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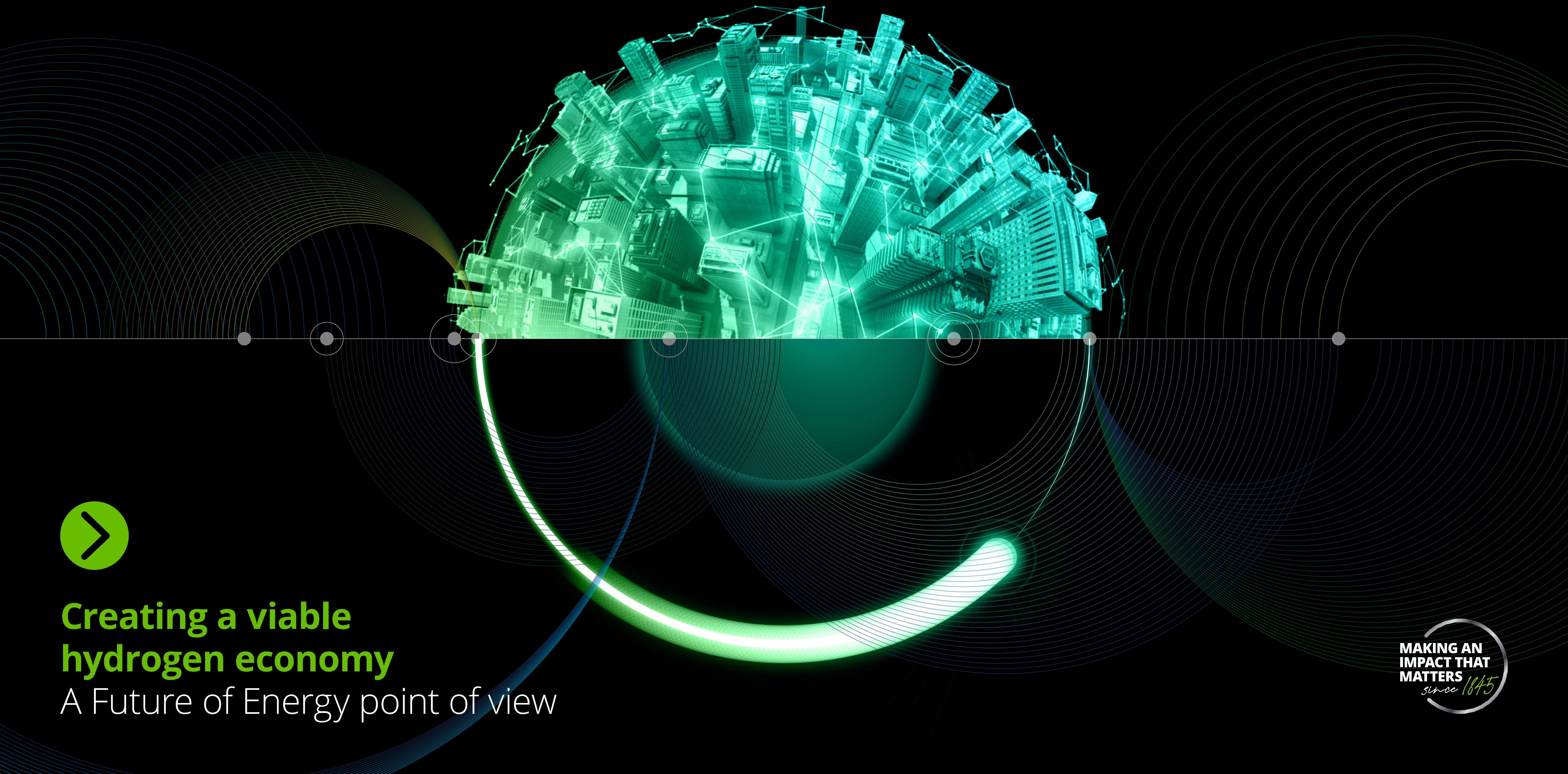

Creating a viable hydrogen economy

A Future of Energy point of view

MAKING AN IMPACT THAT MATTERS since 1845

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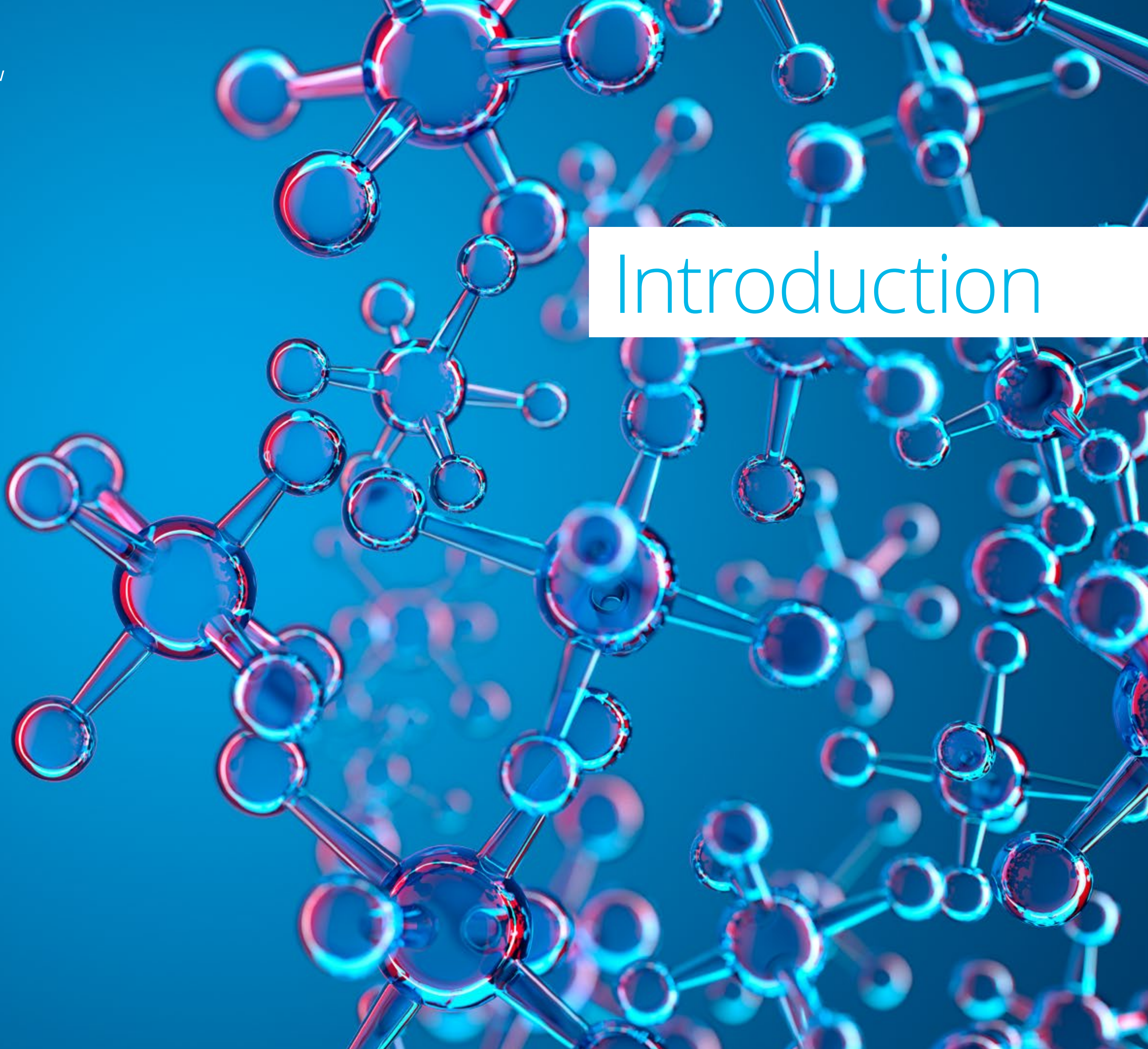
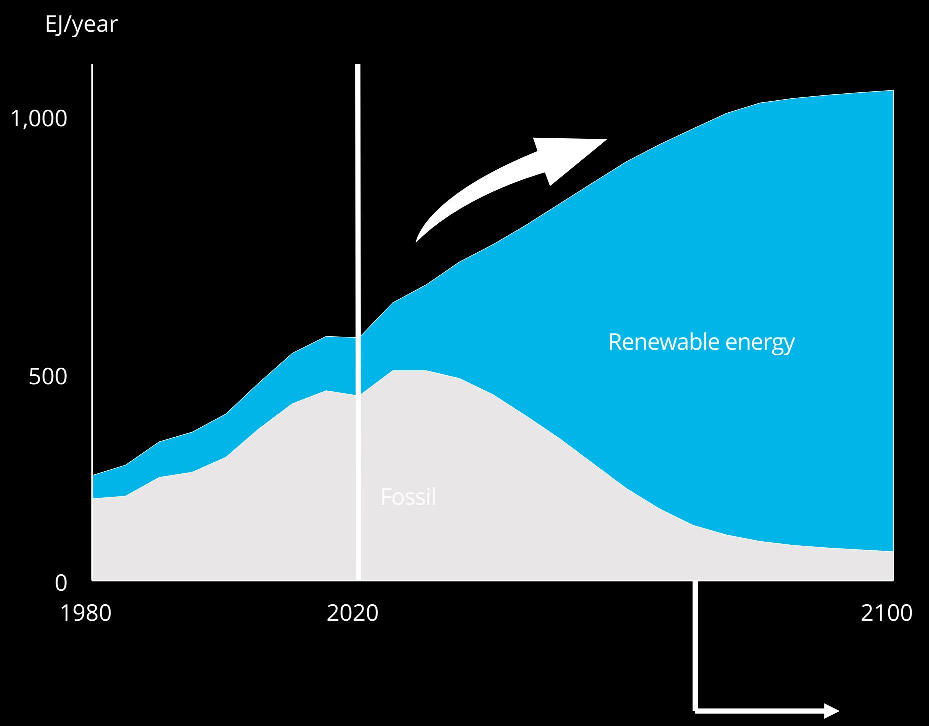


Introduction

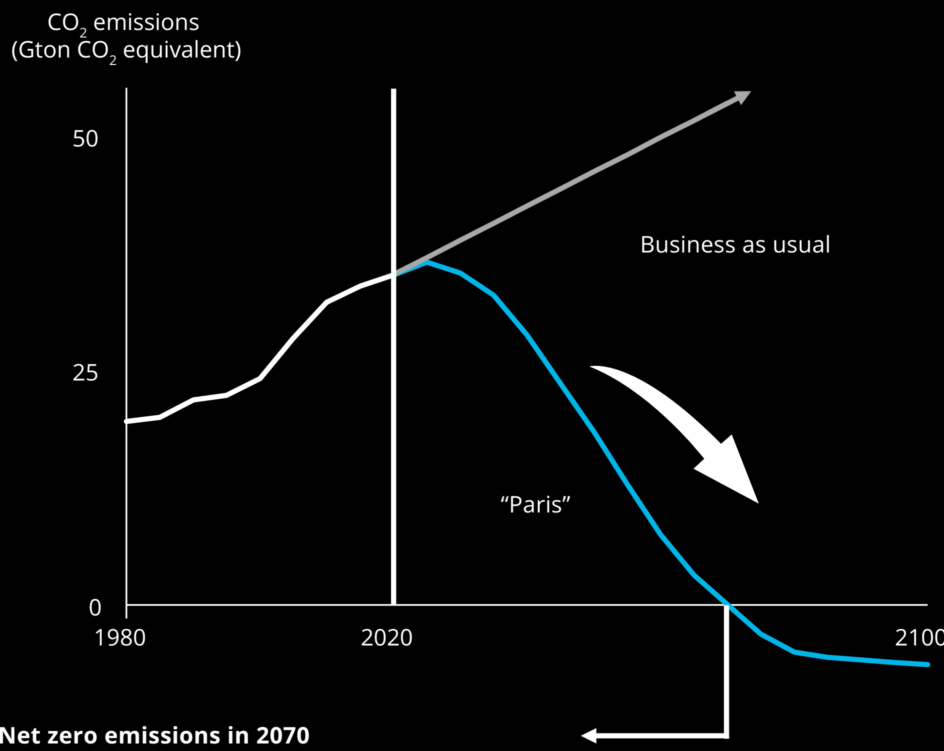
The global energy mix is shifting from fossil fuels to renewables in an effort to reduce CO_2 emissions

Global decarbonisation

Global total primary energy by source



Global net energy-related CO_2 emissions



Net zero emissions in 2070

Note: EJ = Exajoule = 1^18 joule
Source: Deloitte Future of Energy Scenarios; Shell Sky 1.5 scenario

But to what extent, and how fast depends for a large part on global dynamics and societal response to climate change, two critical uncertainties that span our Future of Energy scenarios space

Deloitte's Future of Energy scenarios

- In 2020 Deloitte published its Future of Energy scenarios.
- These four plausible and divergent energy scenarios represent guideposts that can help leaders make decisions and take action in the short term.

Ready, set, innovate

The failure of governments to globally address climate change leads private industry to take it upon themselves to innovate to lower emissions. The build-out of renewables relies on businesses as there is limited coordination between nationalistic governments creating hurdles for the scale-up of these technologies.

One team, one dream

Consumer behavior dramatically favours the long-term health, environmental, economic, and social benefit of the collective, triggering a globally collaborative atmosphere that successfully commercialises low-carbon technology and commits to drastic decarbonisation. Governments introduce a global carbon pricing mechanism.

Me and my resource

Protectionist policies that create trade barriers and limit technology/knowledge transfer prevail. Governments compete for access to cheap and stable energy resources. Innovation focuses on development of local resources, whether renewable or hydrocarbon. Climate change responses are disparate, reactive, and focused on localised infrastructure projects versus abatement.

Rising tide

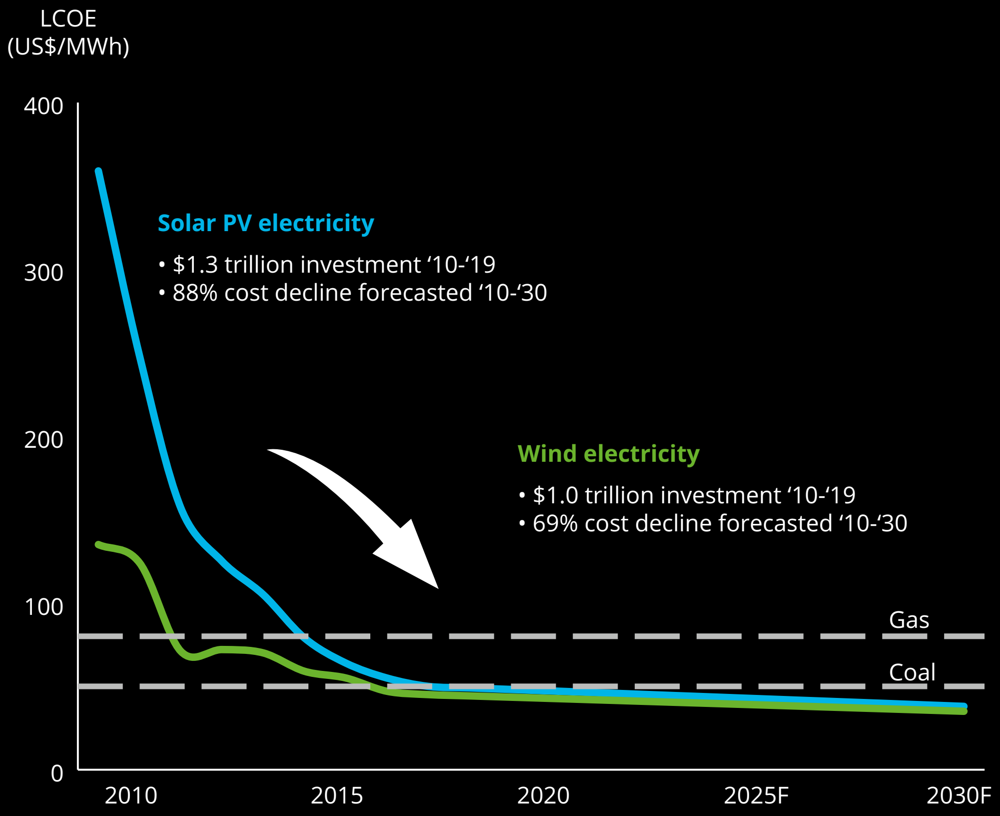
Energy efficiency, affordability, and accessibility drives consumer behavior, resulting in the expansion of both renewables and hydrocarbons. Global powers share the priority of short-term economic growth, which leads to increases in wealth and quality of life for most. Advanced technologies create new options for adapting to climate change.

● Societal response to climate change ● Global dynamics

What is clear is that after a decade of investments targeted at electrification of the energy system solar and wind are cost-competitive and the share of electricity in the energy mix has increased

Electrification of energy mix

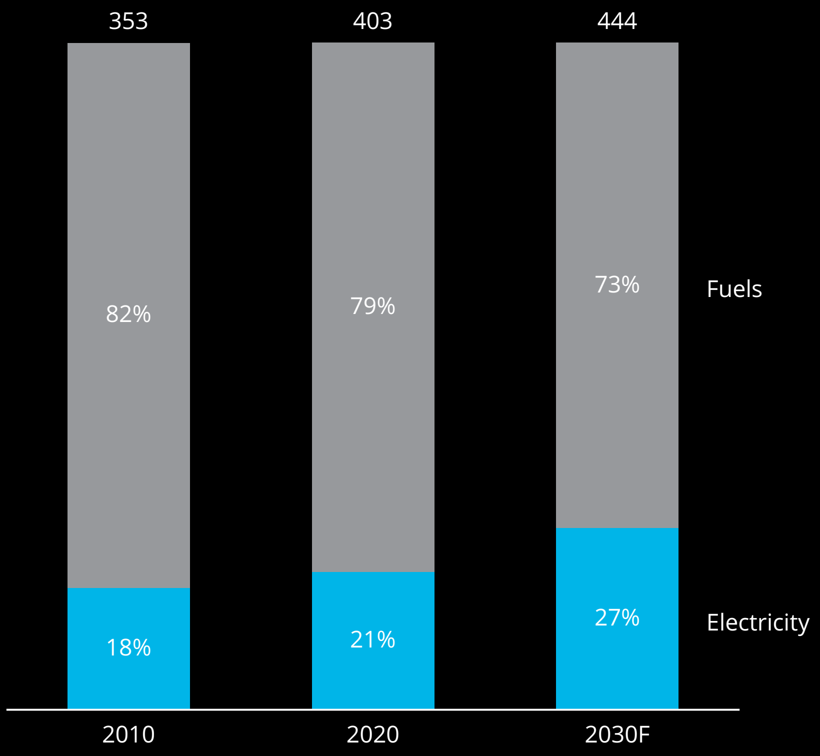
Cost of solar PV and wind electricity



Solar PV electricity
- $1.3 trillion investment ‘10-‘19
- 88% cost decline forecasted ‘10-‘30

Wind electricity
- $1.0 trillion investment ‘10-‘19
- 69% cost decline forecasted ‘10-‘30

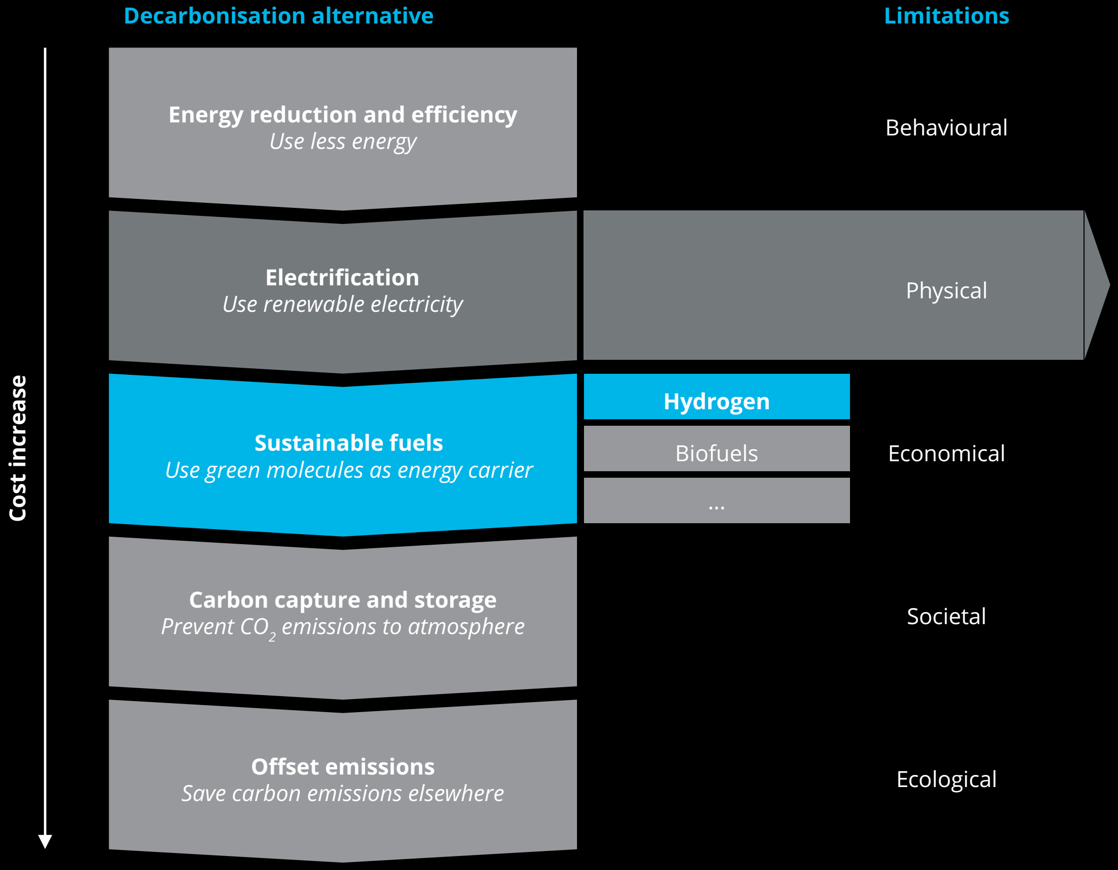
Total energy consumption by source (EJ/year)



Note: LCOE = levelised cost of energy = average cost per MWh over the lifetime of the asset; Solar PV electricity refers to solar photovoltaic electricity; EJ = Exajoule = 1^18 joule
Source: BloombergNEF; Shell sky scenario

However, there are limits to electrification, where hydrogen can be an alternative way to decarbonise energy use

‘Path to Paris’ – Prioritisation of decarbonisation alternatives



Physical limits to electrification when you need:

- **Combustibility** to reach high **temperatures**
- High **energy density** in mobile applications
- **Flexibility** in time and space through **storage**
- **Feedstock** for industrial processes

Note: ‘Path to Paris’ refers to the global agreement to keep a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels

In energy, around 20-50% of demand cannot be physically or economically electrified

Energy electrification potential towards 2050 (% of 2018 consumption, EJ; DE, NL, BE)

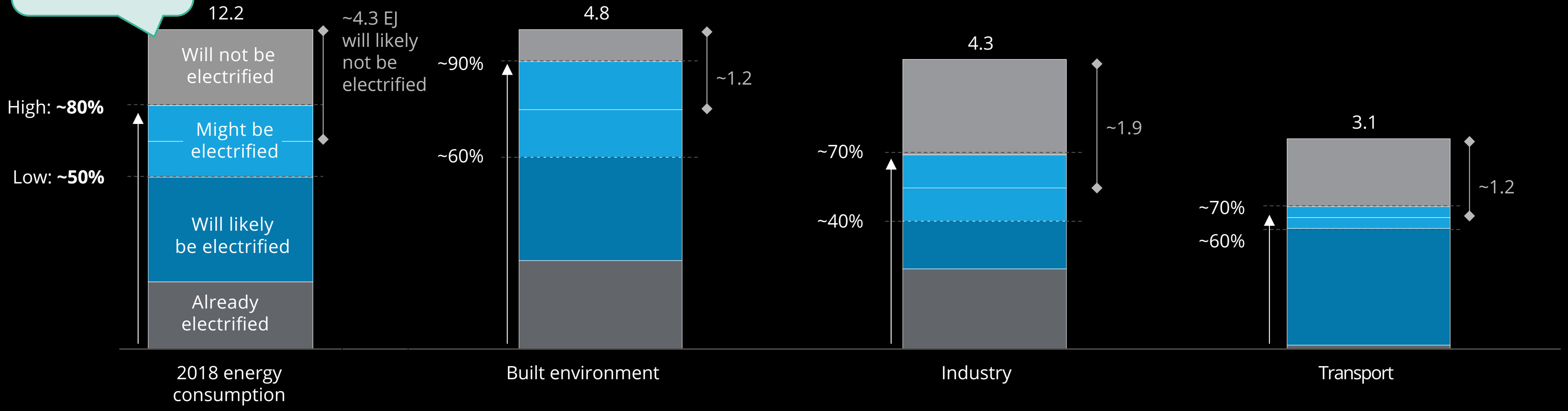
Electrification limitations:

- Poorly insulated buildings less suitable for electric heat pumps
- Central heat can be more economical in urban areas

- High temperature heating very difficult to electrify
- Costs of redesigning processes to new energy sources

- Energy density (range) per kg and m^3 (shipping and aviation)
- Development time (aviation)

20-50% of energy will not be electrified



Source: Deloitte Energy System Model based on Eurostat Energy Balances June 2020 (DE, NL, BE); OECD; Shell Sky; IEA SDS; Zsiborács et al., Electronics 8, 2019; EEA

And although hydrogen has been talked about before, this time the fundamentals have changed...

Why now?

Technology enabled

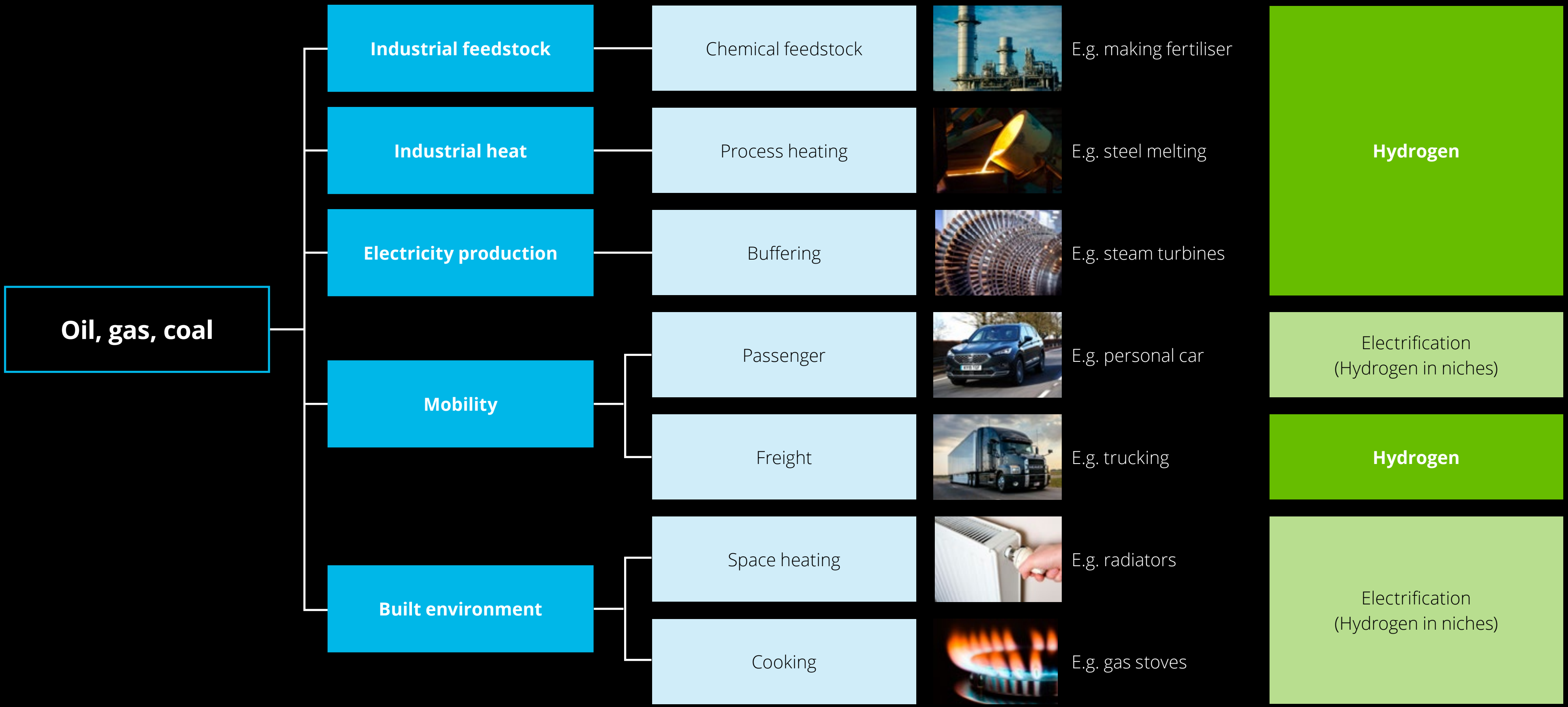
- Renewable power has become **commercial** enabling **green hydrogen production**
- Shares of renewable power have increased to the level that **supply exceeds demand** more often, therefore requiring energy storage
- Electrolysers have shown signs of **steep cost declines** similar to solar PV and wind turbines
- **Electricity grid congestions** in some parts of Europe (e.g. NL) are limiting further renewable power deployment, requiring alternative ways of **transport energy**

Governments pushed

- Policy focus has shifted from renewable electricity to **decarbonising** the **hard-to-abate sectors**
- Governments in Europe are making **large investments** in hydrogen infrastructure as part of COVID-19 recovery packages
- **National hydrogen strategies** are developed to create a strategic advantageous position

… creating opportunities for hydrogen, particularly in industrial chemical feedstock, industrial process heating, the electricity system and freight mobility

Fossil fuel uses and hydrogen potential

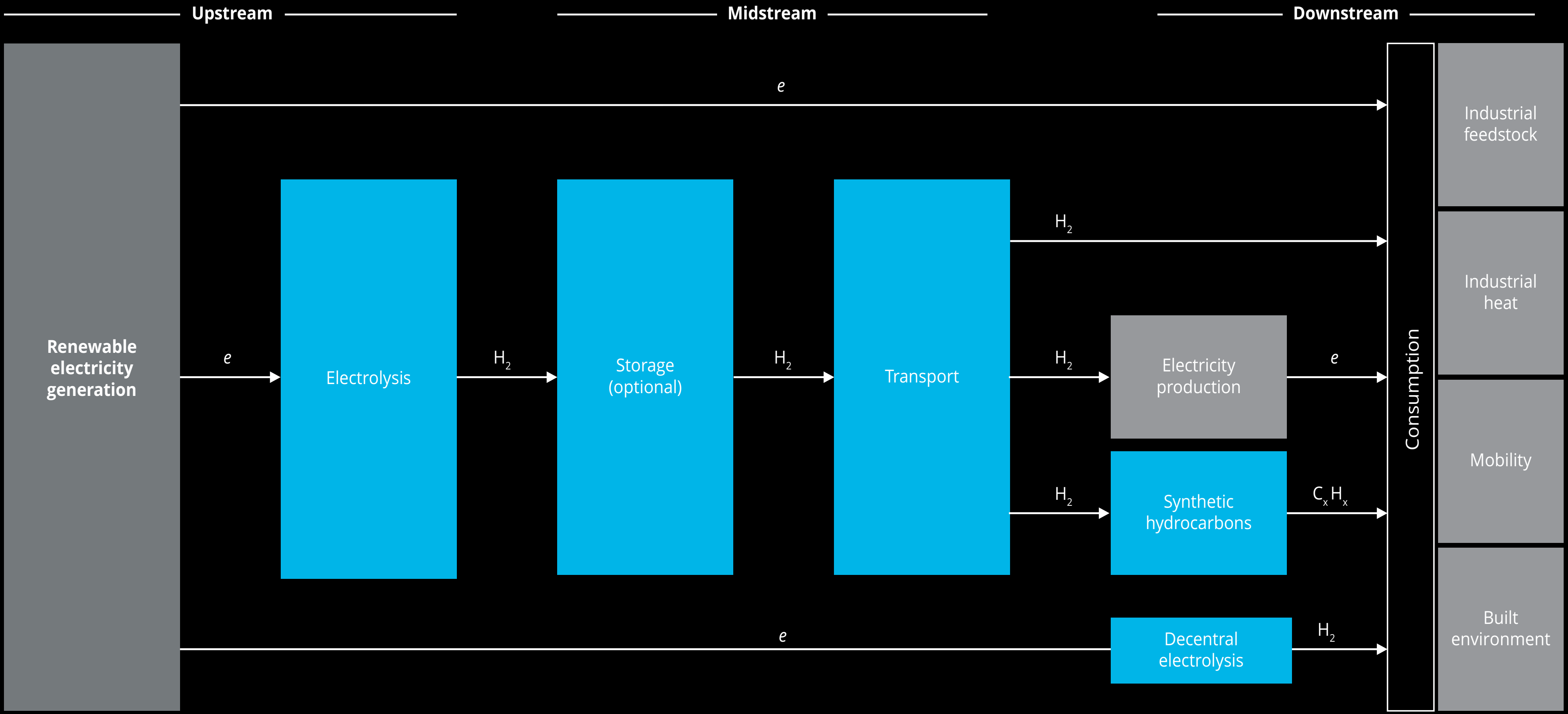


Oil, gas, coal

			Substitution opportunities
Industrial feedstock	Chemical feedstock	E.g. making fertiliser	**Hydrogen**
Industrial heat	Process heating	E.g. steel melting	
Electricity production	Buffering	E.g. steam turbines	
Mobility	Passenger	E.g. personal car	Electrification (Hydrogen in niches)
	Freight	E.g. trucking	**Hydrogen**
Built environment	Space heating	E.g. radiators	Electrification (Hydrogen in niches)
	Cooking	E.g. gas stoves	

Which will create new elements to the energy value chain

Renewable energy value chain and hydrogen role



Upstream

Midstream

Downstream

Renewable electricity generation

e

Electrolysis

H_2

Storage (optional)

H_2

Transport

H_2

Electricity production

e

H_2

Synthetic hydrocarbons

C_xH_x

e

Decentral electrolysis

H_2

Consumption

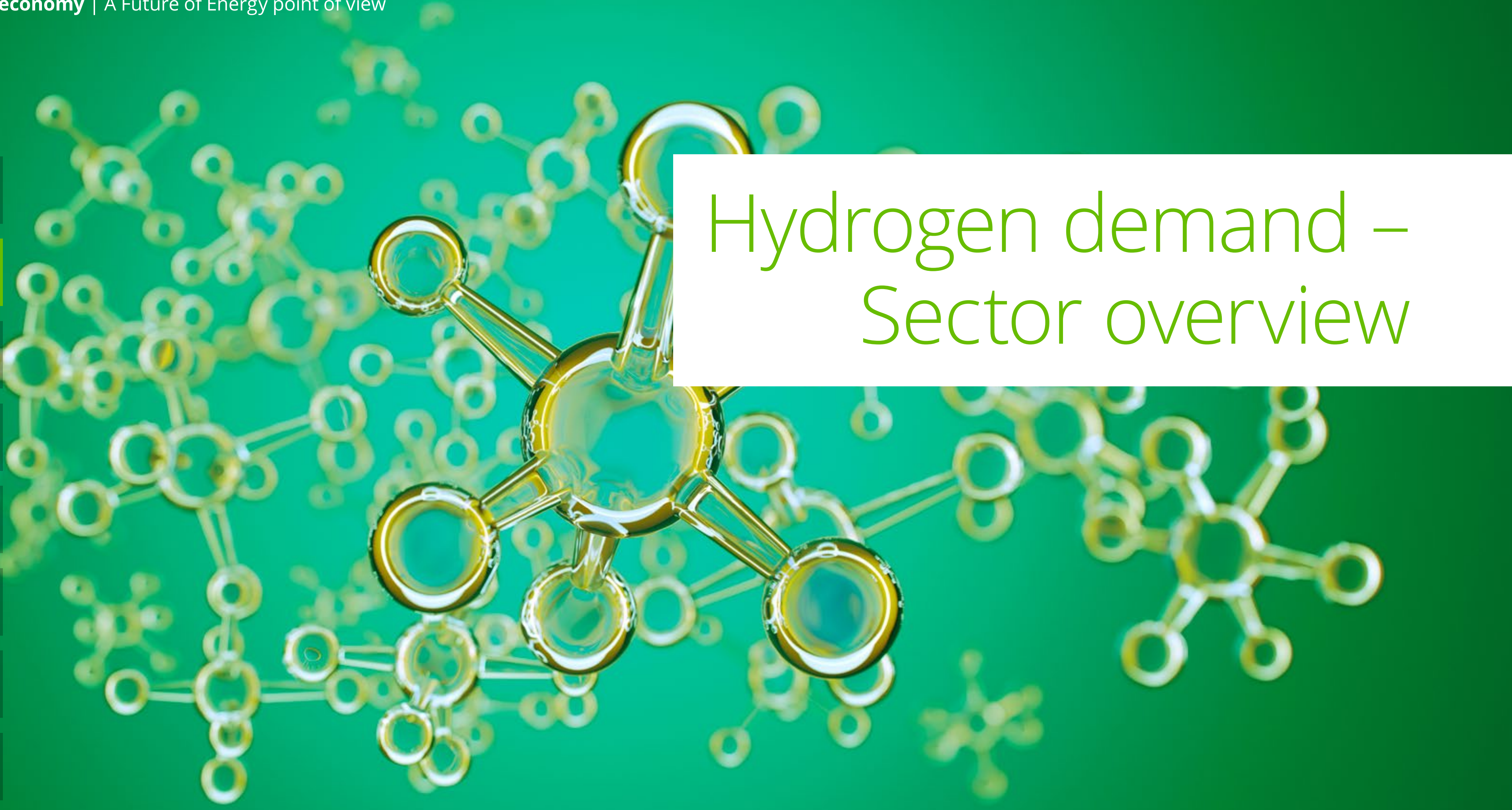
Industrial feedstock

Industrial heat

Mobility

Built environment

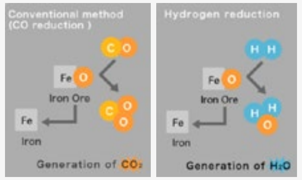
Note: *e* = electricity



Hydrogen demand – Sector overview

In industrial feedstock, hydrogen is potentially more competitive because it substitutes converted hydrocarbons, however uptake will be slow owing to large existing assets

Renewable energy value chain and hydrogen role

	Hydrogen adoption		Example projects
Subsegment	**Enablers**	**Barriers**	
Industrial feedstock – Existing demand	• **Hydrogen application units** are already in place • Hydrogen is **more competitive** as feedstock because it competes with **converted hydrocarbons** (grey hydrogen instead of natural gas) instead of **hydrocarbons directly**	• Production assets for grey hydrogen (steam methane reformers) are already in place (and depreciated) hence **marginal cost** of **grey hydrogen** is **low** • **Difficult** to **obtain premium** for using green energy because of distance to end consumer	• E.g. 1 GW electrolyser to **replace grey hydrogen** from SMRs for i/a **fertiliser** (Yara) and **refining** (Lukoil-Total Refinery) in Zeeland (NL) 
Industrial feedstock – New demand	• Hydrogen is **more competitive** as feedstock because it competes with **converted hydrocarbons** (e.g. cokes instead of coal) instead of **hydrocarbons directly**	• Production and application of hydrogen requires installing **new assets** • **Difficult** to **obtain premium** for using green energy because of distance to end consumer	• E.g. Hybrit, a joint venture between LKAB, Vattenfall and SSAB for a pilot to use hydrogen instead of cokes for **direct reduction** of iron ore  

Source: SDR (2020) '1 GW Hydrogen plant in Zeeland'; Hybrit company website

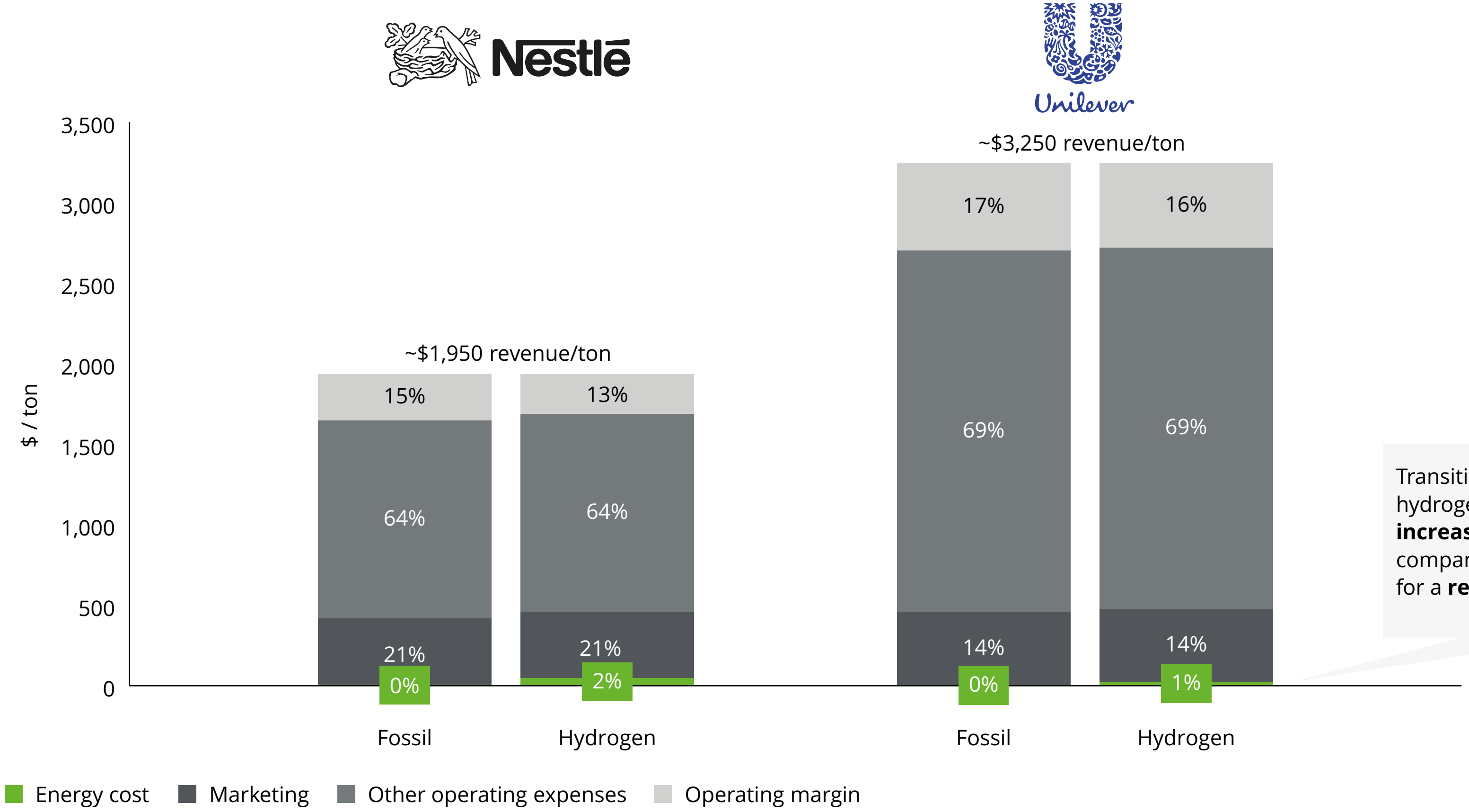
In industrial heat, hydrogen has potential to replace fossil fuels for consumer goods companies that can capture a premium from using renewable energy

Hydrogen potential for industrial heat

	Hydrogen adoption		**Example projects**
Subsegment	**Enablers**	**Barriers**	
Industrial heat – B2C	• Consumer goods companies can **directly benefit** from switching to hydrogen by **charging premiums** to consumers based on green image • **Energy cost** often accounts for **minimal part** of total operating cost • **Technical barriers** are **low**, e.g. burners and boilers can be switched to hydrogen relatively easily	• Consumer-facing companies carefully **balance benefits and risks** as failures are directly linked to the company brand	 • E.g. Unilever piloting the use of hydrogen in an **industrial-scale boiler** for manufacturing **home and personal care products** at its Port Sunlight facility • Uses **blue hydrogen** supplied by Essar Oil via **dedicated pipeline**
Industrial heat – B2B	• **Technical barriers** are **low**, e.g. burners and boilers can be switched to hydrogen relatively easily • Burners can also be converted to run on **0-100% natural gas-hydrogen content**, limiting the risk of downtime due to limited hydrogen supply	• Companies bear additional cost as B2B customers are **not willing to pay** a premium for renewable energy • **Energy** cost often accounts for a **larger share** of total cost relative to B2C companies, therefore increasing the cost impact of switching to hydrogen	• E.g. Nedmag developing a **hybrid burner**, capable of handling 0-100% natural gas/hydrogen mixtures • Handling varying mixtures **mitigates supply lock-in** and **smoothens transition** to (green) hydrogen

Consumer goods companies can switch from fossil fuels to hydrogen to appeal to consumers, at a cost increase that is minimal relative to marketing and operating expenses

Consumer goods companies energy cost



Transitioning from fossil energy to hydrogen would only **marginally increase total cost** of consumer goods companies since energy costs account for a **relatively small share** of total cost

Note: Assumes fossil fuel usage of 100% natural gas at cost of $5/GJ and hydrogen at cost of $35/GJ
Source: 2019 company annual reports; 2019 company environmental performance indicators

In the electricity system, hydrogen could be used as storage medium for renewable electricity production and benefit from buffering, arbitrage and alternative transport compared to direct electricity usage

Hydrogen potential for electricity production

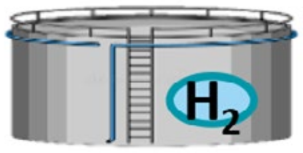
Power surplus

Electrolysis

Storage alternatives

Tank storage

- High CAPEX makes storage not cost competitive with batteries
- No location constraints



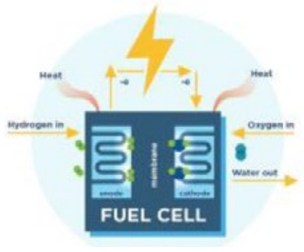
Underground storage

- Low CAPEX enables seasonal storage
- Location constraint and technical complexities

Electricity production

Hydrogen turbine peak power plant

Fuel cell



Electricity production

Advantages:

Buffering: match supply and demand of electricity production and consumption through storage medium

Arbitrage: produce and store energy when electricity price is low and sell electricity when price is high

Transport: prevent congestion of electricity grid and convert existing gas network to transport hydrogen

Hydrogen offers the opportunity to decarbonise mobility, with high energy density that offers advantages of longer ranges and faster charging

Hydrogen potential for mobility

Note for C&I to give NSE Auto team a heads up on this as some of their clients are mentioned.

	Hydrogen adoption		**Example projects**
Subsegment	**Enablers**	**Barriers**	
Trucks & buses	• Cost advantage for commercial fleets from **longer range** (1,200 vs 800 km) and **faster charging** (15 vs 60 minutes) of than batteries[1]	• Requires new **refuelling network** • Higher **energy cost per km** than electricity	• Nikola 
Cars	• Increased convenience from **longer range** and **faster charging** than battery-electric vehicles • However **not required** for typical private trip	• Requires new **refuelling network** • Higher **energy cost per km** than electricity	• Toyota 
Shipping	• **Energy density** of hydrogen is more suitable for global shipping than batteries • Can be used in **fuel cells** or **combustion**	• Industry has **yet to settle** on fuel and technology to replace fossil fuels, with ammonia also in the race	• KOMERI 
Trains	• Avoids **high cost** of electrifying train tracks • Therefore suitable for **long-distance**, **low-utilization** tracks (e.g. rural or mining freight)	• Higher **energy cost per km** than electricity	• Stadler 
Aviation	• **Energy density** of is better than batteries • Can both be combusted in turbines to **boost take-off** and in fuel cells to **power cruise**	• Requires **substantial R&D investments** on propulsion technology and aircraft body design before ready to go to market	• Airbus 
Specialist equipment	• Cost advantage of **faster charging** than batteries, e.g. for forklifts in 24-hr warehouse • On-site usage needs **little refuelling infra**	• Higher **energy cost per km** than electricity	• Toyota 

Notes: Charging time for full range
Source: Transport & Environment (2020) 'Comparison of hydrogen and battery electric trucks'; Company websites

While hydrogen is a feasible alternative for specialist equipment today, additional applications can be found in the future for the freight mobility sector

Hydrogen potential for future mobility

	2030	2050
Trucks and buses	~	✓
Cars	✗	✗
Shipping	~	~
Trains	✗	~
Aviation	✗	~
Specialist equipment	✓	✓

Source: IEA, CO_2 emissions by sector

- Road freight represents ca. **9% of global CO_2 emissions**
- **Common view** that range and charging time will be prohibitive for use of battery electric vehicles (BEVs) in heavy-duty trucks and that **hydrogen fuel cell electric vehicles (FCEV) will be the most likely solution**
- However, our ongoing research on road freight decarbonisation shows that **BEVs may take a foothold in some duty cycles for HDT**
- If BEVs are adopted at scale in the next five years, **hydrogen may be permanently locked** out from the sector

- Shipping represents ca. **3% of global CO_2 emissions**
- Our study shows that hydrogen is among the contenders as "fuel of the future", but **ammonia** is also in the race
- Green ammonia, although using hydrogen ions, requires different infrastructure than hydrogen used as a fuel

> "With small changes to operations, most fleet owners could use **battery electric vehicles for 80% of road freight** duty cycles, at lower cost than hydrogen"
>
> **Vice President from a leading global truck OEM**

> "**Ammonia** could be a **good option** for shipping, and we know how to handle it"
>
> **CEO of a shipping technology provider**

In the built environment hydrogen can be blended in the gas network and used in households, but alternatives are likely more attractive

Hydrogen potential for built environment

Existing uses

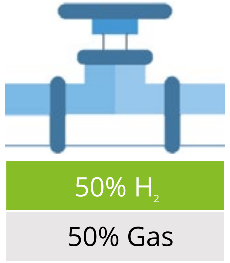
In the building sector, **hydrogen could already be used** through blending in small fractions

- A **5-10%** hydrogen fraction would help to **scale up hydrogen production**, making it more affordable

Short term

Greater blending fractions could be achieved, **more than 30%**, after:

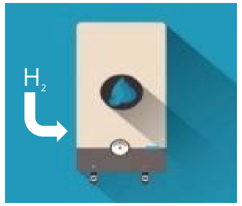
- Improvement of some **components of the gas network**
- Adjustment of the existing **regulation**

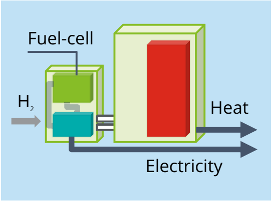


Long term

When gas grids are completely transformed into hydrogen or new hydrogen infrastructure is ready:

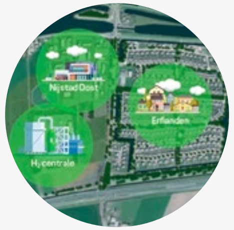
- **Hydrogen boilers** with zero carbon emissions
- **Hydrogen cogeneration systems and fuel-cells** that provide heat and power, enabling off-grid systems





Hydrogen in the built environment will be very limited in 2030, but pilots are being developed

Hydrogen potential for built environment

	Leeds (UK)	Hoogeveen (NL)	Stad aan het Haringvliet (NL)
Examples			
Description	• Conversion of the existing gas grid to carry 100% hydrogen • Total average yearly demand = 5.9 TWh • Blue hydrogen production capacity of 0.15 million tonnes per annum • Incremental conversion of major UK cities' natural gas supply to 100% hydrogen • Convert 3.7 million homes and businesses by 2035 and 15.7 million by 2050	• Conversion of existing gas infrastructure in new and existing residential areas to 100% green hydrogen • (Local) availability of green hydrogen is prerequisite for further growth and application of hydrogen in the built environment • Convert 100 new homes and 400 existing homes	• Conversion of existing gas network in residential areas to 100% hydrogen • All-electric heat pumps are no feasible alternative because of old and detached houses, where required level of isolation is unattainable • Connect to nearby wind turbines for green hydrogen production • Convert 600 existing homes, and potentially the whole city to reach climate neutrality by 2050

Source: H21.green; Leeds Climate Commission; Proefproject Hoogeveen Publiek Rapport 2020; Stedin.net

The first sectors for hydrogen demand will be industrial heat and road freight for consumer goods companies, which can obtain premium from consumers

Hydrogen potential per demand sector

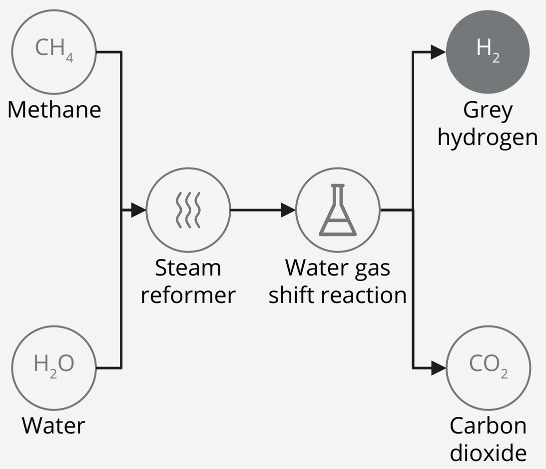
		2030	2050	Assessment of hydrogen potential
Industrial feedstock	**Existing**	Low	High	• High potential because competing with (more costly) **grey hydrogen** instead of with fossil fuels directly • **Slow uptake** due to existing grey hydrogen assets with **low marginal cost** and difficulty to obtain premium
	New	Medium	High	• High potential because competing with (more costly) **converted hydrocarbons** instead of fossil fuels directly • Barrier from requirement for **new technology and assets** and difficulty to obtain premium
Industrial heat	B2C	High	High	• High potential because consumer goods companies can obtain **premium from customers** for using green energy that covers higher energy cost
	B2B	Low	High	• High potential because **technical barriers** are **low** • Slow uptake because of **difficulty to obtain premium** and **large energy cost** as share of total cost
Electricity production		Low	Medium	• Niche potential for **flexibility services** to store excess renewable electricity supply to use as peak capacity • Niche potential for **transport** where cost advantage of pipelines over cables outweighs conversion loss
Mobility	Trucks and buses	Medium	High	• High potential from cost advantage of longer **range** and faster **charging time** relative to electric vehicles • Needs sufficient coverage of **refuelling station infrastructure** to take off
	Cars	Low	Low	• Low potential as **electric vehicles** will likely remain **cheaper** and typical passenger car usage does not need long ranges and fast charging times
	Shipping	Medium	Medium	• Industry has **yet to settle** on fuel and technology to replace fossil fuels • Hydrogen has potential for benefits of **energy density**, but ammonia is also in the race
	Trains	Low	Medium	• Low potential as most trains can be **electrified** at **cheaper** cost than using hydrogen • Some niche potential for **long-distance, low utilization tracks** where electrification has prohibitive infra cost
	Aviation	Low	Medium	• Low potential because of **extreme energy density** needed for aviation which are better provided by biofuels or synthetic hydrocarbons
	Specialist equipment	High	High	• High potential from cost advantage of **longer range** and **faster charging time** relative to electric equipment • Typically needs **little refuelling infrastructure** as usage is restricted to on-site
Built environment		Low	Medium	• Niche potential where electrification or alternatives of district heating or biomass are not attainable, typically for **city-center old buildings** with **poor insulation**

Hydrogen supply – technology overview

Steam reforming of natural gas results in grey hydrogen, or, if carbon dioxide is captured and stored, blue hydrogen, while electrolysis with renewable electricity results in green hydrogen

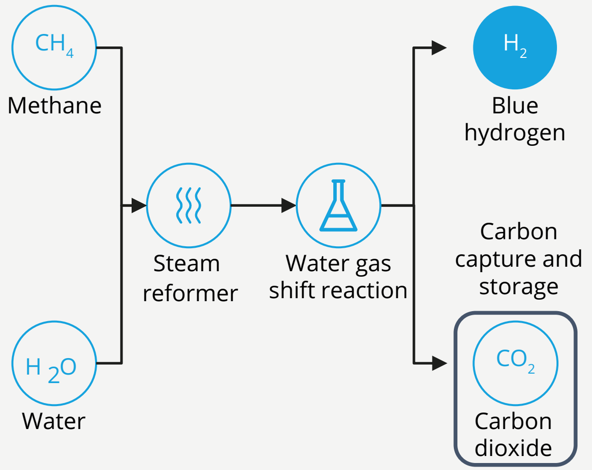
Hydrogen production methods

Grey hydrogen



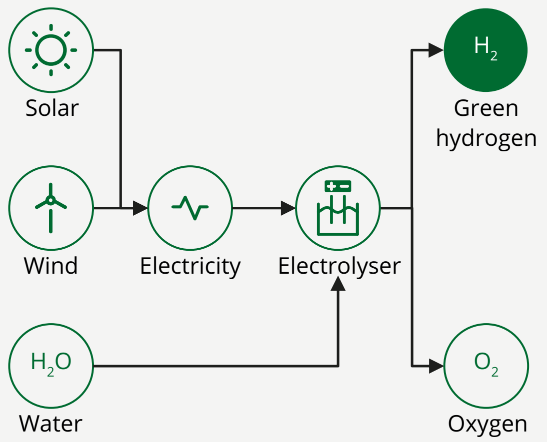
- Current hydrogen production is almost exclusively **grey hydrogen** from natural gas
- Grey hydrogen has **high carbon emissions**

Blue hydrogen



- Blue hydrogen has **same production method** as grey hydrogen, but uses **carbon capture and storage**
- Has **controllable production capacity** hence does not require storage
- Could be the **gateway** towards green hydrogen

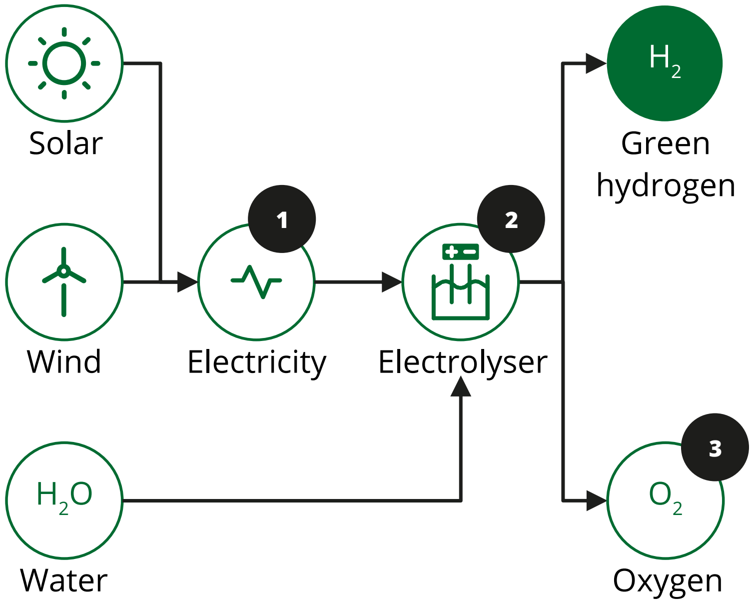
Green hydrogen



- Green hydrogen is the only **100% renewable hydrogen** production method
- Requires **storage** to balance out **fluctuating production** from intermittent renewables with constant demand
- Electrolysis **technologies vary**; mature ***alkaline*** technology is best for **stable electricity** supply, newly developed **PEM** technology for **intermittent** supply

Green hydrogen can become cost-competitive if renewable electricity prices fall, electrolyzer cost decrease and if carbon taxes make fossil fuels less competitive

Green hydrogen production process



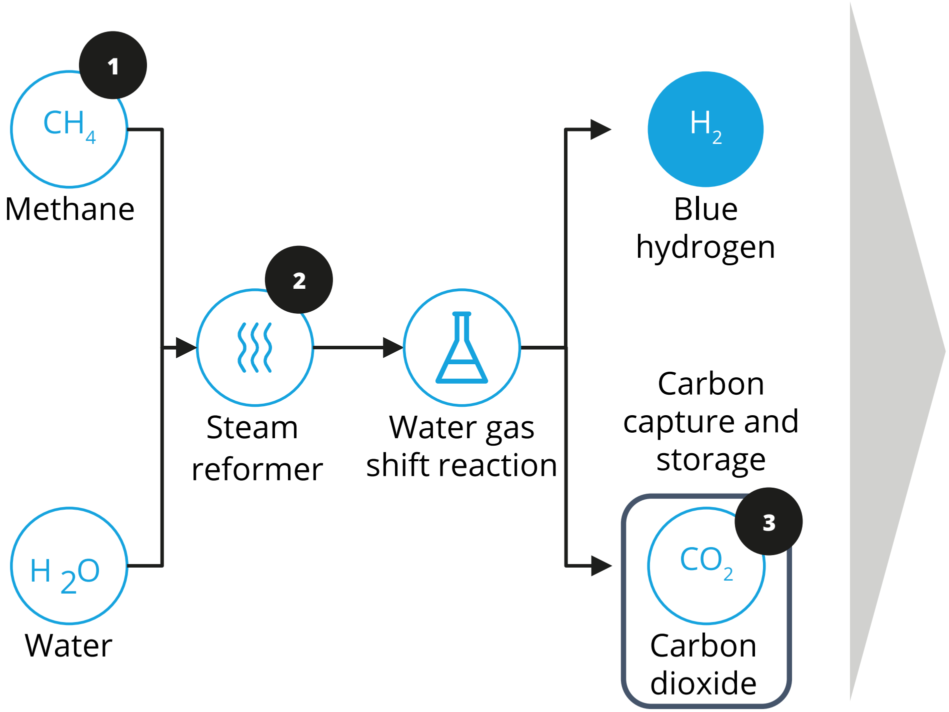
Cost competitiveness of green hydrogen is determined by:

1. Renewable **electricity cost**, the main variable cost, continue to fall
2. **Electrolysers cost**, the main fixed cost, decrease as a result of **technology improvements** and **production at scale** – similar to solar PV
3. **Carbon taxes** make carbon-free green hydrogen more competitive relative to fossil fuels

Large-scale, centralized electrolysis will likely supply the **majority of hydrogen** in the **end-state**.

Blue hydrogen, based on mature technology, may be used in the short term to kick-start supply without having to wait for green hydrogen cost to decrease

Blue hydrogen production process



Cost competitiveness of blue hydrogen is determined by:

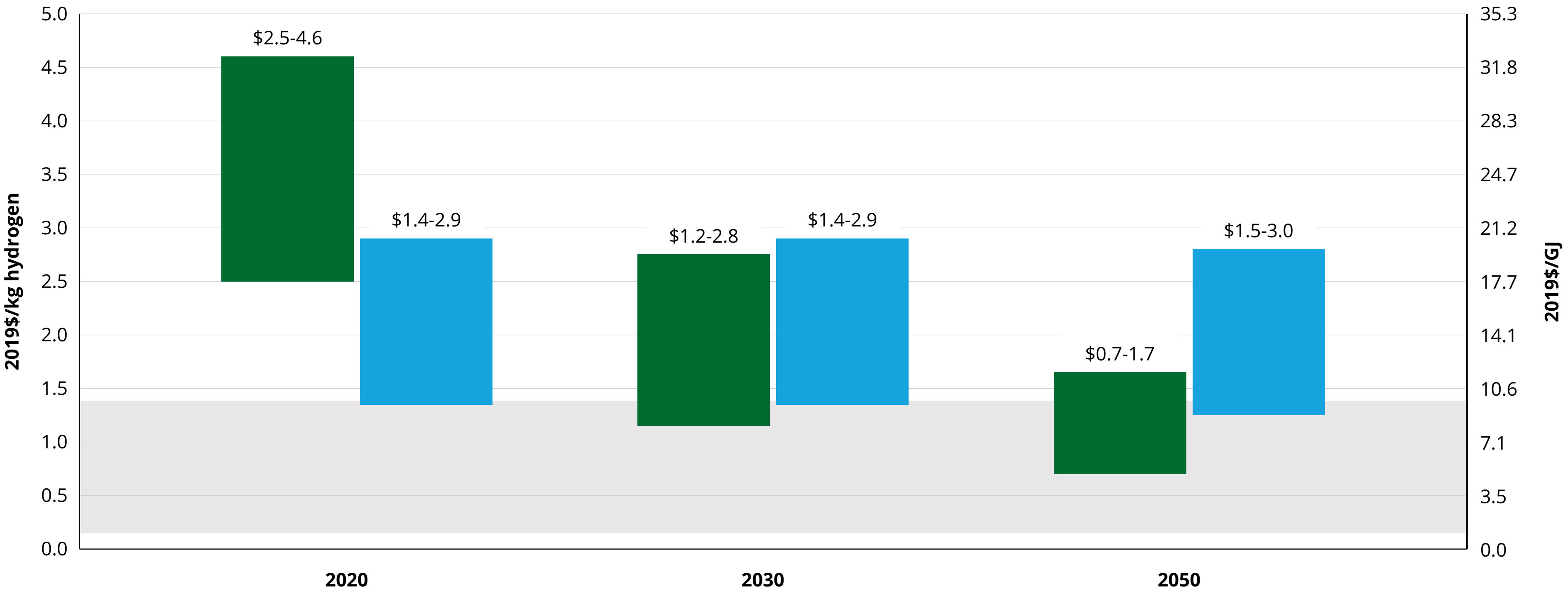
1. **Natural gas**, the main variable cost, is **cheap** and **abundantly available**
2. **Steam reformers**, the main fixed cost, have a cost advantage over electrolyzers as an **existing and mature technology**
3. **Carbon capture and storage/usage can be done cost-efficiently** (e.g. in depleted gas wells or reused in methanol) and yields a saving on **carbon taxes**

Blue hydrogen can **kick-start the transition** by supplying low-carbon hydrogen to companies that **do not want to wait** for green hydrogen cost to come down.

Note: (1) Can also be another hydrocarbon source, such as coal or refining fuel gases

Green hydrogen cost is forecasted to decrease significantly, but more expensive than blue hydrogen in the short term; both will require policy incentives to be competitive with fossil fuels

Hydrogen production cost forecast



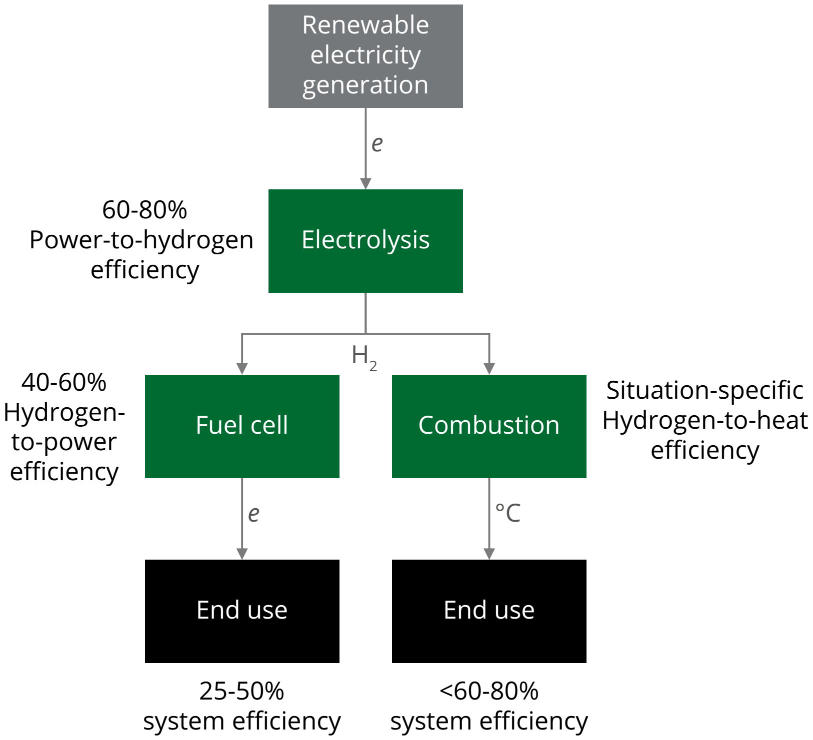
Hydrogen, being produced instead of only extracted, will likely **always be more expensive**than fossil fuels, and therefore needs **policy incentives** to become competitive

Cost range forecast: 🟩 Green hydrogen 🟦 Blue hydrogen ⬜ Natural gas

Source: BloombergNEF (2020) 'Hydrogen economy outlook'

Even though hydrogen system efficiency is reduced by energy losses during conversion, it has advantages over electrification in terms of system cost

Hydrogen conversion efficiency and system cost



Renewable electricity generation

e

60-80% Power-to-hydrogen efficiency

Electrolysis

H_2

40-60% Hydrogen-to-power efficiency

Fuel cell

Combustion

Situation-specific Hydrogen-to-heat efficiency

e

°C

End use

End use

25-50% system efficiency

<60-80% system efficiency

- Power-to-hydrogen-to-power/heat conversion leads to **energy losses** relative to directly using electricity, with **efficiency at only 25-50%**

- However, **lower system efficiency** is outweighed by **lower system cost** of hydrogen relative to electrification

  – Hydrogen allows for **decarbonising end-uses** where electrification has physical limits

  – Hydrogen **pipeline transport** can be **8-15x cheaper** than electricity cable transport per unit of energy

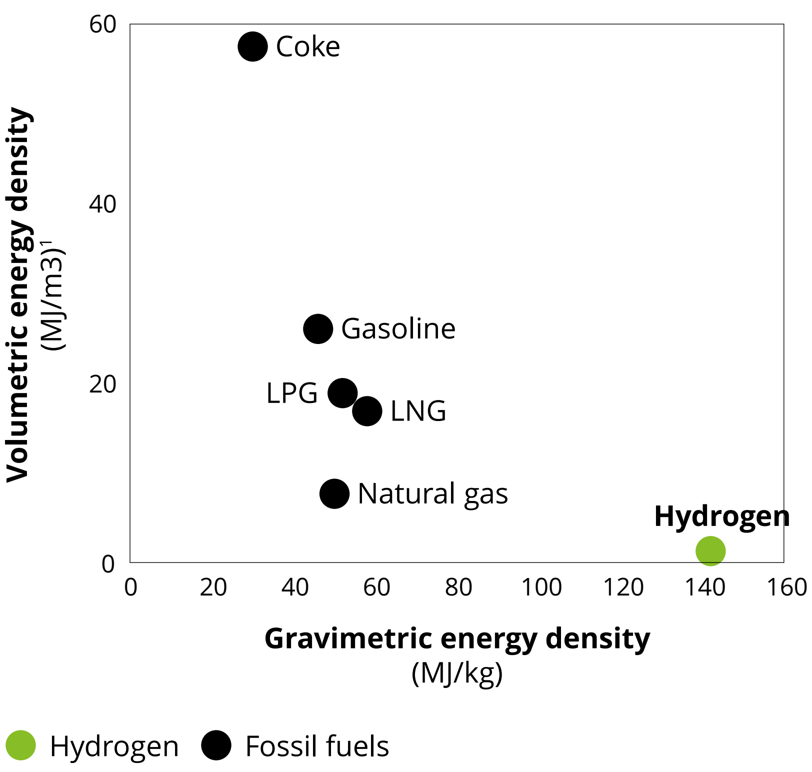
  – Hydrogen allows for **energy storage** and therefore 100% intermittent renewable electricity integration.

Note: Does not take into account inefficiencies in transport and storage; Efficiency in terms of calorific value
Source: Hydrogen Europe

Hydrogen distribution

Transporting energy in the form of hydrogen will be more costly than transporting fossil fuels because hydrogen has a lower energy density per cubic meter

Hydrogen energy density and transport implications

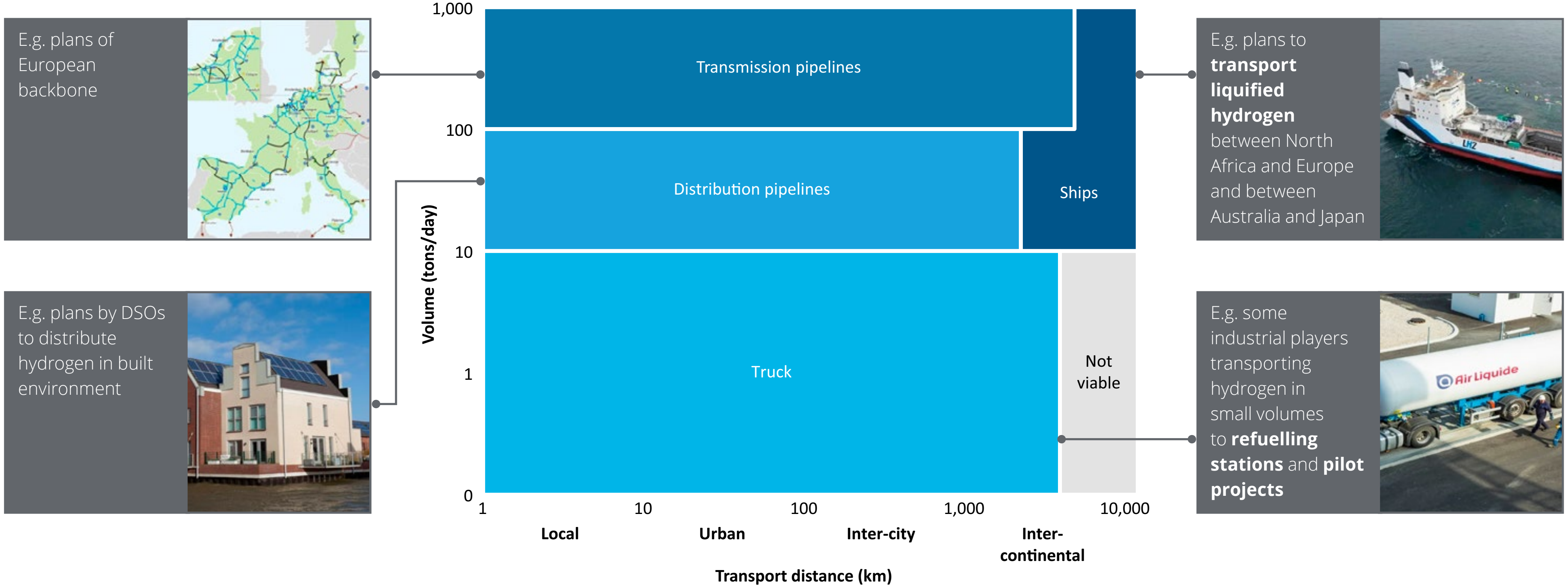


- Lower **energy density** per **m³** of hydrogen (~1/3rd of natural gas) means that **less energy** can be transported in the **same truck or pipeline**, therefore requiring:
  - – Additional **compression or cooling**, hence **cost**
  - – Additional **truck trips**, hence **cost**
- Higher **energy density** per **kg** of hydrogen means the transported **weight** will be **less**
- Hydrogen has higher **flow velocity** (~3x faster than natural gas), meaning:
  - – lower energy density is **partially offset** when evaluating **pipeline transport**
  - – **Pipeline transport** has increased **cost advantage** over **truck transport** in hydrogen relative to fossil fuels

Note: (1) At pressure of 3,000 psi
Source: WEO2019; Grey Cells Energy – Hydrogen Markets; Shell (2018) Hydrogen study

Still, hydrogen transportation alternatives are similar to what we know from fossil fuels, with trucks for small volumes, pipelines for large volumes and ships for long (intercontinental) distances

Most efficient hydrogen transport alternative by distance and volume



E.g. plans of European backbone

E.g. plans by DSOs to distribute hydrogen in built environment

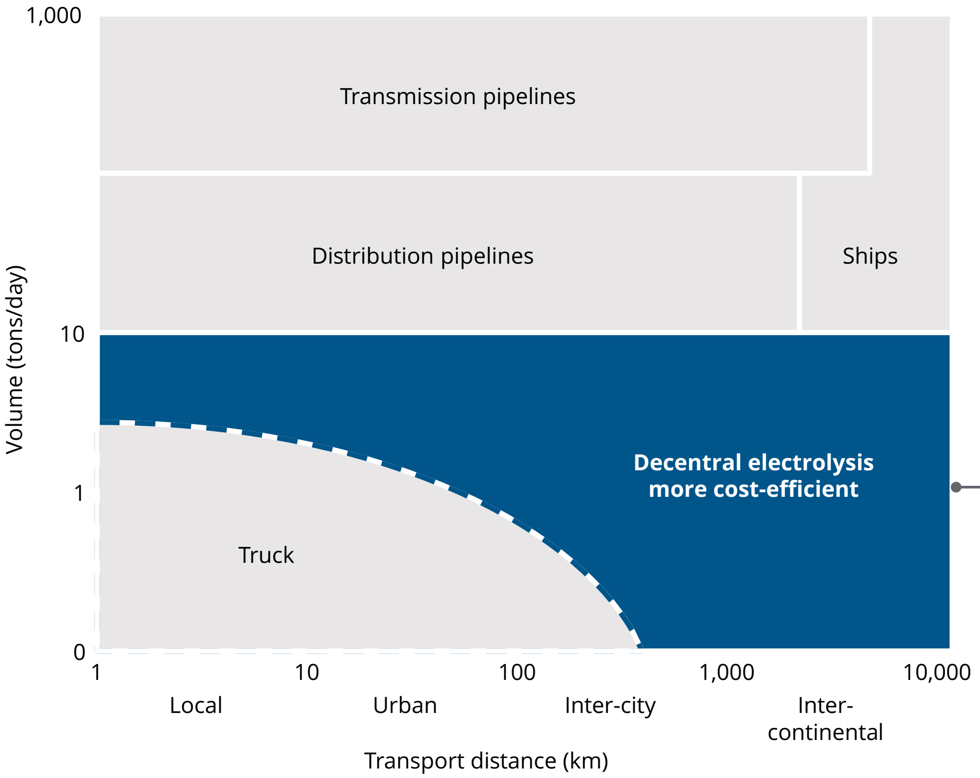
E.g. plans to **transport liquified hydrogen** between North Africa and Europe and between Australia and Japan

E.g. some industrial players transporting hydrogen in small volumes to **refuelling stations** and **pilot projects**

Source: BloombergNEF (2020) 'Hydrogen economy outlook'

Hydrogen does offer the novel possibility of decentral electrolysis, with the advantage of eliminating the need for any transport infrastructure at all

Decentral electrolysis cost-efficiency



Source: BloombergNEF (2020) 'Hydrogen economy outlook'; Monitor Deloitte analysis

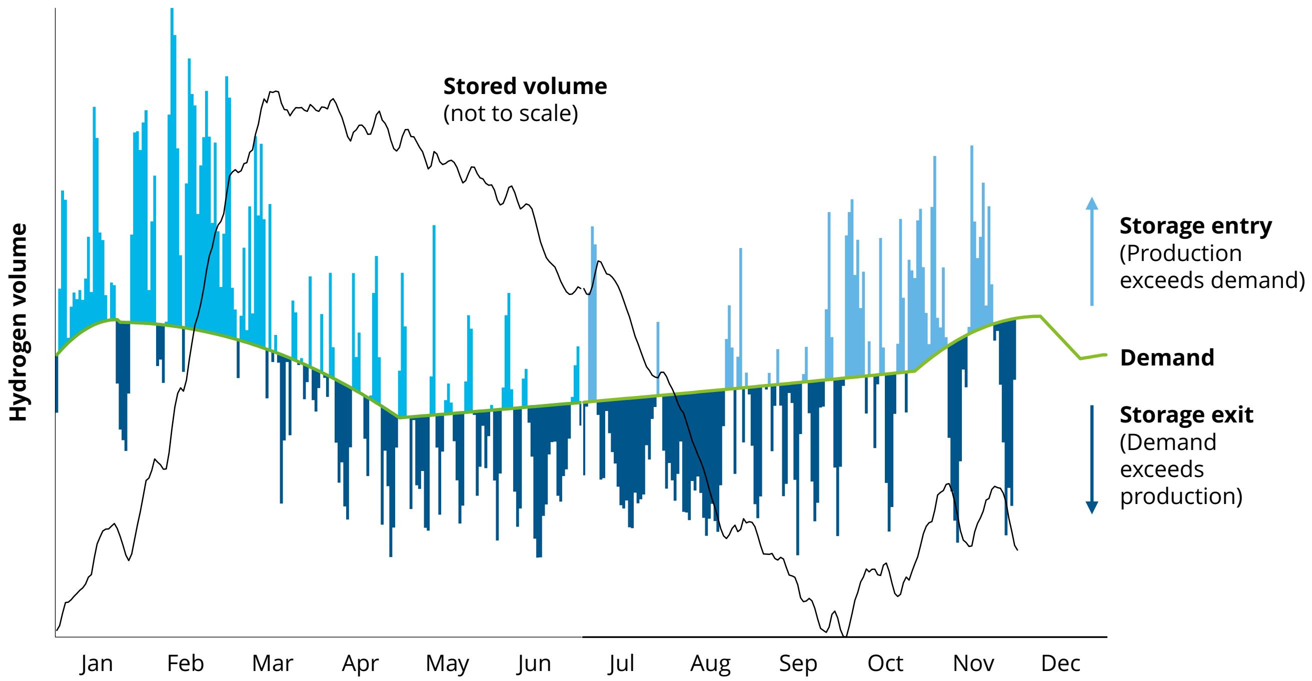
E.g. container-sized electrolyzer at refuelling station

Decentral electrolysis will be more cost-efficient than truck transport when:

- Decentral location has access to **cheap renewable electricity** (from grid or dedicated solar PV or wind)
- Volumes are large enough for **sufficient utilisation** of the electrolyzer, but small enough for pipelines not to be viable
- Distances to a central electrolyser are large hence **savings on transport** are high

Storage has a crucial role to play in enabling the hydrogen transition by stabilising supply and demand, as hydrogen production patterns will follow those from intermittent renewables

Hydrogen entry and exit in storage

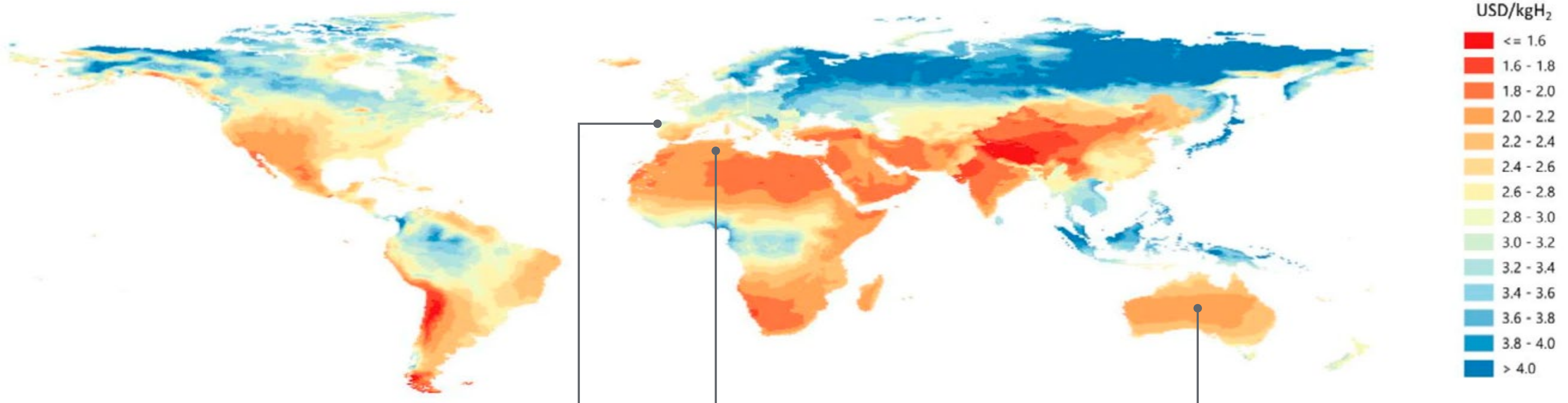


Note: Hydrogen production pattern follows European electricity generation from wind pattern.
The data in the chart is for illustrative purposes only.
Source: WindEurope; IEA; Monitor Deloitte analysis

- Hydrogen demand, particularly for industry, will be **constant**
- Green hydrogen production will **fluctuate** in line with intermittent renewable electricity generation
- Therefore storage will be **crucial**, with a **large share** of hydrogen supply and demand will **pass in and out of storage**
- This requires **rapid response** of transport destinations to production changes, which can only be done with **pipelines**
- Storage is focus for **government** to enable hydrogen transition as well as an opportunity for **business**

Geographical conditions will determine hydrogen cost in the long term, resulting in imports from regions with the lowest renewable electricity costs, either via pipeline or ship

Hydrogen costs in the long term



Portugal and the Netherlands strengthen bilateral cooperation on green hydrogen

“The two countries affirm their intentions to develop a strategic export-import value chain to ensure production and transport of green hydrogen from Portugal to the Netherlands and its hinterland.”

Government of the Netherlands

A North Africa – Europe Hydrogen Manifesto

“A joint hydrogen strategy between Europe and North Africa can help build a European energy system based on 50% renewable electricity and 50% green hydrogen by 2050.”

Hydrogen, the Bridge between Africa and Europe

Australia ‘hydrogen road’ to Japan set to cut emissions

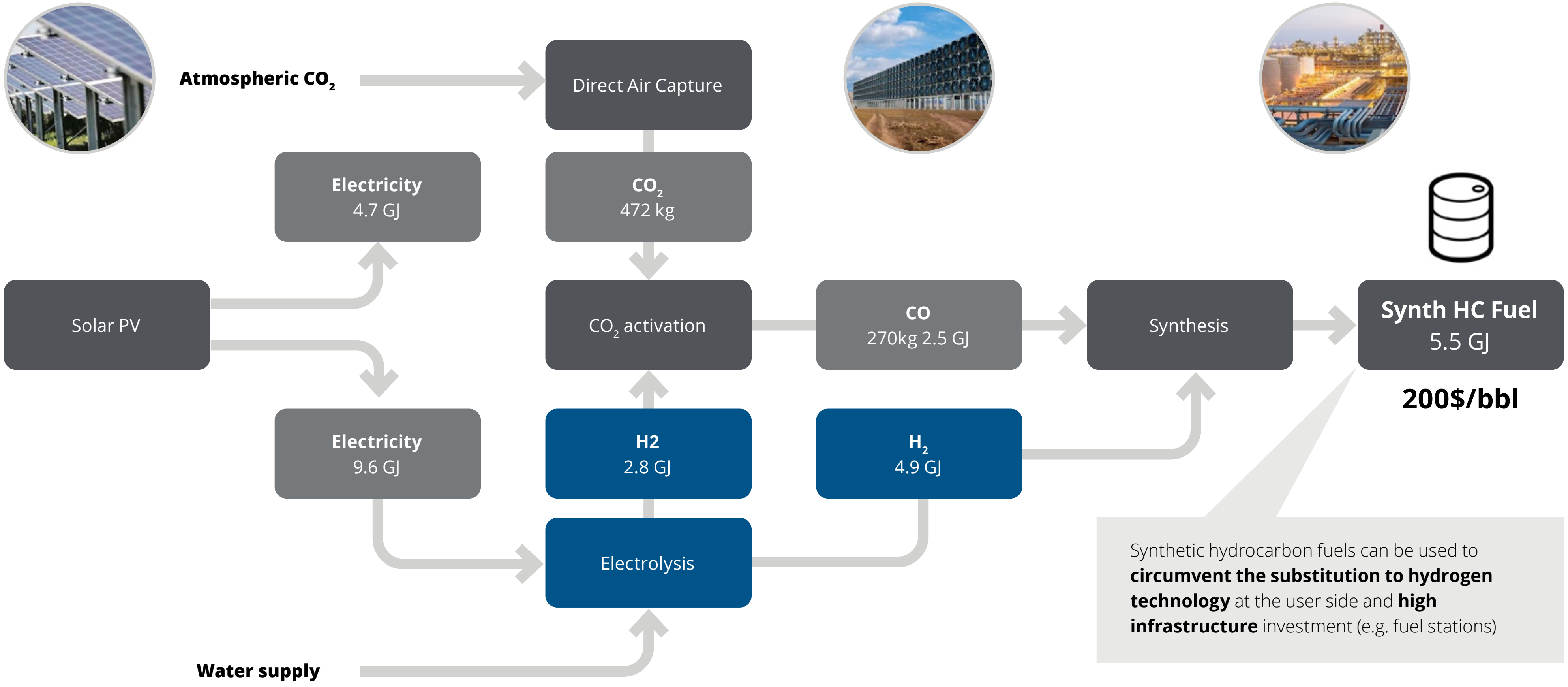
“A consortium’s $500m project will produce hydrogen from brown coal in one of the world’s first zero-emission energy supply chains.”

Financial Review

Source: IEA, The Future of Hydrogen

Synthetic hydrocarbon fuels can be produced from hydrogen with renewable electricity and CO2 from waste streams or directly from air, circumventing new hydrogen infrastructure at the demand side (e.g. aviation)

Production process of synthetic hydrocarbon fuels



Atmospheric CO_2

Direct Air Capture

Electricity
4.7 GJ

CO_2
472 kg

Solar PV

CO_2 activation

CO
270kg 2.5 GJ

Synthesis

Synth HC Fuel
5.5 GJ

200$/bbl

Electricity
9.6 GJ

H2
2.8 GJ

H_2
4.9 GJ

Electrolysis

Water supply

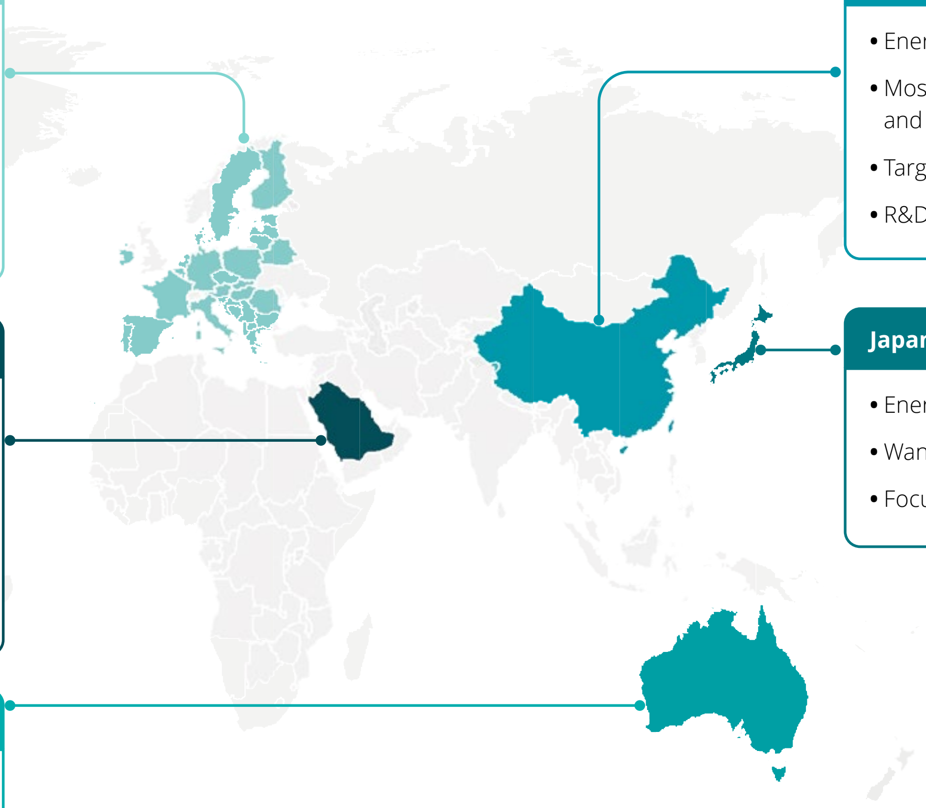
Synthetic hydrocarbon fuels can be used to **circumvent the substitution to hydrogen technology** at the user side and **high infrastructure** investment (e.g. fuel stations)

Source: O. Kraan – On the Emergence of the Energy Transition – Joule 2019

Policy perspective

Hydrogen cost declines will be stimulated by governments that are developing hydrogen ecosystems, in line with their overall energy and industrial policy agendas…

Hydrogen policy goals across the globe



EU: All

- Energy importer
- Wants decarbonisation and energy independency
- Green energy, technology subsidies and demand stimulation
- Leverage chemical and pipeline infrastructure

Saudi Arabia: Supply push

- Energy exporter
- Wants to create employment not dependent on fossil fuels
- Green hydrogen from solar and wind farms as feedstock for fertiliser
- Part of Vision 2030 program

Australia: Supply push

- Energy exporter
- Focus on blue hydrogen to export to Japan

China: Technology push

- Energy importer
- Most cost competitive technology (electrolysers and fuel cells)
- Target of 1m FCEVs by 2030
- R&D grants, usage incentives

Japan: Demand pull

- Energy importer
- Wants to innovate in the transportation sector
- Focus on mobility and electricity production

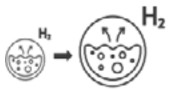
Next to country-specific hydrogen strategies, the EU's hydrogen and energy system integration strategies will set a new clean investment agenda

EU hydrogen strategy

Scope

- Boost renewable hydrogen production in Europe
- Focuses on hydrogen as feedstock, a fuel or an energy carrier and storage agent for applications across industry, transport, power and buildings sectors
- 'Next Generation EU' (Commission's economic recovery plan) highlights hydrogen as an investment priority to boost economic growth and resilience, create local jobs and consolidate the EU's global leadership

Scale up



Today – 2024

- **Installation** of > 6GW (renewable hydrogen) electrolysers
- **Production** up to 1M tonnes of renewable hydrogen

2025 – 2030

- Part of EU's integrated energy system
- **Electrolysers**: > 40GW of renewable
- **Production** of up to 10 M tonnes of renewable hydrogen

2030 – 2050

- Renewable hydrogen will be deployed at a **large scale** across all **hard-to-decarbonise sectors**

Investment outlook

- Now – 2030: investments in electrolysers **€24 and €42 billion**
- Required: **€220-340 billion** to scale up and directly connect 80-120 GW of solar and wind energy production capacity to the electrolysers to provide the necessary electricity
- Retrofitting with CCS: half of the existing plants **~€11 billion**
- Transport and infrastructure: investments of **€65 billion**
- Now- 2050: investments in production capacities would amount to **€180-470 billion** in the EU
- Adapting end-use sectors to hydrogen consumption and hydrogen-based fuels will also require **significant investments**

Demand creation

- Gradually create new lead markets; industrial applications and mobility.
- **Industrial: 1) Reduce and replace the use of carbon-intensive hydrogen** in refineries (production of ammonia, and for new forms of methanol production) **2) Zero-carbon steel making processes**
- **Mobility: 1) Captive uses**, such as local city buses, commercial fleets (e.g. taxis) or specific parts of the rail network, where electrification is not feasible. **2) Heavy-duty road vehicles, Hydrogen fuel-cell trains**, inland waterways and short-sea shipping, aviation and maritime sectors

The funds earmarked for hydrogen in the European fiscal stimulus packages for COVID-19 recovery illustrate the governmental commitment

European hydrogen investment announcements 2020

EU	**Germany**	• June: outlines COVID-19 recovery package including **€9 billion** for the expansion of hydrogen capacity
	France	• September: plans hydrogen investment of **€7 billion**, including €2 billion as part of the €100 billion COVID-19 recovery plan
	Spain	• October: approves hydrogen strategy including 4 GW electrolysis, which needs ***€8.9 billion*** public-private investment
	Portugal	• May: announces national hydrogen strategy which foresees investments of **€7 billion** by 2030
	The Netherlands	• March: minister for Economics Affairs and Climate publishes *"Kamerbrief Kabinetsvisie waterstof"* • September: announces the "Nationaal Groeifonds", budgeting **€20 billion** for long-term investment
	European Comm.	• July: publishes Hydrogen Strategy, expecting **€180-€470 billion** investment in hydrogen by 2050

Public investment will predominantly be directed at subsidising **market-enabling infrastructure** (e.g. fuel stations, pipelines) and **first movers in production** (e.g. first electrolysers)

Source: Public announcements

In line with the investment announcements, governments have various options to stimulate the hydrogen market such as blending obligations, innovation budgets and market instruments

Instruments for market development

	Blending obligations	Innovation budgets	Market-instruments
Description	• Obligation for suppliers to deliver a certain share of hydrogen in natural gas (~5-15%) • Create additional demand for hydrogen with the aim to kick-start the hydrogen market	• Funding programs for demonstration projects (e.g. Innovation fund, growth fund) • Boost economic growth towards climate announcements	• Subsidies for certain products (e.g. SDE++) • Increased taxes on certain products (e.g. carbon tax)
Advantages	• Government can easily mandate the blending obligation • Significant effect on the market • Minor investments required, e.g. compression units and valves as well as application units only to be replaced with increased hydrogen percentage	• Financing support for non-commercial projects • Reduced risks for bank financing • Accelerated R&D	• Structural financial support • Subsidies are technology-neutral
Disadvantages	• Small share will only kick-start the market, but not create a big market • Blending of a high premium product with a commodity product could devalue hydrogen	• Financing limited to one-offs • Commercial parties are stimulated to fulfil funding requirements even if not strategically relevant for the project	• Hydrogen not yet commercial for market funding • Market instruments not designed for energy carriers and limited comparability with solar and wind

Company perspective

The promise of hydrogen has led to several companies to invest in pilot projects, predominantly around the use of hydrogen as industrial feedstock

Hydrogen pilot projects

Steel – Feedstock

SSAB LKAB VATTENFALL

- Joint venture named **HYBRITT**
- **Steel production** via direct reduction technology, using **hydrogen** as **feedstock**
- LKAB pelletises iron with bio-fuel heat; Vattenfall supplies green energy for hydrogen production
- **Pilot** phase until **2024**, plant to be built ≥ 2025

Steel – Heat

OVAKO Linde

- Conducted a trial to use hydrogen to **heat steel before rolling** at an Ovako plant in Sweden
- Hydrogen **replaced LPG** as fuel for combustion

Chemicals – Feedstock

Liquid Wind

- Cooperating with a consortium of a.o. Haldor Topsoe, Axpo, and Siemens Energy
- Combining **hydrogen** with waste CO2 into "**eMethanol**, to be used as fuel or **feedstock**
- Planned to be **operational** in **2023**

Steel – Feedstock

thyssenkrupp RWE

- **Steel production** via direct reduction technology, using **hydrogen** as **feedstock**
- Thyssenkrupp experimented with injecting **hydrogen** in **existing blast** furnace
- Hydrogen (to-be) supplied by RWE
- Full **conversion** of **blast furnace** planned in **2022**

Chemicals – Feedstock

HALDOR TOPSØE

- Haldor Topsoe developed a new technology, SOEC, for production of "**green" ammonia**
- With renewable energy, SOEC **produces hydrogen** and **nitrogen**, both **feedstock** for **ammonia**
- SOEC enables **future ammonia plants** to be as **energy efficient** as **current** state-of-the-art **facilities**
- SOEC **demonstration plant** planned in **2025**, expected to be **commercially available** in 2030

Magnesium – Heat

NEDMAG DNV·GL

- Developing a **hybrid heating solution**, capable of handling varying natural gas/hydrogen mixtures (0 – 100% hydrogen)
- Handling varying mixtures mitigates supply lock-in and **smoothens** the **change** to (**green**) **hydrogen**
- To be tested in **2020** at a Nedmag location

Source: company websites, amoniaindustry.com

Hydrogen supply projects at scale are in the making

Hydrogen

NorthH2 – Green hydrogen

- **Consortium** of energy suppliers, grid and port operators
- Aims to build **integrated chain** from offshore wind to green hydrogen production, transmission, storage and supply
- Targets production capacity of **3-4 GW in 2030** to supply to **industrial users** in the Netherlands and rest of North-western Europe
- Hydrogen is transported via planned **Dutch hydrogen grid** of repurposed natural gas pipelines and stored in **salt cavers**
- **Pre-FID** phase

Zero Carbon Humber – Blue hydrogen

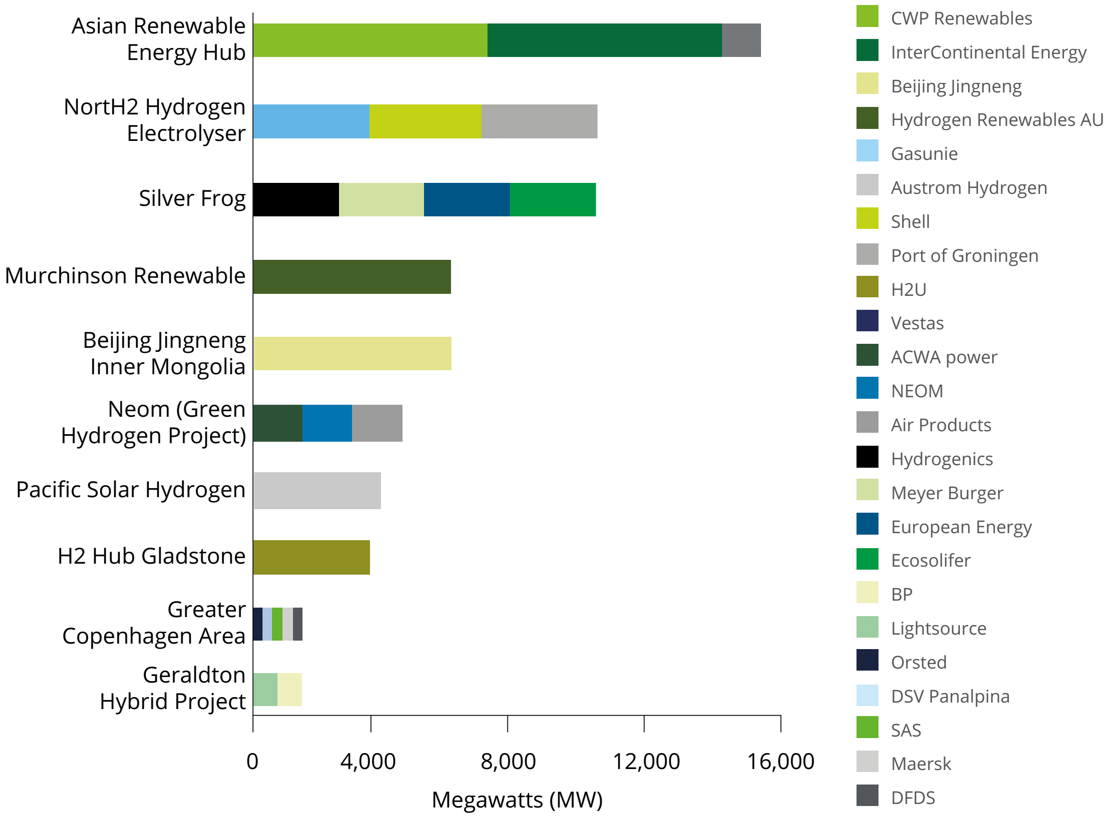
- **Consortium** of energy suppliers and users, grid and port operators
- Aims to transform the Humber **industrial cluster** into the UK's first net-zero carbon cluster by 2040
- Demand for first Equinor production plant (**600MW**) is **secured** by **blending hydrogen** into Triton gas-fired power plant
- Subsequently production capacity can be expanded to supply **industrial heat** to steel and chemicals industry via local **pipeline grid**
- **Pre-FID** phase

Source: Project websites

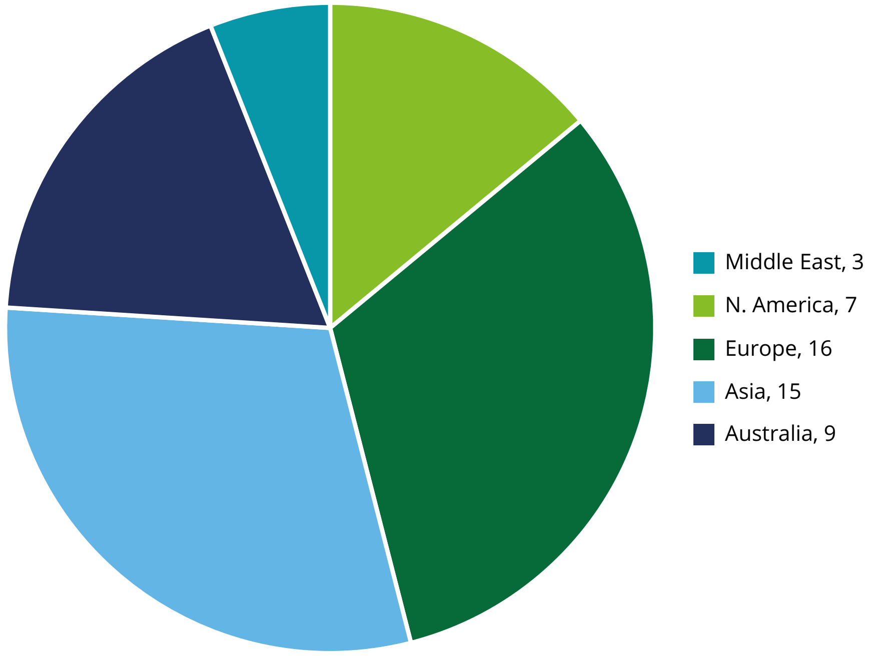
Collaboration through consortia and ecosystems becomes critical to connect expertise and accelerate developments

Large-scale hydrogen projects by company and region

Top 10 hydrogen electrolyser projects by company



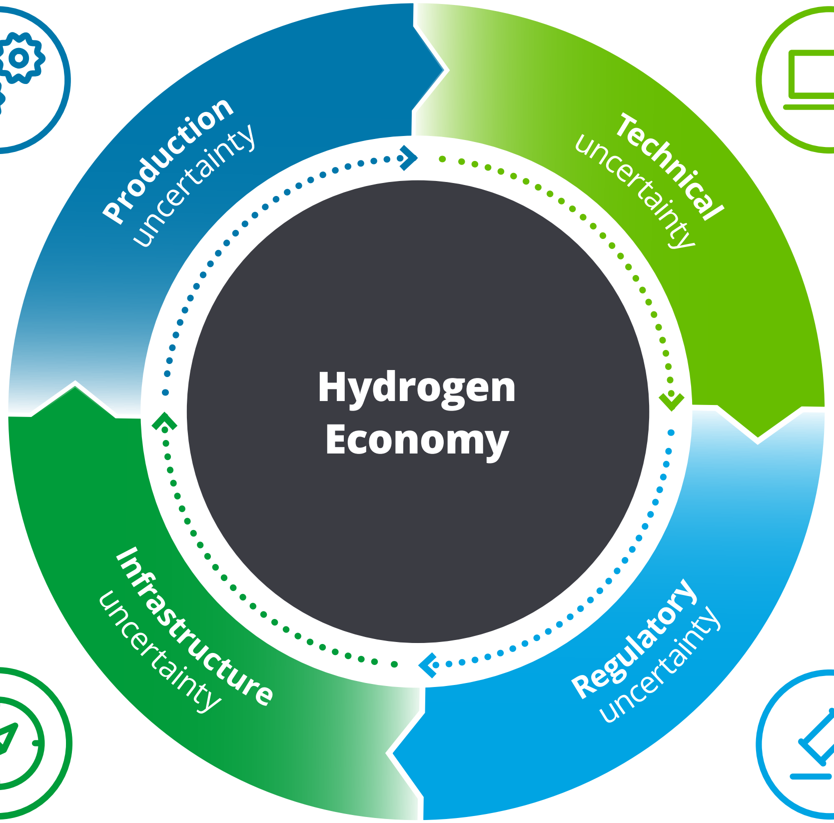
Large-scale hydrogen projects by region



Source: Rystad Energy RenewableCube (2020); Companies, IEEFA estimates

The hydrogen economy faces a vicious circle, with uncertainty around where to begin

Decarbonisation uncertainties



What if there is **insufficient production infrastructure** or the cost is prohibitive?

Which technology will become the industry standard and what if I invest in the wrong one?

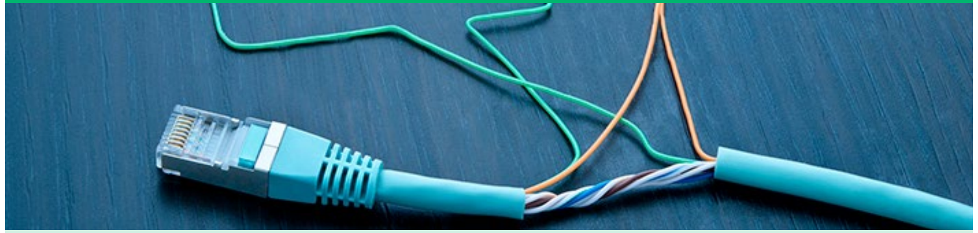
What if **fuelling infrastructure is not available next to my location or different standards**

What if provinces/ states, countries, and international bodies adopt **contradicting regulations**?

We see analogies with similar infrastructure and technology developments, where a breakthrough was enabled on the backbone of other technologies or systematic investments in R&D

Analogies with similar developments

Internet



First public connection through telephone network

- In the early 1990s, the world wide web could be accessed through dial-up connections
- Dial-up connections established a connection with other computers through the telephone network, which would not allow for the parallel usage of the telephone and the internet

Introduction of commercial broadband

- In the late 1990s, broadband connections via cable, digital subscriber line, satellite and FFTX replaced dial-up access as standard technology

Open infrastructure standards enable developments of new technologies

Solar PV

First application in satellites supported by government funds

- In 1964, NASA launched the Nimbus spacecraft, a satellite powered by a 470w PV array
- Massive governmental investments in space programs pushed development to win the space race, alongside investments from electronics and oil companies

More applications for solar PV followed once technology was developed

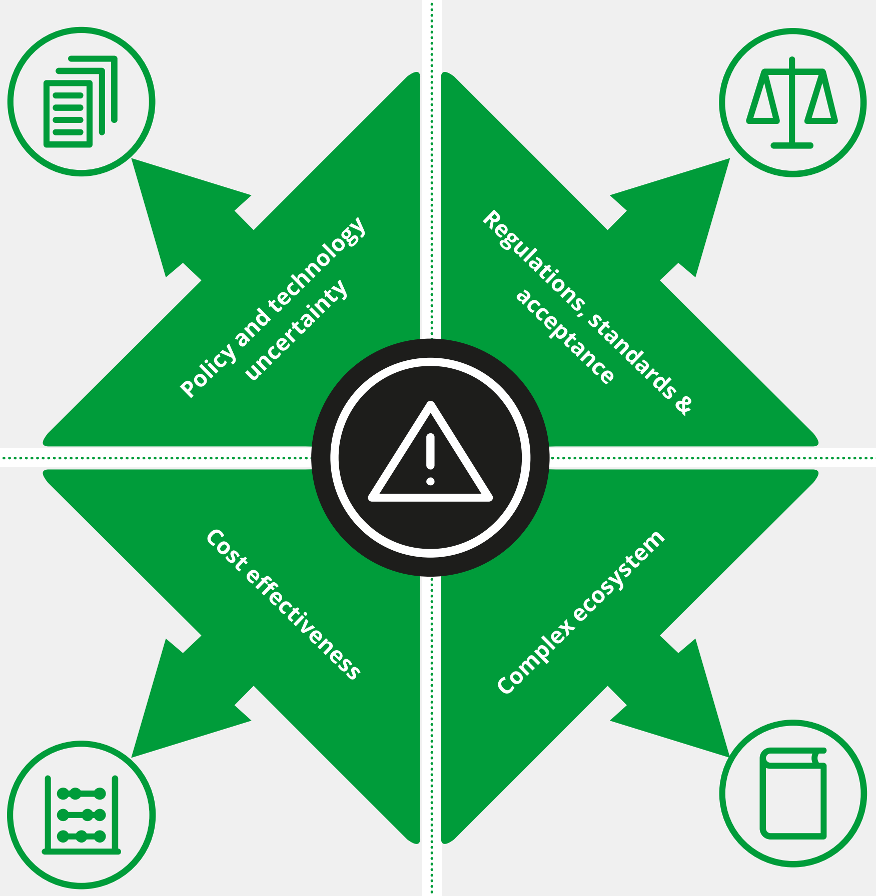
- In 1980, the University of Delaware developed the first thin film solar cell exceeding 10% efficiency with potential application for houses
- Research exploded in 1990s and 2000s, and with it application possibilities

Governmental support is key to kick-start research and development

Source: U.S. Department of Energy

The key to a successful hydrogen strategy is overcoming four key challenges

Key challenges



Government and policy support is required to create an environment for low-carbon hydrogen application to become competitive with other technologies and energy sources.

Currently in its infancy as regulations and standards around the world and in Europe and Middle East do not yet fully support hydrogen uptake or new uses of hydrogen.

By 2035, total levelised cost of hydrogen is more cost effective than diesel.

However, it remains behind natural gas which is a prolific resource even out to 2050. Europe and Middle East is abundant with cheap electricity resulting in headwinds for hydrogen to directly compete with incumbents.

Ecosystem is complex creating a need for investments and policies to be synchronised in scale and time.

Europe and Middle east currently lacks a cohesive integrated hydrogen strategy.

Making strategic bets and building an eco-system while learning and pro-actively connecting with policy makers to create the rules are the lessons learned from the development of the hydrogen market so far

Lessons learned

Make strategic bets	Build an eco-system	Keep learning	Create the rules
✓ Be clever with your investments by investing with a strategic mindset	✓ Create eco-systems to understand the needs of your stakeholders	✓ Be part of project consortia to understand real project difficulties	✓ Be pro-active towards policy makers
✓ Make your bets consistent with your strategy	✓ Create partnerships to spread the risk of non-commercial projects	✓ Invest in start-ups to understand their business models	✓ Ensure favourable market rules
✓ Fail fast, learn fast		✓ Support research consortia to realise where technology developments are going	✓ Understand where subsidies will be going too

The opportunities in a developing hydrogen market differ by sector

Opportunities for different sectors

Oil, Gas & Chemicals

- Handling of hydrogen molecules fits well with current core capabilities
- Experience with large-scale asset projects (offshore wind, pipelines) can be transferred to hydrogen projects
- Opportunity to decarbonise refining operations by substituting grey hydrogen with green hydrogen
- Opportunity to decarbonise chemical production by using hydrogen for industrial feedstock and industrial heat

Power & Utilities

- Potential to exploit the arbitrage opportunity on electricity production
- Increased flexibility to electricity systems and enablement of additional services
- Development of new business opportunities for utility companies

Mining & Metals

- Opportunity to decarbonise operations through hydrogen trucks
- Development of new business opportunities for raw materials used for hydrogen production (e.g. materials used in electrolysers)

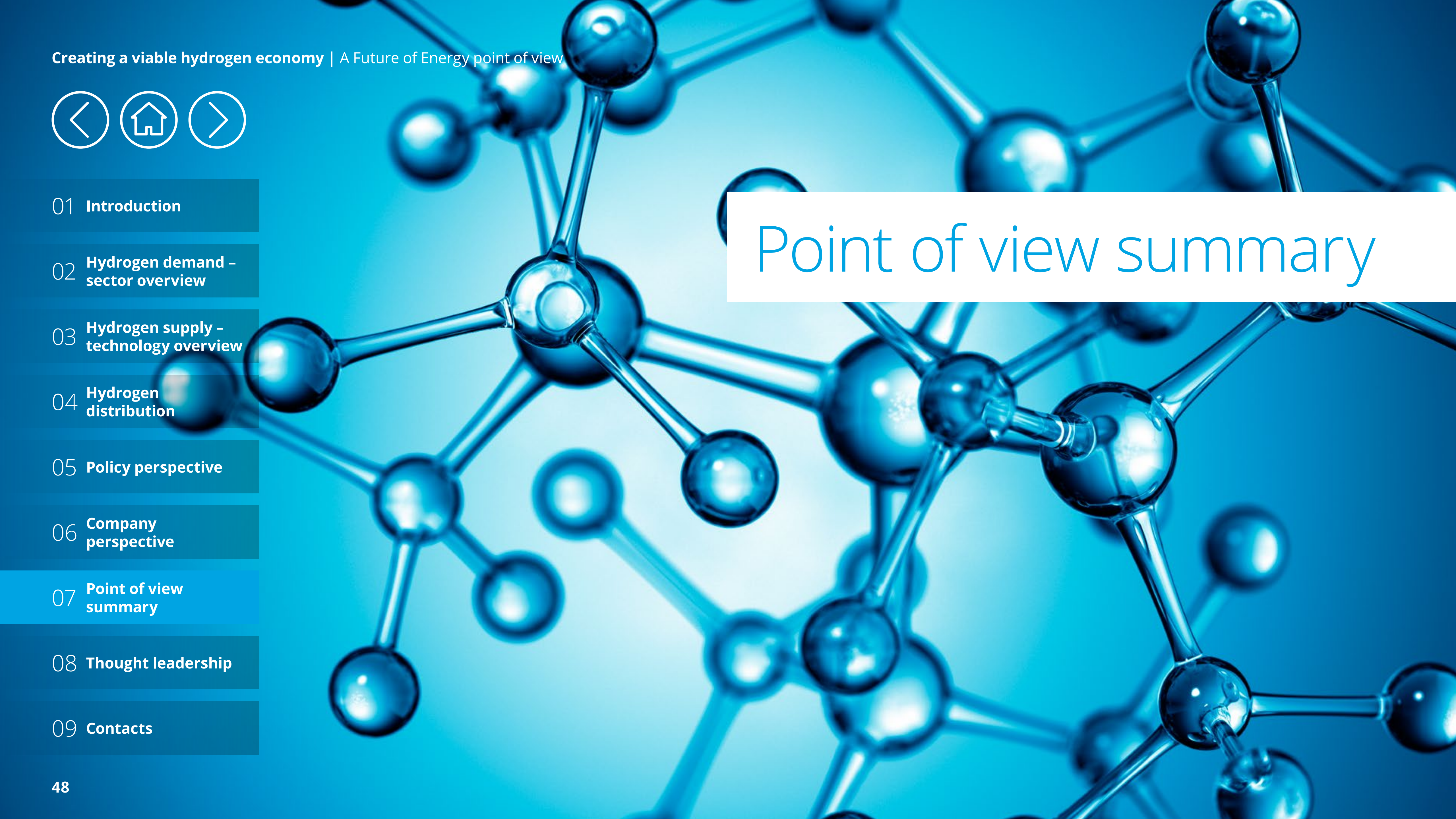
Industrial Products & Construction

- Development of new business opportunities for assets used for hydrogen production, storage and distribution (e.g. electrolysers, burners, fuel cells)
- Opportunity to decarbonise operations through replacement of on-site diesel generators

So what are the next steps for some archetype companies?

Next steps for archetype companies

Archetype company	Next steps
Steel manufacturer	• Connect with **potential customers** to see whether there is enough demand for green steel and analyse market **demand** dynamics in scenario study • **Pilot green steel production** and fulfil all technical and HSSE requirements
Integrated Power & Utility provider	• Analyse the **opportunity for power-to-hydrogen-to-power** in scenario project • Create understanding of applicability of hydrogen in **built environment** and industry
Integrated Oil & Gas company	• Analyse the opportunity for power-to-hydrogen-to-power in **scenario project** • Create understanding of applicability of hydrogen in **mobility** and industry • **Monitor technology** developments of electrolysers and fuel cells
Natural Gas Transmissions System Operator	• Create understanding of **supply and demand** developments by connecting to customers and hydrogen providers • Pro-actively **connect with regulators** to ensure the preferred role in hydrogen market
Industrial B2C company	• Connect with hydrogen suppliers and hydrogen technology providers to **understand possibilities** to transition to hydrogen • Analyse pro's and con's of **technology options**; electricity, biomass and hydrogen



Point of view summary

Executive summary

Hydrogen will play an essential role in decarbonising hard-to-abate sectors where electrification has physical limits. It will also play an important role in integrating intermittent renewable electricity, as transport medium and as storage medium.

Hydrogen demand

In the short term, hydrogen will be applied first in those sectors that are under societal pressure to decarbonise - likely those closest to the customer. Interest from the market is coming from consumer goods companies in Europe which can obtain a premium from consumers substituting their energy needs in production and distribution. Think about a car from green steel (produced with the use of hydrogen) and hydrogen trucks to distribute consumer products.

In the medium to long term, industrial feedstock and electricity buffering are also likely to be decarbonised by hydrogen, as well as potentially some niches in other mobility applications and the built environment.

In the longer term, the production of ammonia and synthetic hydrocarbon fuels produced from hydrogen will enable the decarbonisation of the hardest to abate sectors such as shipping and aviation.

Hydrogen supply

This more widespread use of hydrogen is only possible when green hydrogen costs decrease, which they are projected to do significantly as renewable electricity becomes abundant and electrolyser costs decrease with economics of scale. As long as costs are high in the short run, blue hydrogen will be used to kick-start supply.

Hydrogen distribution

Pipelines, trucks and ships will all play a role in transporting hydrogen. The ability to connect large-scale hydrogen storage for close-to-sea locations makes a pipeline infrastructure favourable, while for other inshore locations its role is to connect supply and demand. Hydrogen distribution via trucks will stay relevant as a dedicated hydrogen network will not be as dispersed as the current natural gas network; import (especially via pipelines and potentially in the future via ships) will be essential as hydrogen demand will likely exceed European domestic hydrogen production.

However, domestically produced hydrogen, especially from low-cost renewable electricity will likely remain competitive against imported hydrogen given the transport (and potential conversion) costs. When the hydrogen demand is really scaled-up, centralised production connected via a pipeline structure to large scale storage becomes favourable over decentralised production, given its ability to provide security of supply.

Policy perspective

Given the pressure to decarbonise, Europe will drive the hydrogen industry on the back of COVID-19 recovery packages which will create opportunities across regions such as the manufacturing industry in Asia (e.g. electrolysers, fuel cells, Solar PV, cars, trucks); export of renewable resources in North Africa and the Middle East; and capitalisation of cheap fossil resources (blue hydrogen) in Australia, Canada and Russia.

Blending can be used as a policy instrument to give security of demand to hydrogen suppliers and eliminate the risk of supply shortfalls to hydrogen users. However, now that there is increasing certainty that hydrogen demand will emerge, blending becomes less of a priority.

To enable the cost decrease of electrolysers (and fuel cells) governmental support in the short term is necessary, but in the longer term, hydrogen will likely always be more expensive than fossil fuels and therefore will need policy incentives to be competitive (e.g. carbon taxes or subsidies).

Company perspective

To be able to take advantage of the opportunities, companies will need to make strategic bets, build an eco-system, keep learning and pro-actively engage with policy makers.

On the demand side, eyes will be focused on the world's big brands that are looking for renewable alternatives for their non-electrifiable energy use driven by their green ambitions. This is likely to trigger a hydrogen equivalent of a PPA market which emerged in the electricity market.

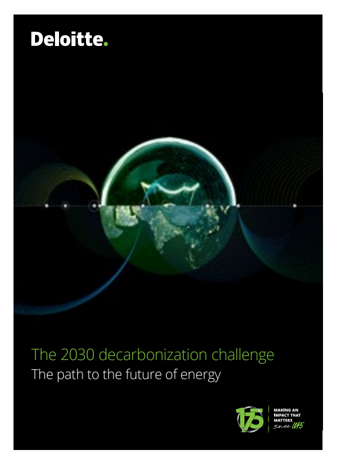
On the supply side, consortia of the world's largest energy companies will drive the development of the hydrogen market given their scale (and subsequent ability to deliver these projects) and their interest in hydrogen as a lifeline for their relevance in a low-carbon world. They will increasingly put pressure on government to enable a hydrogen market to scale.

Thought leadership

As part of its thought leadership on the Future of Energy, Deloitte regularly publishes views on sectors impacted by hydrogen technology, offering clients the latest market insights and cutting-edge perspectives

Future of Energy publications

Examples



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The 2030 decarbonization challenge

The path to the future of energy

Decarbonising Shipping:

ALL HANDS ON DECK

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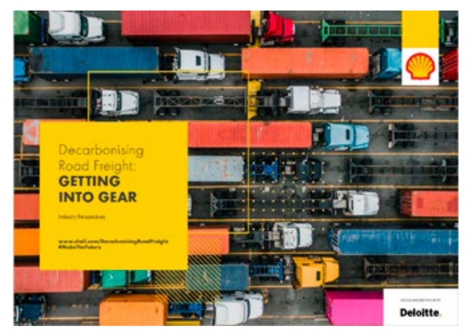
The future of energy

A novel approach to creating advantage in the face of systemic uncertainty, via scenario planning



Decarbonising Road Freight:

GETTING INTO GEAR

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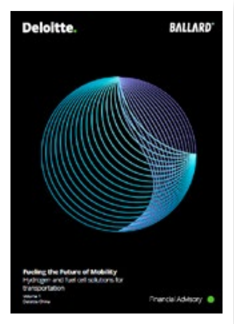

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BALLARD

Fueling the Future of Mobility
Hydrogen and fuel cell solutions for transportation

Financial Advisory

Fueling the Future of Mobility

An exploration of hydrogen fuel cell applications providing in-depth perspectives on fuel cells and compares technologies on:

- Total cost of ownership (TCO)
- Energy efficiency
- Environmental impact

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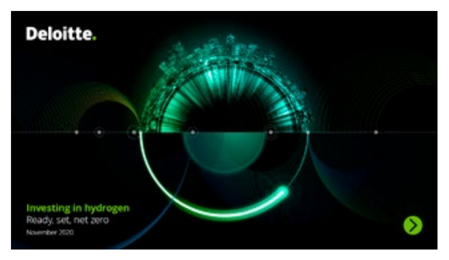
View on the development of hydrogen in the Netherlands

By René Schutte,
programme manager of the
HyWay Programme at Gasunie

"Hydrogen will flourish and thus support us towards a decarbonized economy by 2030."

Making hydrogen happen

Interview with René Schutte, Hydrogen Programme Manager at Gasunie, on the future of hydrogen market in the Netherlands



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Investing in hydrogen
Ready, set, net zero
November 2020

Investing in hydrogen

An overview of the developments in value chain, and the business considerations related to it

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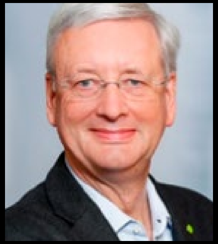

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