imports of iron ore and exports of steel, all these for no local industries with demand for steel. And then global conditions would have to favourable as well: Carbon would need to be priced high (already at historically high levels, and poised to continue under the European ETS), and that global decarbonisation efforts do not run out of steam.

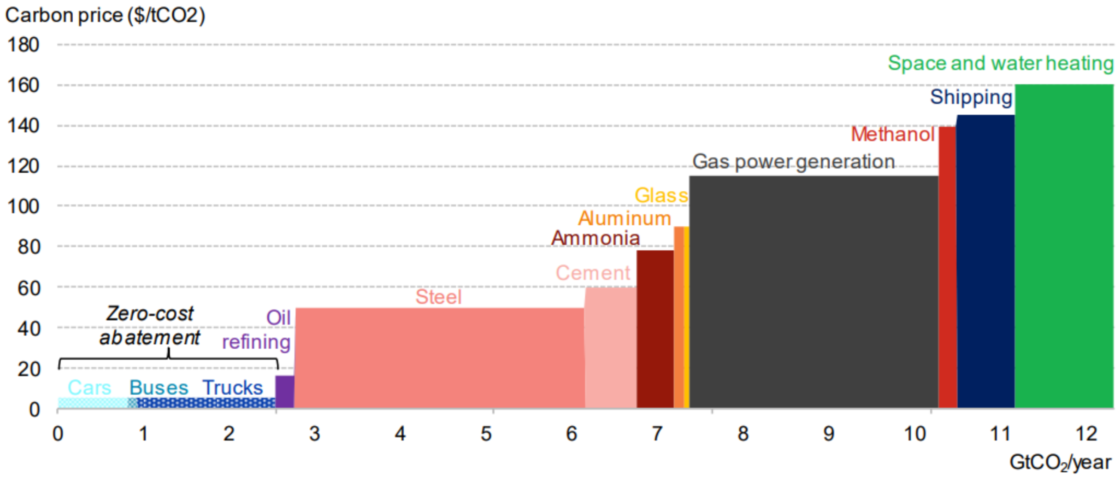


Figure 11: Marginal carbon abatement cost curves from using $1/kg hydrogen for emission reductions, by sector in 2050. Source: BNEF (2020)

In the case of cement (a sector that accounts for 8% of global emissions, see Lehne and Preston 2018), BNEF (2020) has calculated that a carbon price of $60/tCO_2$ would be required for green hydrogen to break even for supplying heat to the cement industry a price that has already been exceeded within the EU, on the back of a strong upward trend that started in mid-2018 and accelerated in mid-2020. This does not however mean that a switch will happen across the whole industrial landscape right away in this pricing environment; switching to a new fuel requires more upfront costs and infrastructural upgrades, as noted by IEA (2019a). This is relevant to Cyprus as there is one cement plant already in operation (the Vassiliko Cement Works PLC[4]) that **needs to investigate if the use of green hydrogen (or ammonia) is a pathway forward**.

The chemical industry is potentially facing similar hurdles to the steel industry: There is no sufficient local demand for most of the products of an industry around chemicals (e.g., plastics, fertilisers) and the demand should be found elsewhere. This may be an insurmountable barrier to overcome given the dominant position of key regional exporting countries with reserves of cheap hydrocarbons (e.g. Qatar), that may resort to heavy use of CCS to decarbonise, at least in the short to medium term (Paltsev et al. 2013). Decarbonisation notwithstanding, it is also unlikely that a system based around hydrogen in Cyprus will be cost effective against an industry underpinned by blue hydrogen likely to develop in hydrocarbon-rich areas of the EMME region.

In all the industrial cases, supporting the switch of industries that use high-temperature heat to hydrogen would usually mean passing over their costs to their final customer, something that may not be an option at this early stage, especially for a country with a relatively small industrial base and a small market unable to absorb price hikes.

There is also another trend that may run counter to the future use of liquid fuels for high-temperature applications: the direct use of electricity. A recent publication by Madeddu et al. (2020) summarised the latest developments and found that over 70% of the current industry-related emissions in the EU can be replaced by the direct use of electricity through the use of current technologies, while 99% of those emissions can be replaced by technologies in development, mostly high-temperature heat pumps. Whether this happens and to which extent heavily depends

[4] Vassiliko Cement Works Public Company Ltd - Home

on the costs of green electricity production and the cost of carbon, as well as upfront costs for making these changes.

Table 3: Cyprus' outlook for hydrogen uses in industry

Status	Demand perspectives	Future deployment outlook
Steel: **H_2** use **non-existent**	Local demand for green steel will probably be **non-existent**, unless heavy industry is promoted and supported on the island. Regional markets exist, but attaining low enough costs and overcoming political hurdles will be a challenge	Most probably an H_2-based steel industry **will not develop** in Cyprus. For this to happen, many items in a long chain need to be positioned and adequately supported.
Cement: **H_2** use **non-existent**	Demand will be **low** but could be **high** if H_2 facilities are built close to the units in a hub configuration. There is a steady demand for cement that feeds the local construction industry and is also exported.	The current (and any possible future) cement kilns in Cyprus will have to eventually decarbonise under the EU's 2050 plan, and the pressure coming from the carbon EU-ETS price. The industry does not have many options to do that, so that H_2 should be considered one of the main ones.
Chemicals: **H_2** use **non-existent**	Local demand is bound to be **non-existent**, unless there is strong support for the development of fertilisers, or ammonia for industrial use.	The use of ammonia in shipping may change the demand dynamics of this sector, but the picture is still unclear.

Cyprus Focus: Hydrogen in Industry

1. The very low industrial base of Cyprus makes direct replacement of processes using hydrogen a possibility, but not one that would result in dramatic emission reductions. The existing cement plant at Vassiliko, however, would probably benefit from investigating the conversion of its energy supply system to one based on green hydrogen, as the current ETS price makes such a conversion tenable.
2. Heavy industries such as steel and chemicals could theoretically thrive, but several things would need to line up favourably, such as a very high global gas prices (that would put pressure on nearby plants in the Gulf region), normalisation of political relations with major regional exporting markets, and connection with other industrial centres to render Cyprus a transit hub for steel and chemical products, among others.

4.5 Hydrogen uses in the domestic sector

Hydrogen Fuel Cells can be used in the domestic and commercial heating sector and are called micro-CHP or mini-CHP plants. Micro-CHP technologies are usually used as a heating solution in single flats, or houses while the mini-CHP systems are usually installed in apartment buildings or commercial buildings, operating to optimise either most of the electricity demand or most of the heat demand. If electricity prices are high, an electricity-led mode of operation is appropriate. Therefore, the purchase of electricity from the grid can be minimised, or the electricity generated from CHP could be feed into the grid and reimbursed. **The main disadvantage of the CHP fuel cell heating system is the high upfront cost. A new micro-CHP fuel cell heating system with an electricity output of 1kW and heat output of 1.45kW would cost around €25k** (Element Energy 2018).

If CHP is utilised in electricity-led mode, the thermal output from the fuel cell heating systems is low. Therefore, the remaining heat requirement needs to be covered by an additional heating system such as a hydrogen boiler. A hydrogen boiler would work in a similar way to existing gas boilers and are expected to be able to achieve high efficiencies, like those of current natural gas boilers.

The penetration of hydrogen in the domestic sector is facing an uphill struggle, as heat pumps have emerged as the dominant heating and cooling option powered by electricity. Currently, heat pumps are standard, mature, off-the-shelf technology that can be purchased now, and they are cheaper than fuel cell heating systems, especially the air source heat pump. **The cost for an air source heat pump and its installation is around €12k** with strong downward trend (Shell and Wuppertal Institut 2017). While the basis of the ground source and air source heat pumps is the same, the cost of having them installed is not, since the ground source heat pumps generally cost around 50-100% more. The International Institute of Refrigeration estimates that there are currently 220m heat pumps in use around the world (IIF-IIR 2019). This can be a particularly handy technology for Cyprus, as it incorporates heating and air conditioning into one.

Cyprus Focus: Hydrogen in the domestic sector

1. It is difficult to see a clear pathway where domestic heating & cooling systems based on hydrogen fuel cells dominate. Cyprus has minimal heating needs at present, with further reductions in these needs projected due to climate change. **Hydrogen would make for a poor solution in a country with dominant cooling needs**, due to cost and complexity.
2. A system where electricity produced from renewables is driving heat pumps would be cheaper, more efficient and with reduced emissions compared to one around a hydrogen fuel cell and a boiler. In the case of a distributed energy system where various energy vectors are in interplay among prosumers, such a solution could potentially have its merits, but this cannot be determined without robust modelling.

5 Proposals for measures to enable the future adoption of hydrogen in Cyprus

The following passages contain proposals and suggestions for maximising the uptake of hydrogen in Cyprus. They are divided in sections based on the focus area of each measure but there are significant cross-links between them, especially for the ones that have to do with policy and implementation, whereas supply and demand should be considered together. A summary of the measures listed below separated by short and medium/long term implementation horizon, as well as the main stakeholders involved in each one, can be found in Table 4 below.

5.1 National Policy

5.1.1 Short term

1. Develop a **long-term decarbonisation plan** that will accurately assess the role of hydrogen for the Cypriot energy system to 2050 together with stakeholders – particularly policymakers, utilities, and the energy-intensive industries. The country's National Energy and Climate Plan (NECP) and its upcoming revision to align with the ambitions of the European Green Deal should be the starting point.
2. Develop a **hydrogen deployment roadmap** that will serve as guidance for the future together with the relevant stakeholders. The roadmap should have quantified milestones for costs per sector, probability of implementation and funding required to 2050, and could be a joint effort amongst research and policy-making institutions of Cyprus.
3. Provide **funding for pilot systems** aimed at localised hubs utilising renewables to produce green hydrogen to serve the main end uses of the future: Port and airport facilities, road freight transport, cement and brick factories, and any other high-temperature industrial uses.
4. **Creation of a hydrogen cluster** will play a very significant role, where production, transformation, and consumption are concentrated, taking advantage of the application of economies of scale, as well as the development of pilot projects (see par. 5.4) linked, among others, to the transport sector. These clusters should concentrate and support the industrial use cases that are relevant and realistic for Cyprus: Now only cement kilns and brick factories use high-grade heat, and these should play a role in any hydrogen cluster. Pilot projects should be promoted and supported to test the conversion of these facilities' processes to using green hydrogen.

5.1.2 Medium/Long Term

5. **Port and airport facilities should be linked** to the above cluster, after relevant upgrades are done to use hydrogen. The early support of these will allow to develop their competitiveness, that could prove strategic given the geopolitical position of Cyprus in the EMME region.
6. **Set targets for the use of hydrogen** in specific sectors (industry, transport, and if relevant in the building sector).

5.2 Regional/EU/International Policy

5.2.1 Medium/Long Term

1. Increase the demand for industrial products manufactured using low-emission processes, including hydrogen. A **demand quota for climate-friendly base substances**, e.g., green steel or green cement, should be considered, with the appropriate provisions to avoid dirtier imports from outside the EU. Such measures would require a clear label to mark out the more climate-friendly or sustainable intermediate and end products.

5.3 Production, infrastructure, and end uses

5.3.1 Short Term

1. **Conduct techno-economic analyses** of the necessary adaptations to the existing electricity generation plants to use clean H_2 as a fuel source, a timeline of the blending ratios towards a 100% conversion.
2. **Assess the suitability of any future industrial scale gas network to accept fuel blended with H_2**, and the possibility to use this network in the future using H_2 alone.
3. **Assess the potential of green hydrogen to store energy** and/or decarbonise the heat sector in both industry and homes, in cases where electrification is not the most appropriate solution, including seasonal green energy storage

5.3.2 Medium/Long Term

4. **Investigate the options for green hydrogen to produce synthetic fuels** (through CO_2 capture and the Fischer-Tropsch route).
5. **Fund the construction of a needs-based refuelling infrastructure for heavy-duty road haulage and public transport vehicles**.

5.4 Research, education, innovation

5.4.1 Short Term

1. **Sanction studies to assess the CCS/CCUS potential for Cyprus** now and in the future in case hydrocarbon exploitation takes place. Assess the costs of applying it to existing and future (based on scenarios) power and industrial infrastructure, and the possible cost and environmental footprint of producing blue hydrogen.
2. **Develop demonstration projects** that will focus on the needs of Cyprus (and isolated energy systems by extension) by combining green hydrogen production with its use in the industry, port, and airport facilities. The aim will be to address some fundamental questions and aspects: and thereby develop supply and technology relations, test robust and modular solutions, and raise the TRL of individual components and of the system.
3. **Support research projects** around hydrogen integration, development of technologies and development of plans for Cyprus.

5.4.2 Medium/Long Term

4. **Foster education and vocational training nationally and regionally** in the field of hydrogen technologies to pave the way for individual workers and companies to be able to handle hydrogen technologies efficiently and safely. Raising awareness could be targeted to younger generations of consumers as well, so they will be more accepting of the technologies once they become available. Support students aiming to pursue advanced degrees in hydrogen related degrees (MSc/PhD) via dedicated scholarships.

Table 4: Summary of proposed measures for accelerating the uptake of hydrogen in Cyprus

Action type	Action summary	Principal stakeholders
National Policy	Develop Decarbonisation Plan to include H_2	Research/academia, MECI
	Develop H_2 roadmap	Research/academia, MECI
	Fund pilot systems	MECI, MoF, Research/academia
	Fund the creation of a hydrogen cluster and link port and airport facilities	MECI, MoF, local H_2 industry, port and airport authorities, industries under the ETS, Research/academia
	Set targets for use of H_2 nationally	MECI, Research/academia
Regional / EU / International policy	Demand-quota for industrial products made using green processes (e.g. green steel, green cement)	MECI, industries under the ETS
Production, infrastructure, end uses	Synthetic fuel production	Research/academia, port, and airport authorities, MECI, liquid fuels associations
	Suitability of gas network to accept H_2	DEFA, CERA, MECI
	H_2 refuelling infrastructure	CERA, MECI, liquid fuels associations
	H_2 short-term storage for industry, commerce, and domestic uses	CERA, Research/academia, MECI
	H_2 as a solution for seasonal storage	CERA, TSO, Research/academia, MECI
Research/education/innovation	Investigate CCS/CCUS	RIF, Geological Survey Dept., MECI, Research/academia
	Develop integration demo projects	RIF, Research/academia, local H_2 industry
	Support research projects on H_2 use and integration	RIF, DGEPCD, MECI
	Education / vocational training for H_2 use	Research/academia, MECI, Energy NGOs

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