The **Making Mission Possible** Series

Making the Hydrogen Economy Possible:

Accelerating Clean Hydrogen in an Electrified Economy

April 2021
Version 1.0

Executive Summary

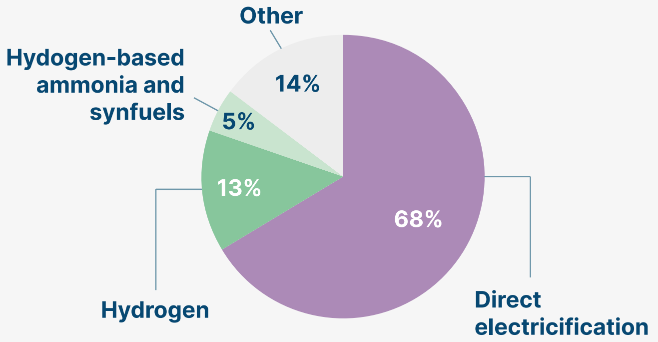
Energy Transitions Commission

Energy Transitions Commission

MAKING THE HYDROGEN ECONOMY POSSIBLE

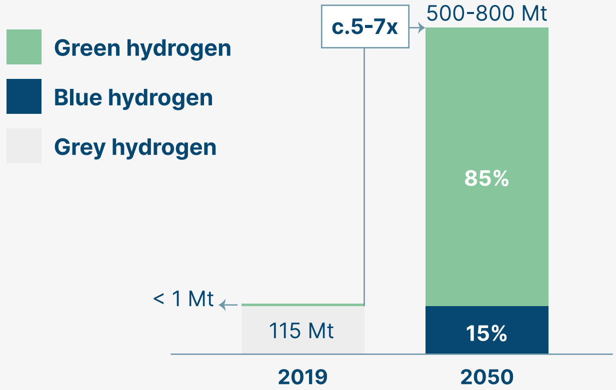
HYDROGEN: THE SECOND DECARBONISATION VECTOR

Final energy demand, ETC 2050 Indicative Scenario



A 5-7 FOLD INCREASE IN HYDROGEN PRODUCTION TOWARDS NET-ZERO

Hydrogen production 2050
Mt Hydrogen / year

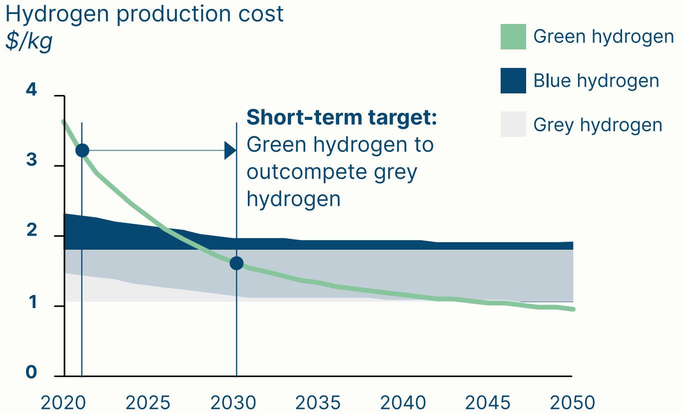


What will it take?

SIMULTANEOUSLY

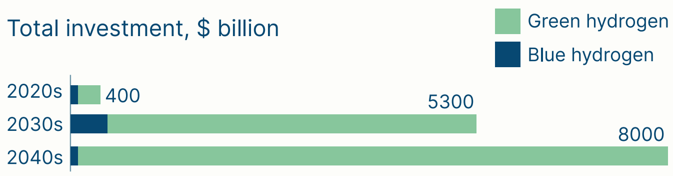
GROW PRODUCTION VOLUMES TO MAKE GREEN HYDROGEN COMPETITIVE

Hydrogen production cost
$/kg



TO UNLOCK LARGE-SCALE INVESTMENT IN HYDROGEN SUPPLY

Total investment, $ billion



RAPIDLY ACCELERATE DEMAND FOR CLEAN HYDROGEN

From grey to clean

Refining / Ammonia / Methanol

Development needed but large long-term need

Steel / Shipping / Aviation / Chemicals / Power

Potential transitional

Co-firing / Blending

Possible future uses if electricity doesn't win

Trucking / Residential heating / High temperature heating

DEVELOP TRANSPORT AND STORAGE INFRASTRUCTURE WHERE NEEDED

Clusters

Early use cases will develop around industrial clusters with shared hydrogen production, distribution and storage infrastructure.

Inter-regional

Limited international trade will be mainly supported by interregional pipelines and sometimes ammonia ships where final use is ammonia.

Executive Summary

The Paris climate accord committed the world to limiting global warming to well below 2°C above pre-industrial levels, while striving to limit it to 1.5°C. To meet this commitment, the world must bring CO_2 emissions to net-zero by mid-century, and the Energy Transitions Commission (ETC) has described in a number of reports how this can be done.[1] Clean electrification must be at the heart of the global decarbonisation strategy – electrifying as much as possible while fully decarbonising electricity supply. The ETC's report on massive green electrification, issued in parallel with this report describes how to meet that challenge.[2]

But there are some sectors where direct electrification is likely to be impossible or prohibitively expensive, and hydrogen will play a key role in decarbonising these. In steel production, it can replace coking coal as the energy source and reduction agent; in the form of ammonia, it could decarbonise long-distance shipping; and it is likely to play a major role as a storage mechanism within the power sector. Across these and multiple other sectors, total hydrogen use could grow from today's 115 Mt per annum to around 500 to 800 Mt by mid-century, with hydrogen (and fuels derived from it) by then accounting for about 15-20% of total final energy demand on top of the close to 70% provided by direct electricity use (Exhibit A).

All of this hydrogen must be produced in a zero-carbon fashion via electrolysis using zero-carbon electricity ("green hydrogen") or in a low-carbon fashion using natural gas reforming plus CCS ("blue hydrogen") if deployed in a manner that achieves near-total CO_2 capture and very low methane leakage. Blue hydrogen will often be cost-effective during the early stages of the transition, particularly where existing "grey hydrogen" production can be adapted and retrofitted with CCS. But, in the long-term, green hydrogen will very likely be the cheaper option in most locations, with dramatic cost reductions to below $2/kg possible during the 2020s. This green hydrogen production will in turn generate a very large electricity demand, increasing total required supply of zero-carbon electricity by as much as 30,000 TWh.

Strategies for net-zero emissions by 2050 must therefore recognise the major role of clean hydrogen and the implications for clean electricity supply required. They must also ensure a sufficiently rapid take-off during the 2020s to make the transition to 2050 feasible. This requires policy support since hydrogen use in end applications will often impose a 'green cost premium' versus today's high carbon technologies, even if hydrogen production costs fall dramatically. Policy must combine broad instruments such as carbon prices, focused support in specific end use sectors, and the development of geographically focused clusters of clean hydrogen production and use.

This report therefore sets out:

- The role of clean hydrogen in a zero-carbon deeply electrified economy;
- How to drive the transition to large-scale clean hydrogen supply and demand;
- Critical industry and policy actions required in the 2020s.

1 This includes (not exhaustive): ETC (2020): *Making Mission Possible: Delivering a Net-Zero Economy*; ETC (2017), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors*
2 ETC (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy*

Final energy mix in a zero-carbon economy: electricity will become the dominant energy vector, complemented by hydrogen and fuels derived from it

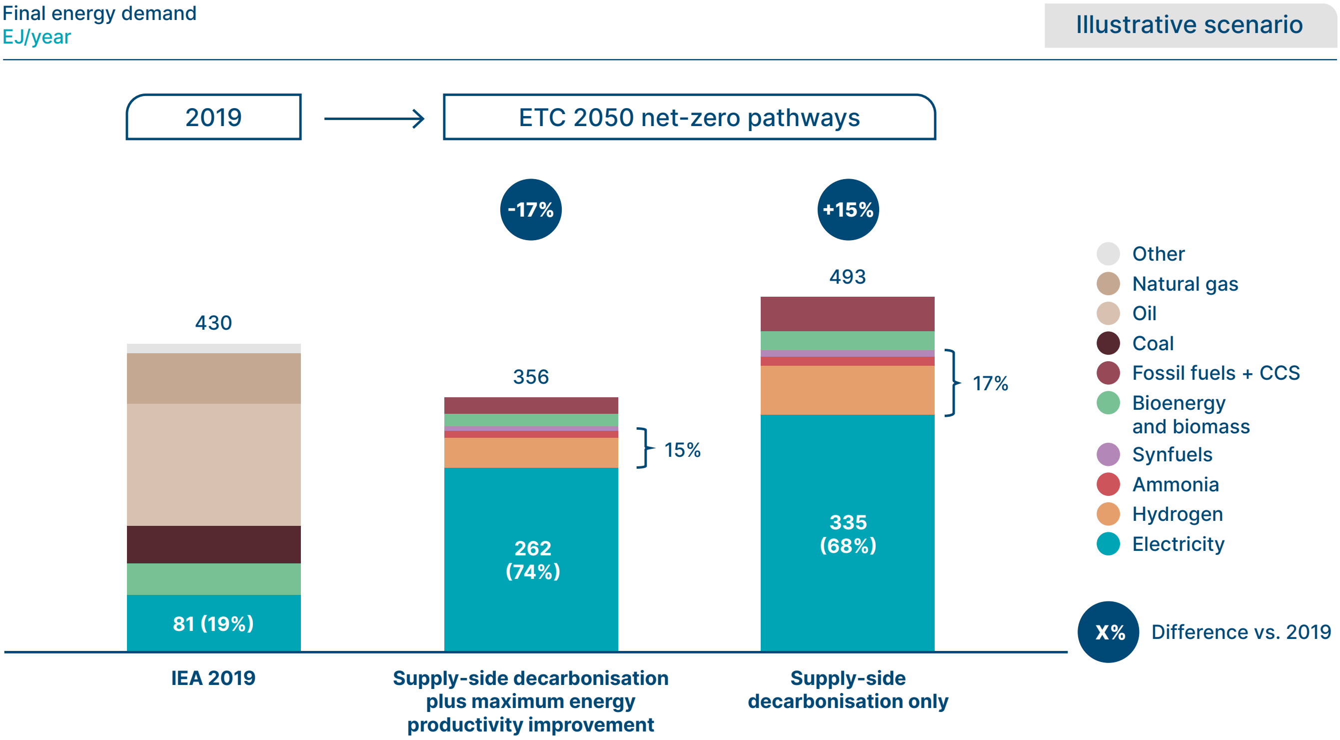


Exhibit A

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2021); IEA (2020), *World Energy Outlook*

I. A vision for 2050: Hydrogen's role in a zero-carbon, deeply electrified economy

In 2018, about 115 Mt of hydrogen was used globally, of which 70 Mt was produced via dedicated production predominantly from natural gas (71%) and coal (27%).[3] This production resulted in about 830 Mt of CO_2 emissions, around 2.2% of the global energy-related total. Over the next 30 years, hydrogen use is set to increase dramatically, and hydrogen production must become zero-carbon for clean hydrogen to be used as a decarbonisation solution in existing as well as multiple new applications.

Potential demand growth

Likely applications by sector

The potential uses of hydrogen in a zero-carbon economy can be usefully categorised into four groups:

- Existing uses of hydrogen, where clean hydrogen production should replace "grey" production as rapidly as possible (crude oil refining, ammonia and methanol production.)

- Highly likely and large long-term uses, where hydrogen use will grow slowly as the relevant application technologies develop and capital assets are replaced. These include steel production, long-distance shipping and perhaps aviation. There will also very likely be a major use of hydrogen for seasonal storage within power systems.

3 The 45 Mt difference stems from hydrogen produced as a by-product in a number of industrial processes such as catalytic naphtha reforming, chlor-alkali electrolysis and steam cracking of propane. Source: IEA (2019), *The future of hydrogen*

- Potential short-term but transitional opportunities which may enable partial emissions reductions of existing high-carbon assets that will eventually need to be phased out (e.g. co-firing hydrogen with natural gas in power production).

- Possible uses where the relative advantages of hydrogen versus other decarbonisation options are still unclear. These include heavy-duty road transport, residential heating, hydrogen for back-up power generation at specific energy-intensive sites (e.g. data centres) and plastics production.

An illustrative scenario

If all potential use cases of hydrogen materialise, total demand could reach as much as 1000 Mt by 2050, but a reasonable estimate of probabilities by sector implies a range of about 500-800 Mt (Exhibit B). This would imply that hydrogen (and its derivatives) could account for about 15% to 20% of total energy demand on top of the roughly 70% to be met by direct electrification. Our estimates suggest the same order of magnitude as recent scenarios produced by the Hydrogen Council and BloombergNEF, but with a different mix of sectoral applications. Government and national strategies for hydrogen should therefore assume that hydrogen will play a major role in a zero-carbon economy even if the precise balance of decarbonisation technologies by sector is uncertain.

Clean hydrogen will play a growing role across the economy as the world transitions towards net-zero

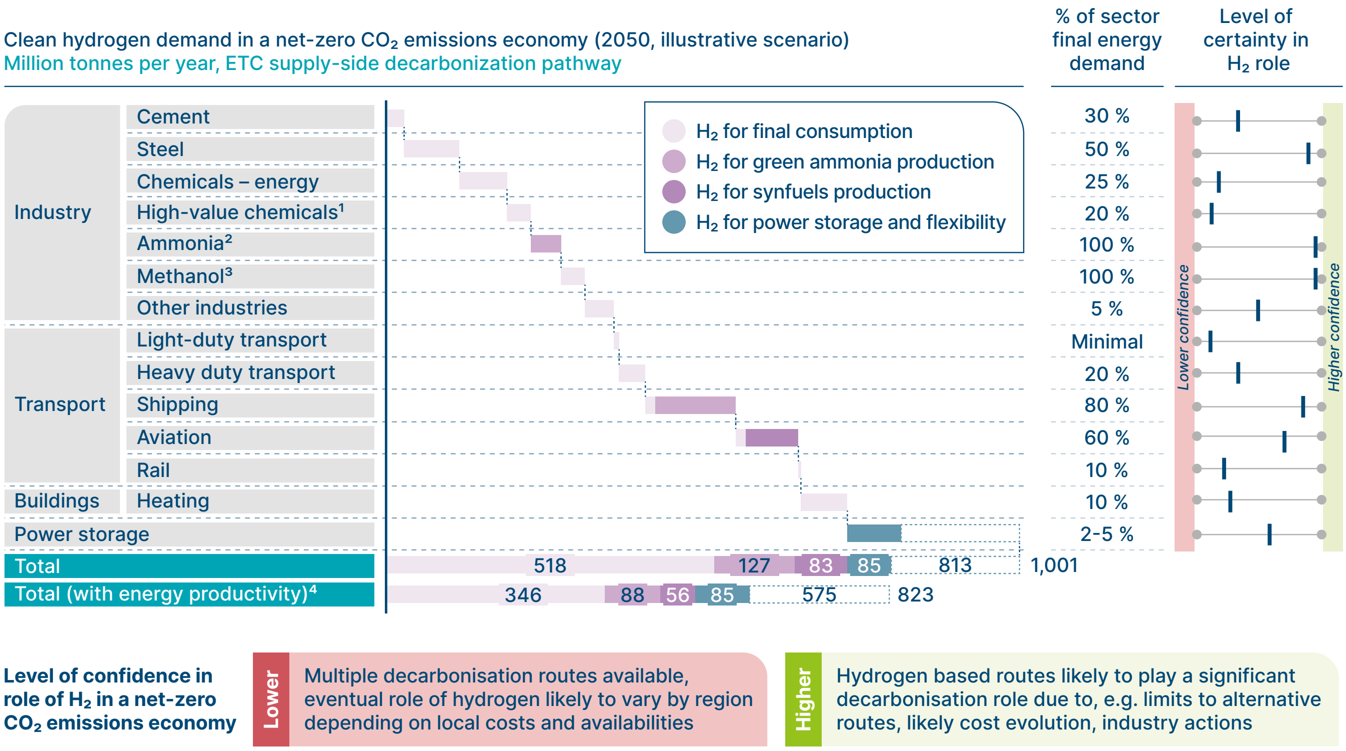


Exhibit B

NOTES: ¹ High value chemicals predominantly used to produce plastics, which could potentially be produced via Hydrogen and CO_2 in the future (via methanol and MTO process); ² Around 80% of ammonia (excl. shipping) is used to produce fertilisers; ³ Methanol is used as intermediate in numerous chemical processes, including plastics production. ⁴ ETC scenario including maximum energy productivity improvements.

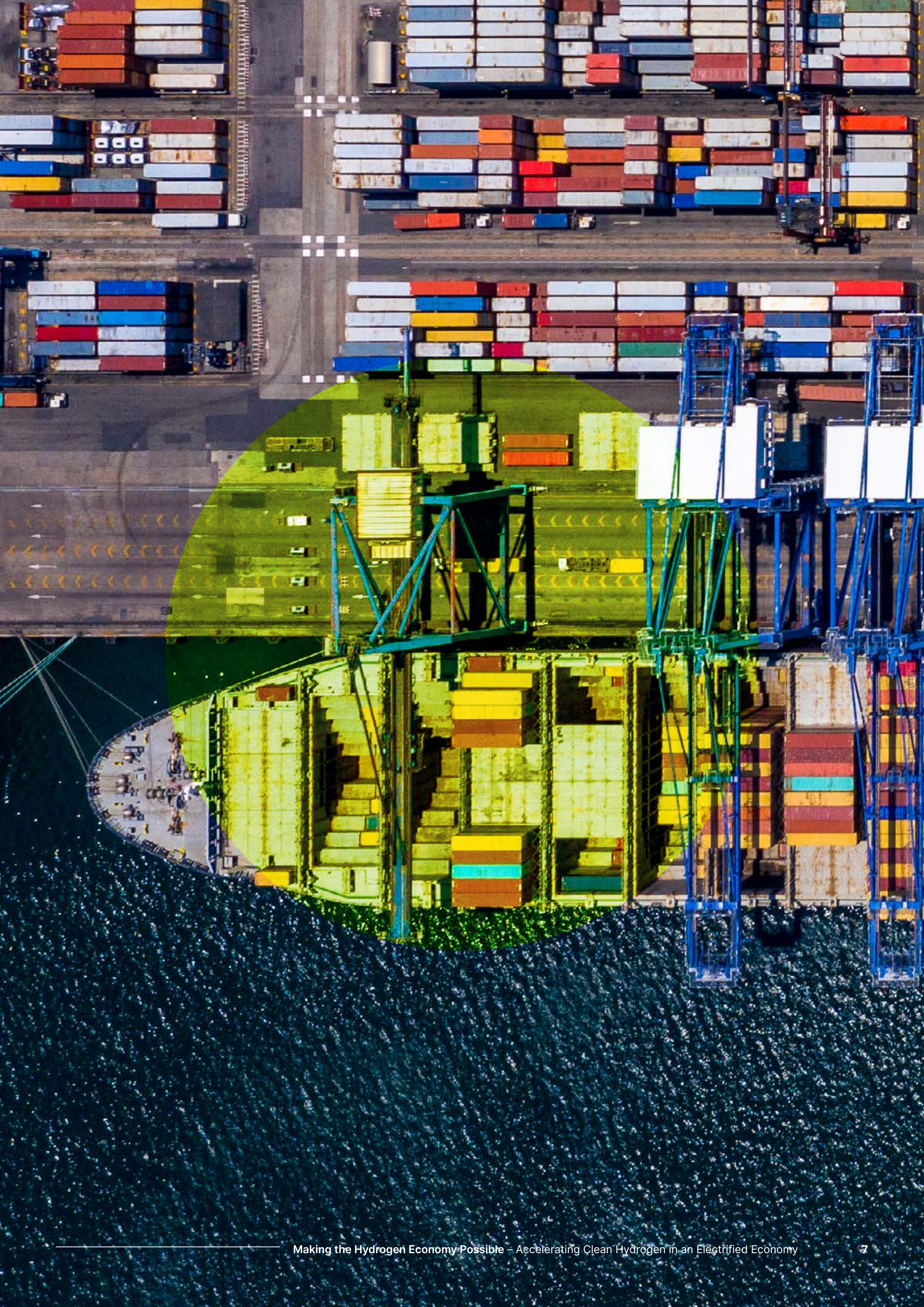
SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2021)

Falling production costs for green and blue hydrogen: implications for electricity demand

Any hydrogen used in 2050 must be produced in an almost zero-carbon fashion. This can be achieved through either[4]:

- Green hydrogen production via the electrolysis of water. Can deliver completely zero-carbon hydrogen if all the electricity used comes from zero-carbon sources.

4 Hydrogen can also be produced from coal starting with a gasification process, or via other technologies such as pyrolysis (sometimes labelled "turquoise hydrogen) among others. These are discussed in the full report and appendix.



- Blue hydrogen production, deriving hydrogen from natural gas, with carbon capture and storage (CCS) applied. This can result in low but not zero-carbon hydrogen, with the size of residual emissions determined by the completeness of the carbon capture process (with at least 90% required) and the scale of methane leaks in natural gas extraction, transport and use.

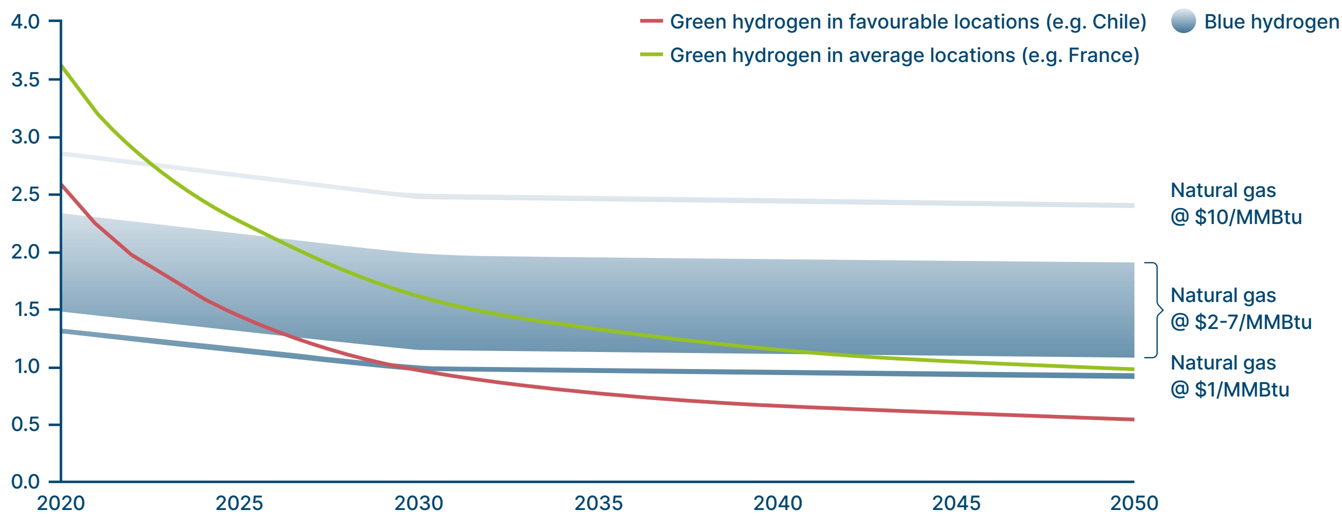
Feasible blue hydrogen production costs ($1.3-2.9/kg) are currently below those for green hydrogen ($2.6-4.5/kg) and the production of grey hydrogen (hydrogen from fossil fuels without CCS) is cheaper still ($0.7-2.2/kg).[5] Excluding the impact of any carbon tax, the "blue" route will always be more expensive than producing grey hydrogen due to the extra cost of CCS. By contrast, green hydrogen costs depend on two factors – the cost of zero-carbon electricity and the capital cost of electrolysers – both of which are likely to fall rapidly.[6] As a result, green hydrogen costs are likely to fall below blue hydrogen costs in some locations before 2030 and in most by 2050 (Exhibit C).

It is therefore likely that the "green" production route will be the major production route in the long term, though with a significant role for "blue" in transition and in specific locations where gas costs are very low. Our base case scenario assumes that by 2050, 85% of the 500-800 Mt of annual production could be produced via the "green" route. This would require about 30,000 TWh of electricity input[7] on top of the 90,000 TWh potentially required for direct electrification.

Exhibit C

Green hydrogen from electrolysis likely to become cheapest clean production route long term, in favourable locations it could be competitive with blue in the 2020s

Cost of hydrogen production from different production routes (excluding transport & storage costs)
$/kg H_2



NOTES: Blue hydrogen production: i) forecast based on SMR+CCS costs (90% capture rate) in 2020 transitioning to cheaper ATR+CCS technology in the 2020s; Green hydrogen production: i) favorable scenario assumes average LCOE of PV and onshore wind of lowest 33% locations (falling from $22/MWh in 2020 to $10/MWh in 2050) and average scenarios assumes median LCOE from lowest 75% locations (falling from $39/MWh in 2020 to $17/MWh in 2050) from BloombergNEF forecasts, ii) additional 20% (favorable) and 10% (average) LCOE savings included due to directly connecting dedicated renewables to electrolyser, iii) 18 % learning rate for favorable & 13 % for average scenario. Electrolyser capacity utilization factor: 45%. Comparison to BloombergNEF most favorable ($0.55/kg) and average ($0.86/kg) and Hydrogen Council favorable (ca. $0.85/kg) and average (ca. $1.45/kg) in 2050.

SOURCE: BloombergNEF (2021), *Natural gas price database* (online, retrieved 01/2021), BloombergNEF (2020), *2H 2020 LCOE Data Viewer*; BloombergNEF (2021), *1H2021 Hydrogen Levelised Cost Update*; Hydrogen Council (2021), *Hydrogen Insights*

The green cost premium at intermediate and end consumer level

Producing zero-carbon hydrogen will not impose a large cost on the economy in the long run. However, sometimes, using hydrogen will likely impose significant costs compared to the use of an unabated fossil fuel based technology. This is due to the remaining cost differential between hydrogen and fossil fuels (without a carbon price) and to capital expenditure triggered by the switch to hydrogen-based technologies. There will therefore be a "green product premium" when applying hydrogen to achieve decarbonisation.

5 Low and high case for grey/blue hydrogen relate to natural gas price range of $1-10/MMBtu. Green hydrogen costs are based on an electricity input cost of $25-60/MWh and electrolyser CAPEX of $850/kW. Sources: BloombergNEF (2019), *Hydrogen – the economics of production from renewables*; Expert interviews.
6 The capacity utilisation factor (i.e.. how many hours the electrolyser is running) at the given cost of electricity and the efficiency are other key factors.
7 Assuming 45 kWh per kg, versus today's typical 50-53 kWh per kg

However, except for the case of aviation, the "green consumer premium" (i.e. how much more consumers will need to pay for the products and services they directly purchase) will still be trivial since intermediate products or services typically account for only a very small proportion of total end product cost.

In that context, demand for zero-carbon hydrogen will not develop without strong policy support at intermediate product level and pass through of costs to end consumers.

Transport, storage and international trade

Vastly increased demand in more applications will require extensive systems for hydrogen transport and storage. This will add costs, but may also create opportunities to produce hydrogen in favourable, low-cost locations for use elsewhere.

Technology options and costs

Hydrogen can be transported in different forms: compressed, liquified or as ammonia. Lowest-cost transportation options will depend on the required volumes and distances involved. Significant storage will be needed to support some large-scale applications. Requirements will be greatest when hydrogen is used to provide seasonal supply balance within the power system. For distributed applications such as road transport, distribution and storage costs could add circa $1.3 per kg to production costs below $2 per kg.

Opportunities for international trade

The scale of international trade in hydrogen will be limited by three factors: i) the potential use of long-distance electricity transmission as an alternative to green hydrogen transport; ii) the potential use of natural gas pipelines as an alternative to blue hydrogen transport; and iii) the likelihood that falling renewable electricity costs across regions will reduce the cost differential between regions faster than transport costs decline.

As a result, long-term opportunities for profitable international trade in hydrogen may be limited to where cheap high-capacity pipelines are economic (typically up to 1000 km, particularly where existing gas pipelines can be retrofitted), or transporting ammonia for end use as ammonia (avoiding costly, energy intensive reconversion to hydrogen). Further, a limited number of countries may have an energy deficit (e.g., due to lack of land area for local renewable energy generation) which forces them to import energy even if costs are relatively high. Moreover, it is likely that the emergence of a hydrogen economy will, over time, lead to changes in the optimal location of hydrogen-intensive industries, such as steel.

II. Driving the transition to large-scale clean hydrogen supply and use

It is clear that hydrogen can and must play a major role in the future zero-carbon economy. The challenge is to ensure that the transition occurs fast enough to first unlock low-cost production and then put the sector on a growth trajectory to meet 2050 objectives.

Reducing green hydrogen production costs

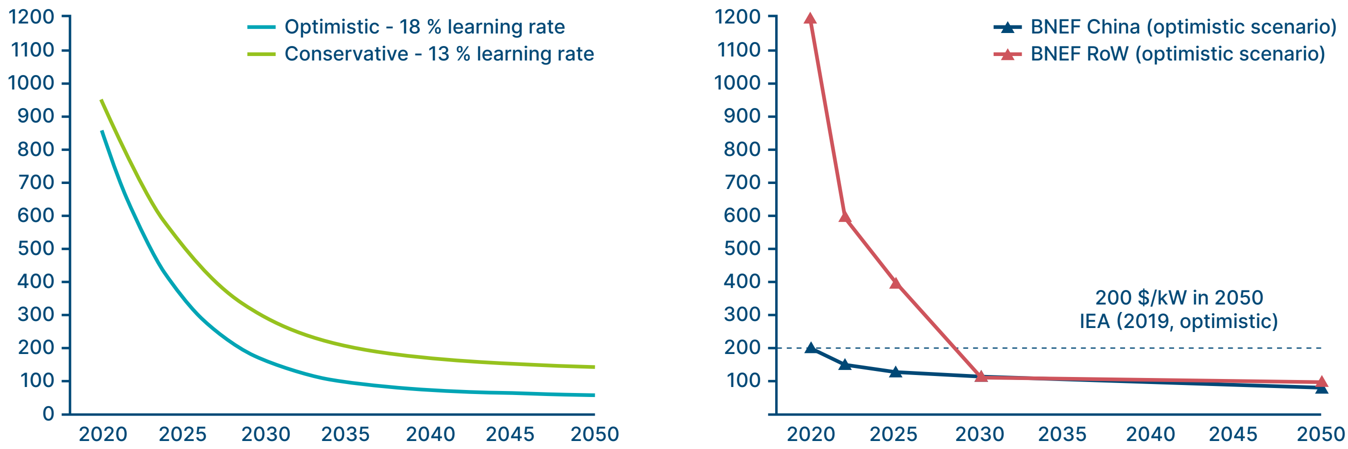
While green hydrogen is not competitive today, if already announced public policies and private plans materialise, they would be sufficient to drive strong cost reductions in the 2020s, making it competitive with blue hydrogen and grey in some locations.

The costs of both the key inputs – electrolyser equipment (Exhibit D) and renewable electricity – are likely to fall rapidly in the 2020s.[8] The cost of green hydrogen production is therefore likely to fall below $2 per kg and in some locations below $1.5 per kg during the 2020s. Several private investment projects are already targeting production at those costs.

8 Electrolyser costs are expected to fall from ca. $850/kW fully installed cost today to below $300/kW in 2030. Electricity costs from dedicated renewable energy generation for hydrogen production is expected to fall below $25/kW in average locations by 2030.

Green hydrogen production costs are expected to fall driven by both falling cost of electrolysers and continued declines in renewable electricity prices

Fully installed system capex forecast of large alkaline electrolysis projects
US$/kW



Electrolyser capacity (GW)	15	225	1300	3300	5500	7800

Exhibit D

NOTES: CAPEX figures include full installation costs for a large scale (>20 MW) alkaline electrolyser including stack, balance of plant (power electronics for voltage transformation, hydrogen purification and compression), construction and mobilisation and soft costs (project design, management, overhead, contingency and owners cost). There are significant differences in electrolyser CAPEX forecasts likely related to differences in definitions of what is included/excluded in quoted figures and differences in system size (costs decline significantly with order and module size). Hydrogen Council suggests electrolyser CAPEX could drop to about $200-250/kW (IRENA: $360/kW in Transforming Energy Scenario) by 2030 at the system-level but do not include installation and assembly, building, indirect cost.

SOURCES: BloombergNEF (2019), *Hydrogen – Economics of production from renewables*; BloombergNEF (2021), *1H2021 Hydrogen Market Outlook*; Hydrogen Council (2021), *Hydrogen Insights;* IRENA (2020), *Green hydrogen cost reduction*; Expert interviews.

Accelerating demand growth

By the late 2020s, clean hydrogen is likely to be cost-competitive with grey hydrogen in some locations. However, end-use applications of hydrogen, and thus total demand, may not grow fast enough in the 2020s to allow a credible path to the 500-800 Mt required. Public policy should therefore support faster demand growth in the 2020s than is required simply to secure a decline in the cost of green hydrogen.

Key priorities are to drive rapid decarbonisation of all existing hydrogen production and accelerate rapid technology development and sufficient early adoption of hydrogen in other key sectors – particularly those with lower technology-readiness but large potential demand, like steel production and ammonia in shipping – to make rapid take-off in the 2030s feasible.

Enabling rapid capacity growth

Strategies for the development of the hydrogen economy should also anticipate the scale of investment ramp-up required and identify and remove any barriers.

- For green hydrogen, natural resources are clearly sufficient to support massive growth, but plans for power system developments must anticipate the very large electricity demand for green hydrogen production.[9]

- Blue hydrogen development could be slowed due to long project lead times, difficulty to develop shared pipeline networks and public resistance to CCS, hence the need for clear national strategies to support appropriate development of blue hydrogen.

9 ETC (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy*

In a mass-electrification scenario, what could the scale up of the hydrogen economy look like?

Scenario 2: ~85% 2050 supply green, ~15% blue

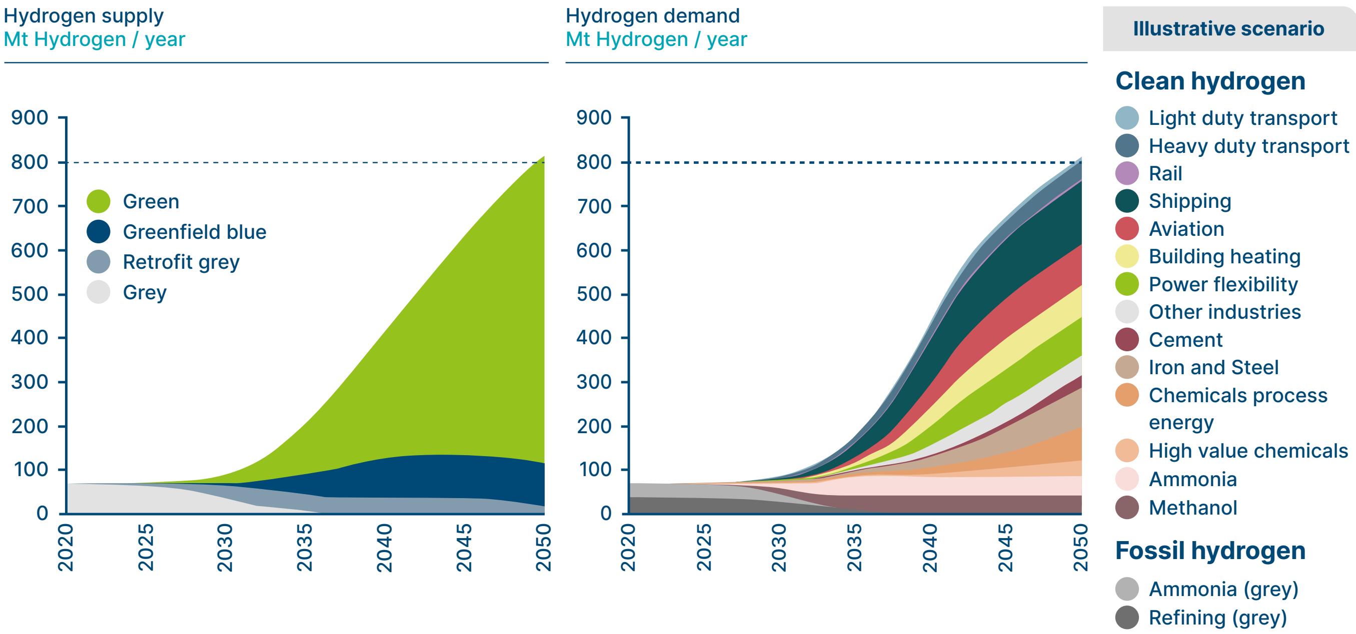


Exhibit E

SOURCE: SYSTEMIQ analysis for Energy Transitions Commission (2021)

The actual balance between green and blue hydrogen will reflect future trends in technology and cost, varying in line with specific national and regional circumstances. Exhibit E shows an illustrative picture of how demand by sector and sources of supply could evolve over the next 30 years.

Developing hydrogen clusters

Strategies to simultaneously develop low-cost hydrogen production and demand growth will often be most effective if initially focused on “hydrogen clusters” in which hydrogen production, storage, transport and end use can develop concurrently. Clusters can provide hydrogen producers with greater certainty on local hydrogen demand, enable different users to share costs, and minimise initial need for investments in large-scale transport.

Details of potential cluster developments will depend on specific geographies and initial starting points, but 4 variants may be important:

- Existing refining, petrochemical and fertiliser clusters, where production should be decarbonised and new industrial applications could be added;
- Ports, which need to support future shipping decarbonisation and are also transport hubs, often located close to heavy industry sites;
- Non-coastal transport and logistics nodes, with co-location of different transport-related uses;
- Steel plants large enough in themselves to be the anchor for cluster development.

Safety, quality and low-GHG standards

Hydrogen’s major role within a zero-carbon global economy could be facilitated by international rules and standards on safety and purity. Clear standards for greenhouse gas emissions measurements are also essential.

Total investment needs – dominated by power sector growth

Building a hydrogen economy that accounts for 15-20% total final energy demand, with hydrogen use increasing by 5-7 times relative to today's 115 Mt,[10] will require very large investments. In total, investments could amount to almost $15 trillion between now and 2050 – peaking in the late 2030s at around $800 billion per annum.[11] Of this, about $12.5 trillion (85%) relates to the required increase in electricity generation.[12] These would be additional to investments required for massive direct electrification described in our parallel report.[13] Clear long-term strategies for massively expanded clean electricity supply are therefore vital to achieve a zero-carbon economy where direct electricity and hydrogen along with its derived fuels will together account for over 85% of all final energy use.

III. Critical policy and industry actions in the 2020s

A feasible pathway to a mid-century net-zero economy requires a significantly accelerated ramp-up of clean hydrogen supply and use by 2030. Progress must occur along two critical dimensions:

- The production of clean hydrogen should reach 50 Mt by 2030, unlocking average clean hydrogen production costs of well below $2/kg in all regions and putting capacity scale-up on a trajectory to reach 2050 targets.
- The majority (60%+) of the corresponding demand should stem from decarbonisation of existing hydrogen uses, combined with early scale-up of key new uses of hydrogen.

As a result, public and private action to drive hydrogen application must combine broad policy levers with sector-specific interventions. Key priorities should include:

1. **Carbon pricing,** which should ideally be part of the policy mix in all countries, providing broad incentives for decarbonisation of hydrogen supply and of potential use cases, and creating a level-playing field for clean hydrogen technologies (and other decarbonisation options) versus fossil fuel technologies.
2. **Sector specific policies to support demand growth and compensate the "green premium"** in particular applications, via a combination of:
   - Mandates and regulations requiring a percentage use of low-carbon energy (e.g., fuel mandates in shipping or aviation) or setting lifecycle emissions standards;
   - Voluntary private-sector commitments to purchase low-carbon products and services (e.g., logistics firms committing to low-carbon trucking & shipping);
   - Green public procurement policies (e.g., "green steel" in public construction);
   - Financial incentives for hydrogen uptake, through mechanisms like contracts for difference to bridge the "green premium" of low-carbon products.
3. **Targets** for the development of large-scale electrolysis manufacturing and installation and public investment support for the first large-scale electrolysis manufacturing and installation projects.
4. **Public support and collaborative private-sector action to bring to market key technologies and capabilities** across production (e.g., electrolysers with faster ramping), transportation and storage (e.g., new forms of bulk hydrogen storage such as rock caverns), and use (e.g., hydrogen-based direct reduction of iron).
5. **The development of clean hydrogen industrial clusters**, through coordinated private-sector action, supported by national and local government.
6. **International rules and standards** on safety, purity and clean hydrogen certification.

10 IEA (2019), *The future of hydrogen*
11 The average investment need over 30 years is ca. $500 billion per year which is on the same order of magnitude as upstream oil and gas spending during the last 10 years ($400-600 billion per year). Source: IEA (2020), World Energy Investment 2020.
12 In some instances, additional transmission infrastructure may also be required, e.g. in the case of dedicated renewable power from offshore wind.
13 ETC (2021), *Making Clean Electrification Possible: 30 years to electrify the global economy*

ACCELERATING CLEAN HYDROGEN IN THE 2020S

Energy Transitions Commission

2030 TARGETS:

SUPPLY

50 Mt — Clean hydrogen production

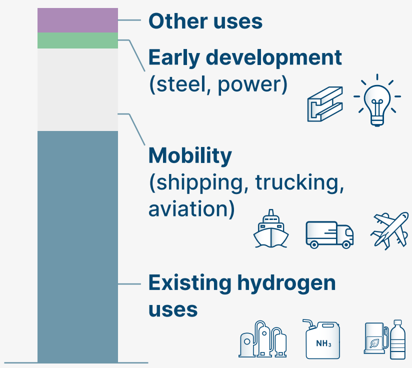
<$2/kg — Average clean hydrogen production cost

DEMAND

> 60% — Clean hydrogen demand from existing hydrogen use

> 30% — From new mobility and industry use-cases

HYDROGEN USE



TOP 5 ACTIONS ACROSS VALUE CHAIN

SUPPLY

1. Direct investment support and access to low-cost capital for clean hydrogen industrial clusters
2. Access to lower power prices through corporate purchase agreements, grid-tariff waivers and power market design
3. Ban new greenfield unabated grey hydrogen plants
4. Streamline permitting process for VRE generation and CCS for clean hydrogen production

TRANSPORT AND STORAGE

1. Adapt and expand existing regulatory & safety frameworks for hydrogen and ammonia
2. Geological siting of potential hydrogen storage locations (e.g. salt caverns)
3. National infrastructure planning to design (inter-) national hydrogen networks where required
4. Government support (e.g. blended finance) for storage & transmission network build out

DEMAND

1. Carbon taxes of $100/ton by 2030 with further increase until mid-century
2. Sector specific policies & actions to create early demand (e.g. mandates, public procurement, voluntary green market)
3. Sector specific financial support mechanisms for investments and to overcome the cost premium (e.g. contracts for difference)
4. Establish clean hydrogen & product certification scheme

INNOVATION

5. Supply: Electrolyser technology improvements (e.g.faster ramping for alkaline and less scarse catalysts for PEM)
5. Transport and storage: Development of rock caverns and depleted gas fields for large scale hydrogen storage
5. Demand: Improve technological readiness of hydrogen use in heavy industry and liquid transport fuels (ammonia, synfuels)

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