Προς μια οικονομία υδρογόνου στην Κύπρο:
Προτάσεις πολιτικής για έγκαιρη και ταχεία υιοθέτηση

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Structure

1. **General overview of tech (H_2 colours)**
2. **Global demand and production**
3. **Current costs and cost trends**
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4. **Focus on technologies**
    1. Production outlook and cost projections
    2. End uses: Road transport, inland haulage and public transport
    3. End uses: Shipping, aviation, industry, domestic sector
    4. Power generation & storage
5. **Policy proposals for accelerated adoption in Cyprus**
    1. Situation today: EU and national policies/roadmaps for H_2
    2. Short and Long term policies

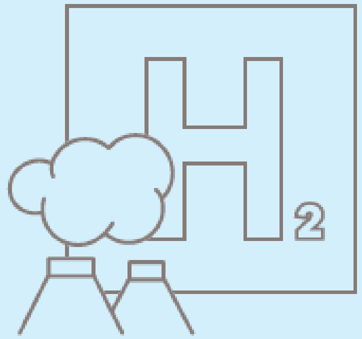
Fundamentals

Hydrogen – why now?

It has been overhyped in the past – what has changed?

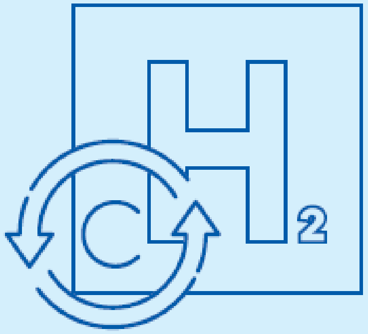
1. Pressing need for **total decarbonisation** vision, including sectors hard to abate (shipping, aviation, freight/bulk transport, heavy industry)
2. Hydrogen has the ability to answer **a wider range of policy objectives** (energy security, local air pollution, local economic development, to name a few)
3. Green hydrogen **complements variable renewables** very well
4. Is also seen as a saving grace by **a portion of the fossil fuel industry** in the face of pressures to decarbonise, when combined with CCS (more on this later)
5. There are more colours: **Turquoise** hydrogen (from pyrolysis), or **purple** hydrogen (from nuclear)

Almost all hydrogen right now is produced by either natural gas or coal



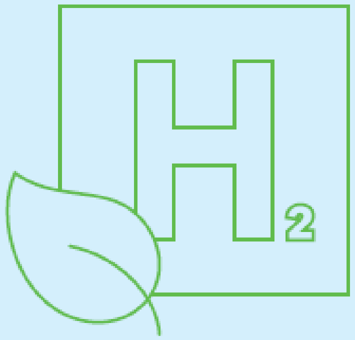
Grey & **Brown** (or **black**) Hydrogen

- From NG (via steam methane reformation, SMR)
- From coal (via gasification)



Blue Hydrogen

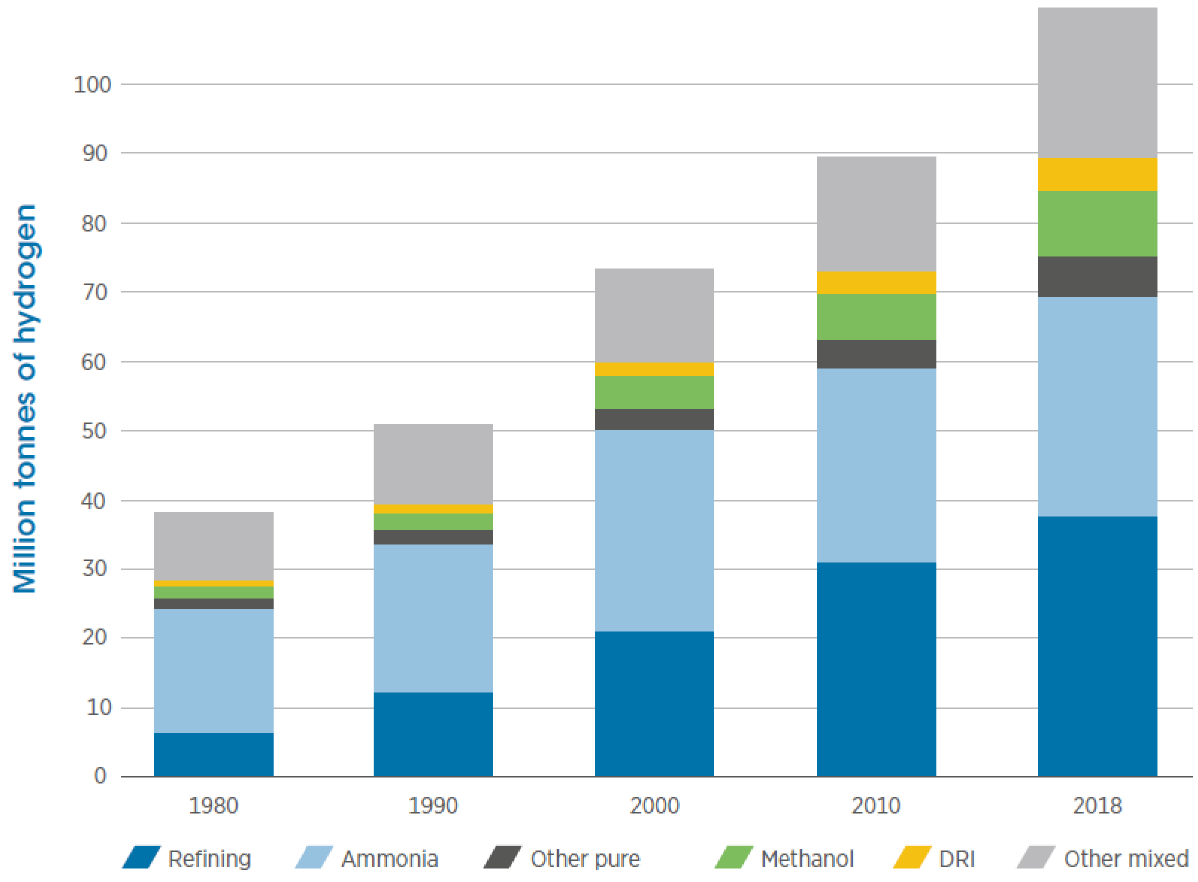
- Same methods as grey and brown, but with CCS/CCUS
- Sometimes referred to as a 'bridge' towards green hydrogen



Green Hydrogen

- Produced by the electrolysis of water
- If input is renewables, can be a zero-emissions fuel

Demand: Situation today



Source: IEA (2019). DRI = direct reduced iron steel production

Demand for pure hydrogen is steadily rising, but for the time being most is in industrial processes

Refining demand

- Hydrogen demand in refineries is rising due to its use in **reducing the sulphuric content of diesel**

Ammonia

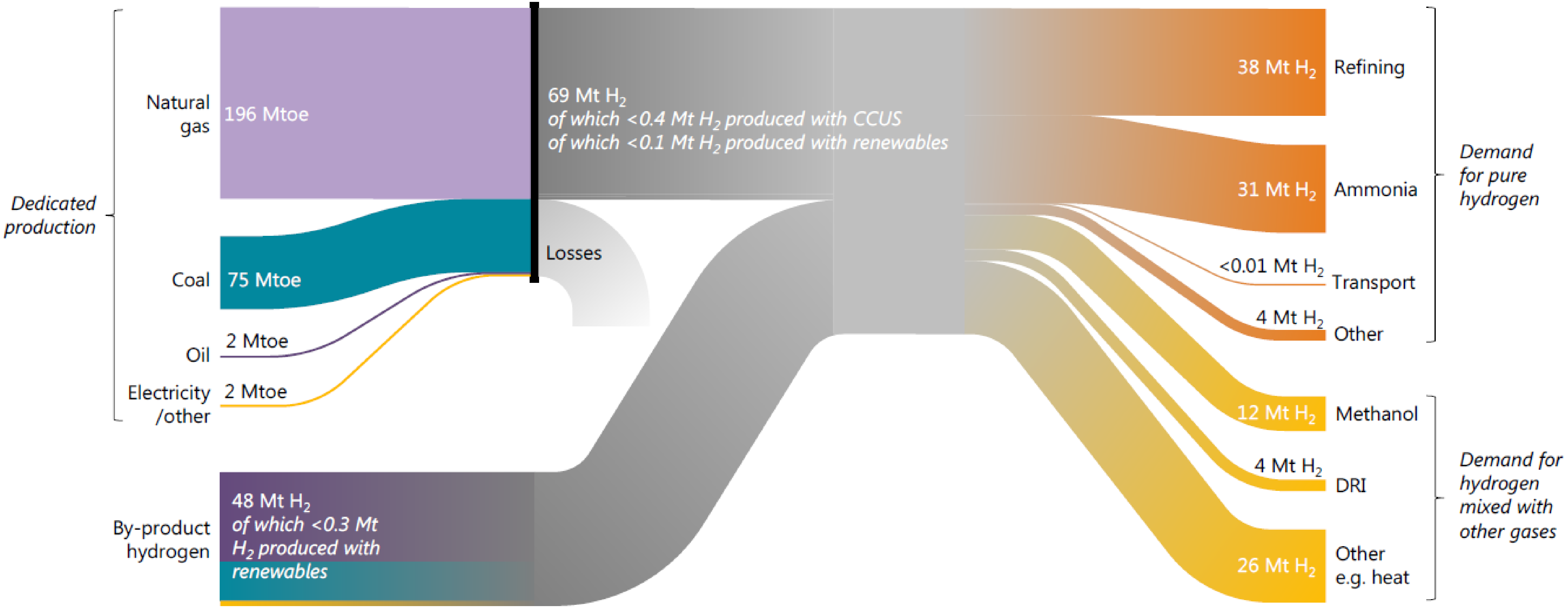
- Input in fertilisers

Other

- Methanol, DRI and "other mixed" represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock

Recently, **merchant supply of hydrogen has overtaken on-site production** from SMR from Natural Gas, mainly as a by-product of other chemical processes

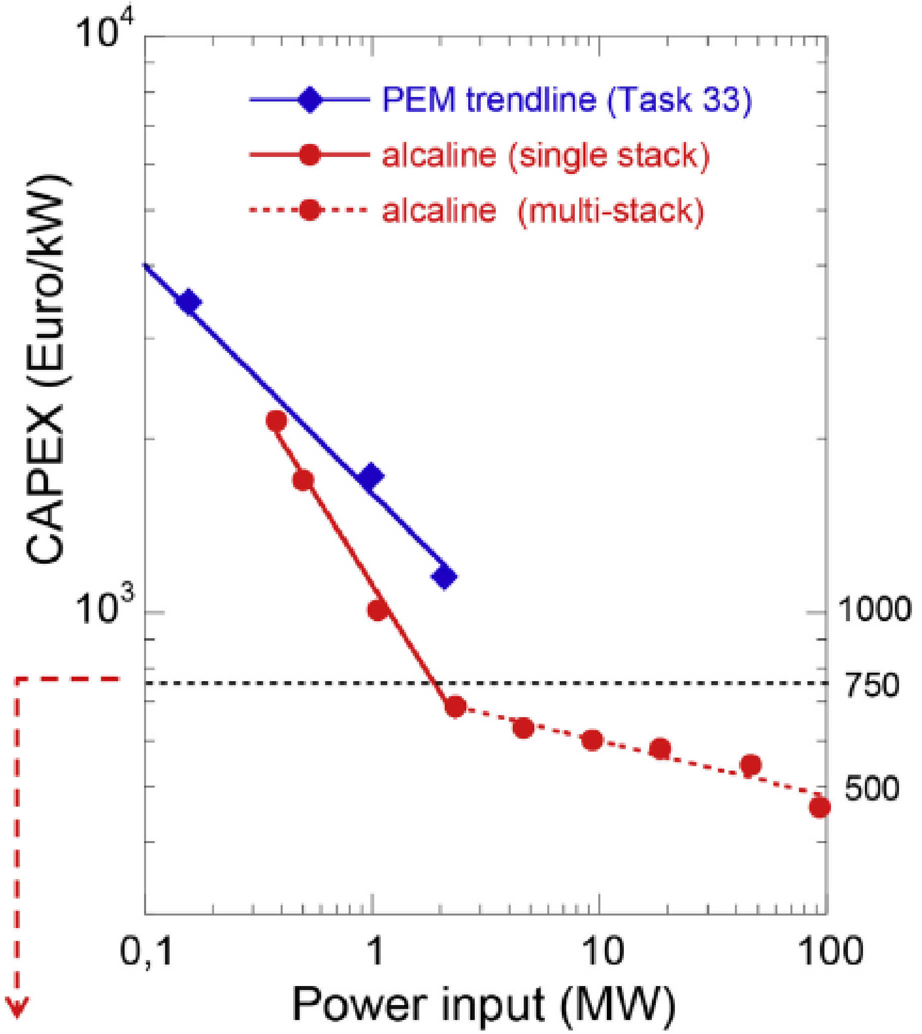
Gas (and coal) dominate



Source: IEA (2019)

NG is the dominant fuel, renewables can be used via electrolysis

Electrolysers' cost



Utility providers today have set the capital cost of storing renewable electricity at around 750 €/kW.

Source: Proost 2019

Alkaline electrolysers

- Mature, well understood technology
- Relatively low costs
- Scales up well – by stacking
- Lower H_2 purity
- Corrosive electrolyte

Polymer electrolyte membrane (PEM) electrolysers

- High gas purity
- High current density (suitable for variable input such as RES)
- More expensive
- Upscaling harder

Solid oxide electrolysers (SOEC)

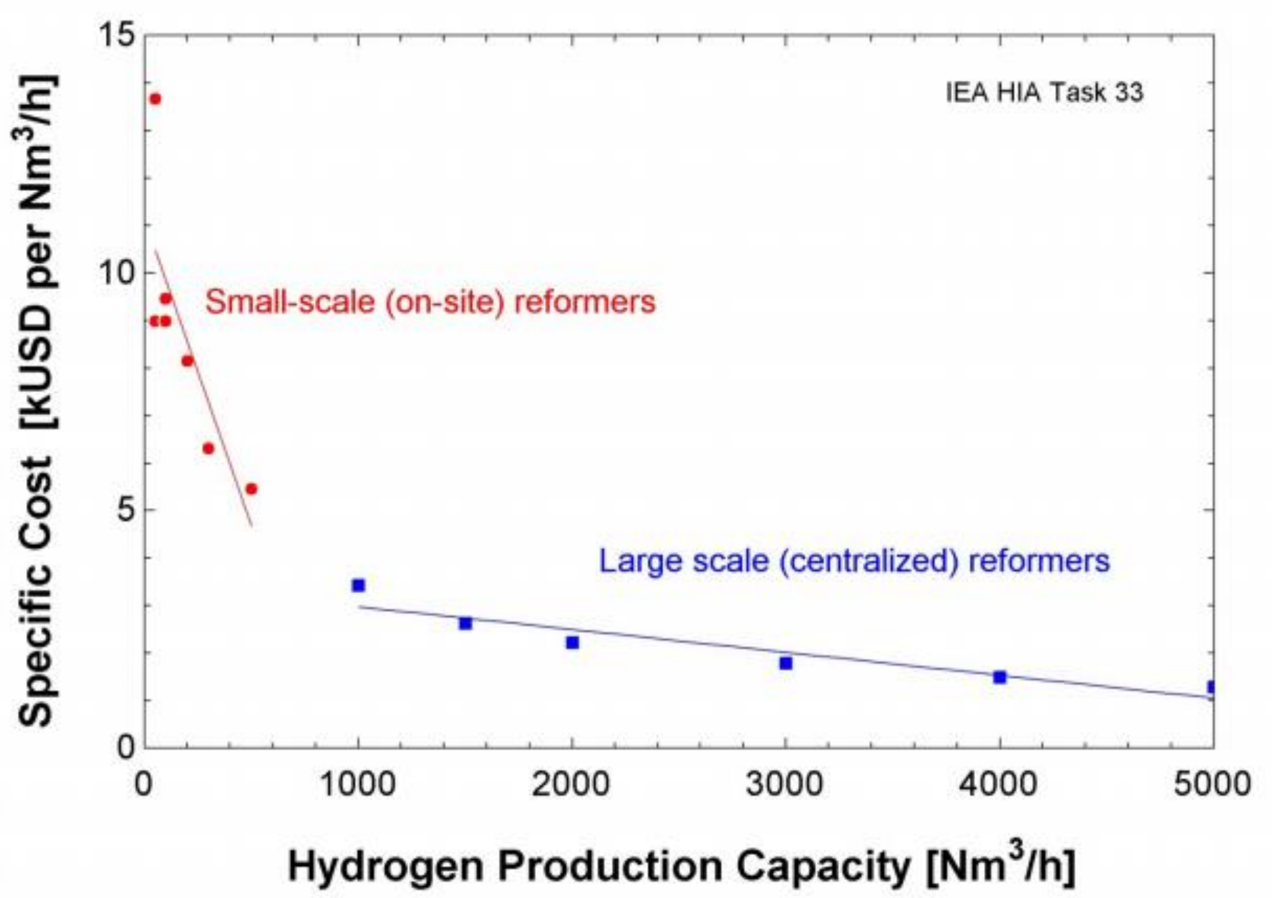
- Operate at higher temperature
- Higher efficiency compared to AEL and PEM
- Requires a heat source (materials might be a barrier)
- Least advanced method – not yet commercial

Scaling up of electrolysers in the MW-scale is essential for the widespread adoption in the key areas that H_2 is targeting

Not very clean

- Relying on SMRs for large scale H_2 production *without* CCS, will actually result **in more emissions compared to the direct use of fossil fuels** due to conversion efficiency losses
- Even when CCS is employed**,** expected capture rates will **reach 85-90% at best**, while flagship projects nowadays **barely get over 30%**
- CCS aiming at geological storage must be the norm for blue H_2. **Enhanced Oil Recovery** is usually preferred **(CCUS)**, but leakage rates vary, are often high (~5-70%), and oil use is obviously **not a long-term goal**

Steam Reformers



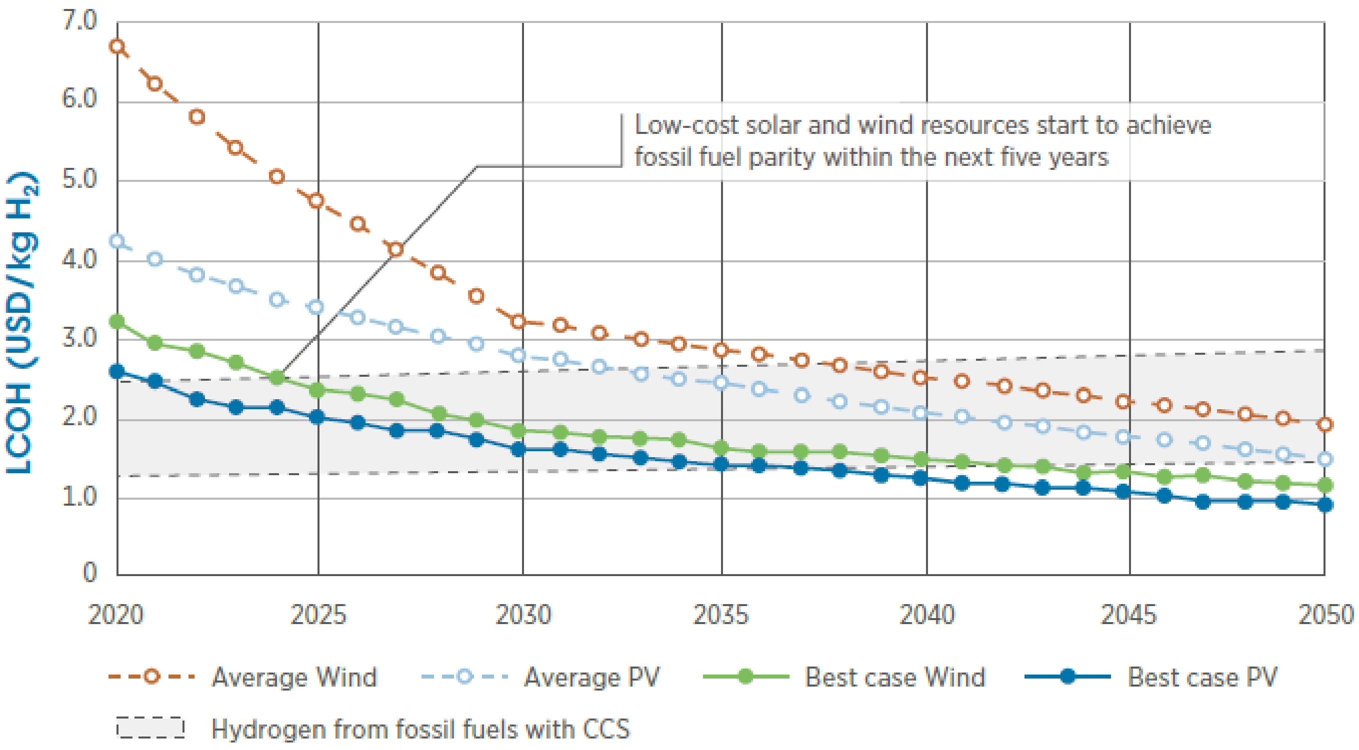
Source: IEA HIA Task 33, 2016

Scaling up can substantially reduce costs

CCS

While identified early on as a necessary condition for the uptake of H_2, CCS remains off-track for both power generation and industry

1. While capture rates may improve, costs are not expected to fall
2. Output falls between 10-15%, but this is better compared to adding CCS to power plants
3. Storing CO_2 adds to the costs and complexity
4. **Adding CCS to an existing NG SMR process adds around 30-35% to the overall cost** (but assigning a price to CO_2 brings these closer)

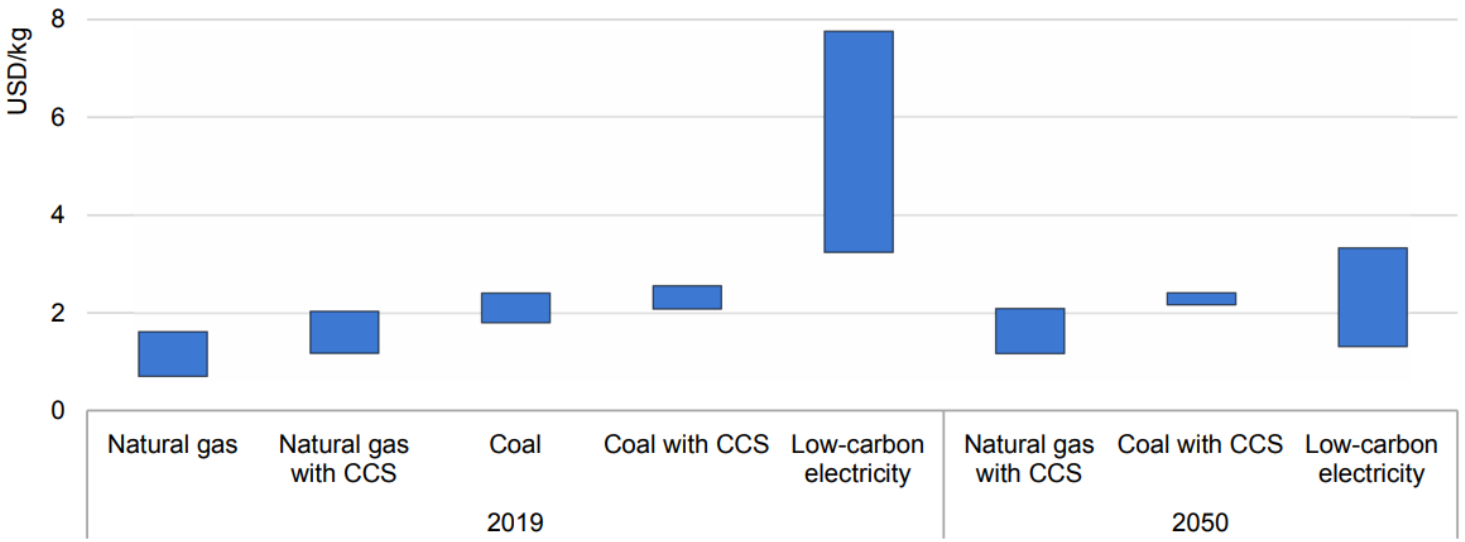


Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

Source: IRENA 2019

The well-to-gate greenhouse gas emissions of steam reforming of natural gas with CCS with 90% capture is **1 $kgCO_2eq/kgH_2$**, and **4 $kgCO_2eq/kgH_2$** with a capture rate of 56% (IEA, 2019)

Overall costs comparison



Electrolyser utilisation rate is key for green H_2 competitiveness – needs to be at least 50%

Overall picture

- Cheapest generation tech right now is **NG SMR at around €1.5/kg** in the EU, depending on Gas prices, notwithstanding CO_2 price.
- With CCS, the costs **goes up to around €2/kg**
- Green hydrogen (using electrolysers) is **right now placed between €2.5-€5/kg**, but costs are coming down
- We should expect green hydrogen costs converge (and even drop below) conventional production costs, **but electrolyser and generation RES costs need to fall**
- Carbon prices in the range of **€55-60/tonne of CO_2** would be required to bring the CCS option level with the pure fossil fuel-derived hydrogen

End uses

Passenger vehicle

Hydrogen heavy duty truck

Hydrogen logistic vehicle

Hydrogen forklift

Hydrogen bus

Public transportation vehicles

Photo: Hydrogen fuel cell bus in Aberdeen (JIVE project)

1. Hydrogen fuel cell vehicles can offer more advantages to the operator compared to battery electric vehicles, such as **faster refuelling**, **longer ranges and lower powertrain weight**. But: expensive purchase cost and expensive refuelling station

2. Buses are becoming more attractive, esp. in China, still more expensive in western markets.

3. Aim to drop the cost for a standard 12-meter fuel-cell bus in Europe down to around **€650k** by mid-2020s (down from about **€1m** now) by increasing production levels (*JIVE project*).

4. Hydrogen refuelling stations suffer from a chicken-and-egg problem, but more are being built, but costs **remain high at around $5m average** for a station that can fill up to 25 buses a day.

Transportation: HGV fleet

Photo: Nikola Corporation

Making inroads

1. Similar picture for trucks – China is leading, **globally several start-ups are generating interest** (pictured)

2. HDVs: uncertainty around technology cost and fuel consumption. On average a rigid HGV with 242km daily mileage **in 2025** is estimated to cost around **€207k for a hydrogen fuel cell vehicle, €100k for a battery electric vehicle.**

3. Major urban centres in Cyprus are **less then 150km away from the country's ports and airports,** therefore battery electric trucks may be more suitable

Aviation

Source: AirBus, 2020

Assuming advances in propulsion tech, higher compression containers, 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*)

Major challenges ahead

1. Future relies either on **H_2 or on synthetic fuels**; or *large-scale buying of permits*
2. For hydrogen, **passenger capacity and range may have to be more modest** compared to now due to the lower energy density of H_2
3. Hydrogen refuelling facilities at airports will also have to be added, and **airport design may have to be overhauled**
4. Other options (e.g. Battery electric planes) are still at early stages, with **obstacles hard to overcome** (e.g. battery weight)

Shipping

At least $1tn will be required to decarbonize the shipping industry by 2050

*Mao et al. 2020: *Refuelling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?*
https://theicct.org/sites/default/files/publications/Zero-emission-container-corridor-hydrogen-3.5.2020.pdf

Liquified H_2

1. No full-sized commercial ship in operation yet; fuel cells rather than combustion is preferred

2. A recent study by the International Council on Clean Transportation (ICCT)* 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

Ammonia

1. Almost **twice as much energy as liquid hydrogen by weight** and nine times the energy density of lithium-ion batteries

2. Combustion is possible, **but storage and handling is tricky** – it's highly toxic (and has a pungent smell)

3. **Green ammonia** would seriously need to be stepped up

Industry

Steel and cement are at the forefront

blah

Steel

1. Clean H_2 crucial in the **low-emissions production of DRI** at T<1,200°C
2. There is no direct market for steel in Cyprus and an **export industry will struggle to find markets**
3. The **current high price for ETS carbon** may be a reason to look into it in more detail, but generous support will be required

Cement

1. Decarbonising the Cypriot cement industry using hydrogen **is more likely** – there is already production
2. The CO2 price threshold set by BNEF is at $60/t, it's at €53/t now (14 June '21)

Chemical industry

1. **No local industry** (for now)
2. Local demand is insufficient to base an industry on / the export market for **fertilisers based on NH_3 can be an outlet**, perhaps combined with production for shipping

H2 in the domestic/commercial sector

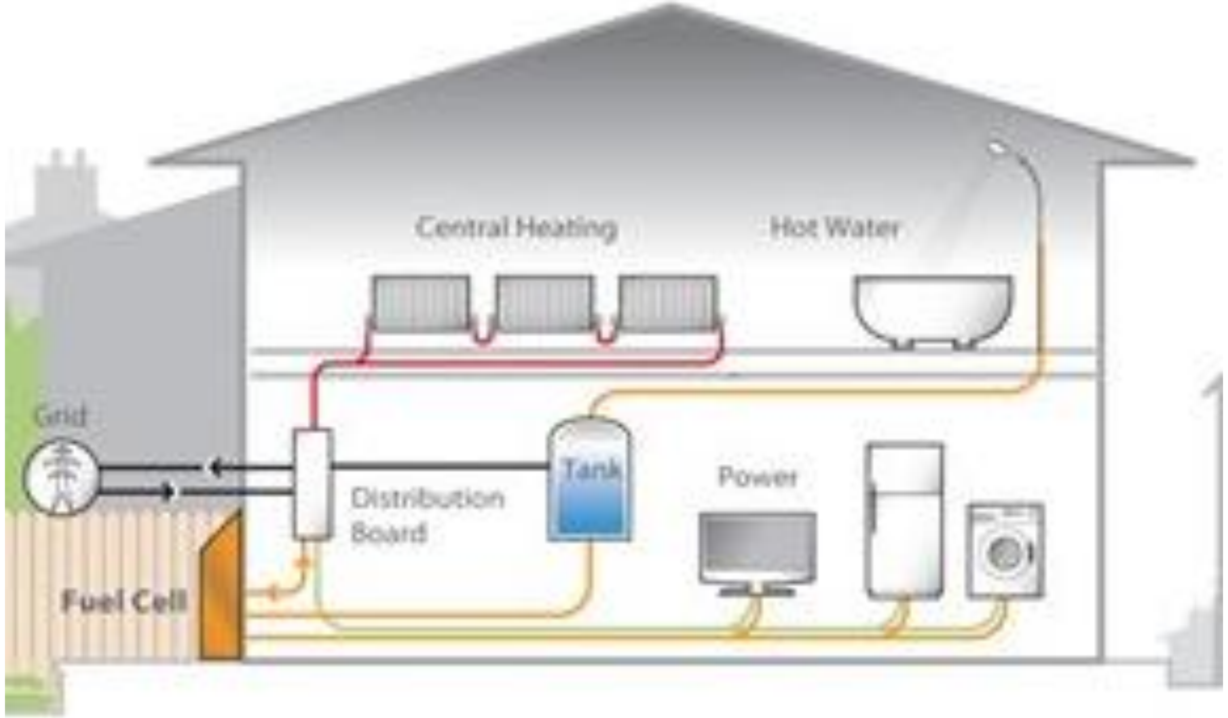


Photo: CHP fuel cell heating system

1. Decarbonisation options for domestic and commercial heating: hydrogen fuel cell boilers (CHP systems), hydrogen boilers, and heat pumps.

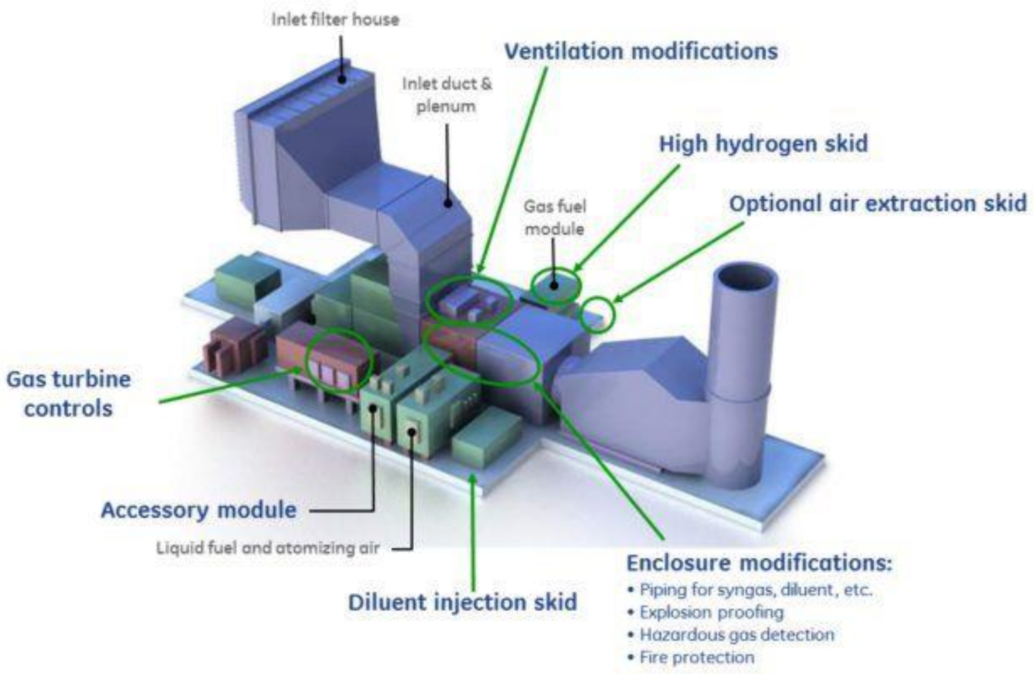
2. Combined heat and power (CHP) systems can supply electricity and heat. **High overall efficiency** but the **costs** of acquiring them are **high,** around €24k assuming limited production capacity

3. When a CHP system in in place, the peak heat demand needs to be covered by a hydrogen boiler. Hydrogen boilers: **cheap** and expected to achieve **high efficiencies**, similar to natural gas boilers.

4. **Heat pumps** are mature technology that can be purchased now, and it **is cheaper** than fuel cell heating systems. It uses electricity to run. Cost around €12k.

Storage & Power Generation

- Hydrogen storage for excess electricity can have significant impacts for Cyprus to better integrate renewables
- High cost of storage and technical challenges will be a drawback
- Maturity of the above however opens the possibility of strategic seasonal storage of Hydrogen for power generation in a system based on renewables – **not now, but in the future**?



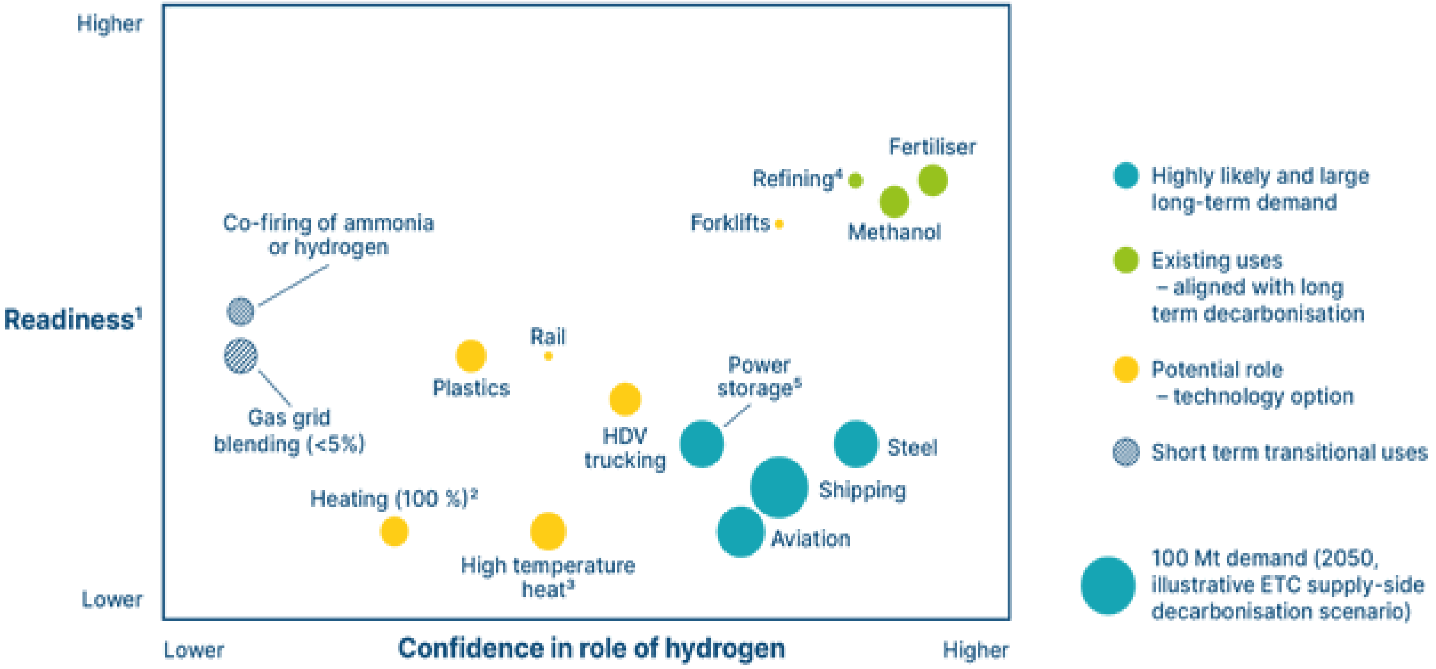
Due to the very low density of hydrogen, its storage is more challenging than that of fossil fuels

1. Geological storage is the most efficient (and low cost) solution, either in salt caverns, oil/gas depleted reservoirs or aquifers.
2. Metallic vessels is gaining popularity (simple holders – low pressure; spherical – up to 20bar; pipe – up to 100bar)
3. Compressed H_2 (at 700bar, small systems) however has around 15% the energy density of gasoline
4. Liquified H_2 requires very low T (-250C) and liquefaction consumes around 45% of the energy content of the fuel itself
5. Storage in the form of ammonia, synthetic methane, or synthetic liquid fuels is usually the preferred solution when transportation is involved (typically over 1,500km)
6. Ammonia (NH_3) requires heat typically up to 650^{o}C for complete dehydrogenation, depending on catalyst used

Market readiness

Some applications are more ready than others

Multiple potential uses of hydrogen in a low carbon economy, some of which can provide early 'off-take' for clean hydrogen



NOTES: [1] Readiness refers to a combined metric of technical readiness for clean hydrogen use, economic competitiveness and ease of sector to use clean hydrogen. [2] 'Heating (100%)' refers to building heating with hydrogen boilers via hydrogen distribution grid, [3] 'High temperature heat' refers to industrial heat processes above ca. 800°C [4] Current hydrogen use in refining industry is higher due to greater oil consumption. [5] Long-term energy storage for the power system.

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2021)

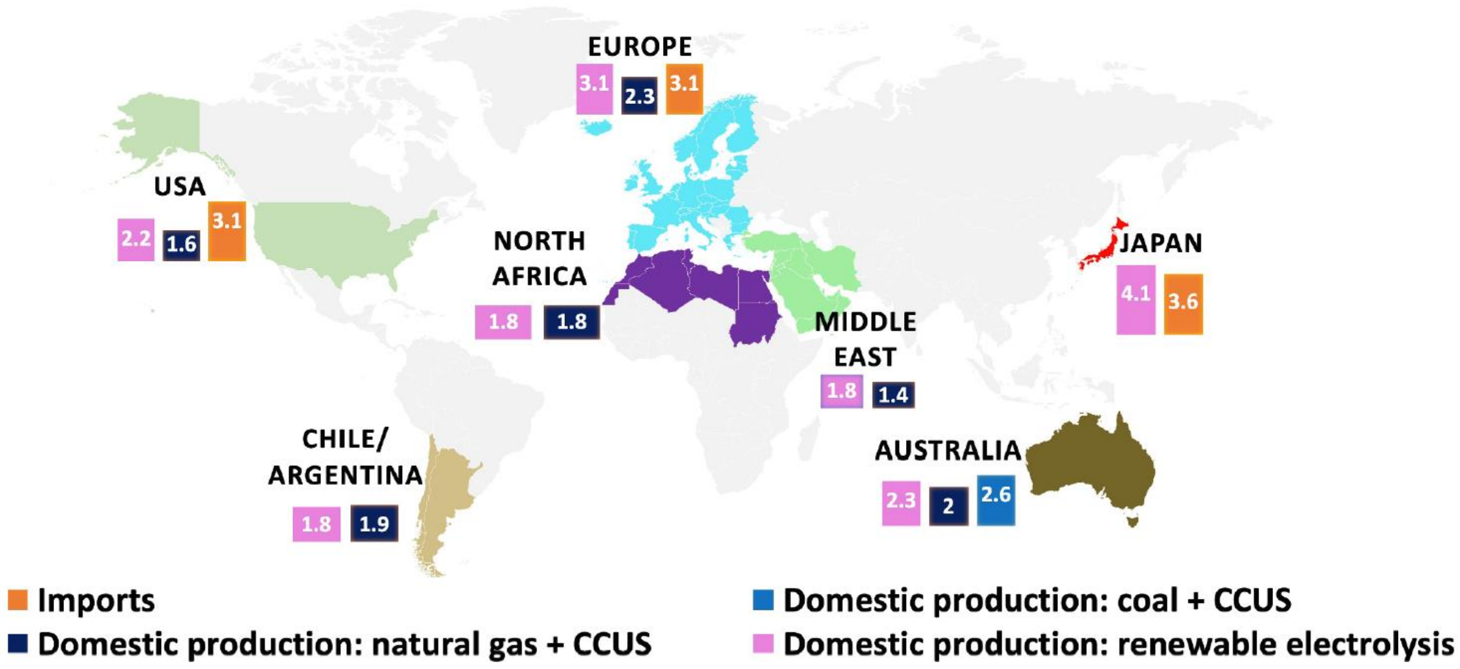
Research & Policy

General Research Directions

Three main ways forward for H_2 research (at least as far as the EU is concerned)

1. **Larger and more efficient electrolyzers** in the GW scale. 100MW were asked for in the Green deal call, larger in the future (even at low TRL)
2. **Advances in refuelling stations** – for passenger cars, but also larger scale stations in ports, airports and freight transport hubs
3. **MW-scale fuel cells.** These will be fitted to freight trucks, trains, short-haul planes and smaller ships

Geopolitics



Costs of different hydrogen types by location, USD per kg of hydrogen

Source: Van de Graaf et al., 2020

The new oil? – surely not yet

1. By 2050, H_2 can provide 24% of the world's energy needs [IEA, 2019], 13-14% in EU's strategic vision [EC, 2018]

2. An '**exporting belt**' of H_2 may develop with lower costs in areas with a rich solar resource; A pipeline network will be required, already steps are taken in some Western countries

3. Since H_2 can be technically produced anywhere, **weaponization of trade** will be much harder

4. Petrostates **take an interest in blue hydrogen**, as it leaves the current business model largely intact – but CCS is still a pipe-dream and freshwater availability can be a problem

5. China can emerge again as leaders, **with low cost electrolysers**

H_2 National/EU Policy

EU documents (both July 2020)

1. A H2 Strategy for climate-neutral Europe

2. An EU strategy for systems integration (incl. H2)

The strategy document sets explicit electrolyser capacity targets of **6 GW by 2024 and 40 GW by 2030**; as well as production targets of **1 million and 10 million tonnes of renewable hydrogen per year** for those two milestone years

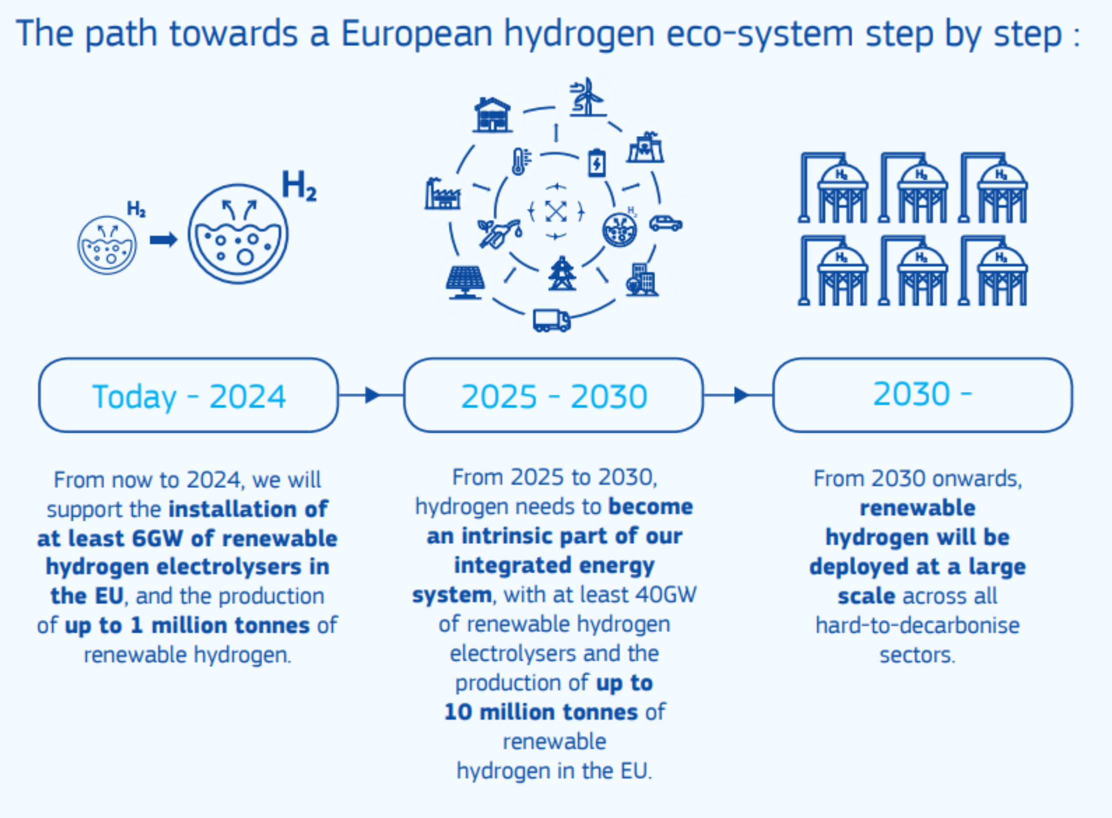
National roadmaps and targets (last 18 months)

1. **Asia & Oceania:** Japan, South Korea, Australia

2. **Europe**: Netherlands, Germany, Norway, France, Spain, Finland, Portugal

3. **Americas**: Chile, Canada

All these documents reserve a significant role for Green Hydrogen via renewables, or, in the case of France, **also by nuclear power**



H_2 for Cyprus

Resources

1. NG: Can be used in a blue H_2 path, total decarbonisation will be hard to achieve, CCS still unknown

2. Solar potential: The right conditions to position itself for large-scale production. Production system almost independent

Potential pathways?

1. **Export** Green H_2 to EU countries in the north
2. **Airport hub** for refuelling by green **H_2**
3. **Attract industry** to use local **H_2** (chemicals, steel?), support local cement production
4. Develop **renewable desalination + green hydrogen** production in one (**heavy demand for water!**)
5. Green hydrogen refuelling at **ports for Med shipping**
6. Green ammonia for **shipping (and fertiliser industry?)**

Policies: Short term measures for Cyprus (up to 5 years)

National Policy	• Fund the creation of a **hydrogen cluster** (incl. high-T industry) • Support **local industrial H_2 uses cases**: Process integration, compression, storage, production? • Support **demonstration projects** in Cyprus focussing on advantages (e.g. high solar potential)
Regional/EU/International Policy	• Advocate for the inclusion of **aviation, shipping, and transportation sector** into the EU-ETS
Research, education, innovation	• Develop a national **hydrogen technology roadmap** (similar to the ones already published) • Assess the feasibility and cost of deploying **CCS/CCUS** in Cyprus • Develop a **decarbonisation plan** for 2050 taking into account hydrogen's advantages
Production, infrastructure and end uses	• Technoeconomic assessment of introducing H_2 to **power generation** (blending with NG, eventual replacement) • Assess the potential of green H_2 to store energy and/or decarbonise the **heat sector** in both industry and homes

Long term measures (>5 years)

National Policy	• Link **port and airport facilities** to hydrogen cluster/valley • **Set targets** for H_2 use in various sectors / give appropriate support
Regional/EU/International Policy	• Advocate for important products made using **low-emission processes**, incl. low-emissions hydrogen
Research, education, innovation	• Foster education and vocational training nationally and regionally to **prepare local industries for the hydrogen transition**, where applicable
Production, infrastructure and end uses	• Investigate **H_2 synthetic fuels** (electrofuels) production in Cyprus (link with airports?) • Assess H_2 as solution for **seasonal energy storage** • Fund the construction of a needs-based **refuelling infrastructure for vehicles**, aimed primarily at heavy-duty road haulage vehicles and buses

Observations

Hydrogen can be significant in a decarbonized energy system by 2050, but challenges are substantial

1. There is no question on the **suitability of producing green hydrogen in Cyprus, especially via solar** – however it's a matter of cost and potential end uses, since one must consider if it's more practical and cheaper to directly electrify many of the end uses
2. If H_2 is deployed at scale, it will have **significant implications for the power sector** – enormous amounts of capacity in renewables must be added, this is important for energy planners in Cyprus
3. While geological storage would be the preferred option of storing H_2, **there are no suitable sites in Cyprus** – no salt deposits, no depleted hydrocarbon reservoirs, so NG+CCS must be considered **very carefully**
4. Depending on how European markets develop, **Cyprus can have a role as an exporter of green hydrogen**, subject to the right conditions
5. But: Freshwater feed for electrolysis **can be an issue**

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