POLICY BRIEF

July 2021

The current state of play of the Hydrogen ecosystems in the world

Florian Dommergues & Joël Ruet

Retrospectively, 2021 might well prove to be the breakthrough year for the ecological transition towards climate neutral societies. With the election of Joe Biden, who reinstated the United States in the Paris Agreement hours after coming into office, the ecological transition has gained new momentum.
By the end of 2020, more than 110 countries had pledged to reach climate neutrality by the mid-century, including China by 2060. Large-scale recovery plans were launched by OECD countries, such as Biden's $1.9 trillion American Rescue plan, France's €100 billion recovery plan (of which €30 billion are dedicated to the ecological transition), or the EU's €1800 billion plan, of which one third is dedicated to the European Green Deal to reach climate neutrality. These plans have been seen as a chance to accelerate further the ecological transition and to invest in the technologies and energies of tomorrow.
In this context, one energy in particular, or more precisely one energy carrier, gained particular drive: hydrogen (H2). The aim of this policy brief is to provide an overarching view of the current state of affairs of the hydrogen ecosystem and a review of the institutional reports and national blueprints or strategies.

Overall, we believe these reports adopt an approach that tend to have an insufficient understanding of the structuring issues specific to each hydrogen ecosystem locally, and on the contrary adopt a vision of one homogenous hydrogen ecosystem globally that ignores the specificities of each national or subnational economy. Such analyses align themselves it in the continuity of a classical economic analysis that treats hydrogen as a standardized commodity, with common specificities. Hydrogen should actually be approached in its diversity, as hydrogens in the plural, and similarly, energy system dynamics should be approached specifically for each economy. Therefore, broad, uncharacterized and unspecified policy options appear to have limited utility and does not take sufficiently into account the specifies of each system's inertias and structuring issues.

POINTS CLES

- The dialectic between hydrogen industrial actors and public policy maker will be one of the main dynamics that will determine the evolvement of hydrogen ecosystems in the years to come.
- Hydrogen exports will remain limited since the molecule cannot be assimilated to a standardized commodity such as oil or minerals. It is more accurate to talk about *hydrogens* rather than one hydrogen, because of the multiplicity of its mode of productions, of its use, and of its captive use in many production locations.
- A "philosophy" of the energy transition should be thought through by policy makers and within that framework, green hydrogen should be understood as a *complementary* vector, essential for the decarbonization of current industrial uses, for stabilizing the power grid and for favoring energy system integrations, but not, however, a central tool of the transition. Electrificaiton must indeed remain the priority solution whenever possible, as a consequence of the efficiency limitations of hydrogen in a world with limited renewable energy ressources.
- The multiplication of hydrogen national strategies as well as NGOs' hydrogen reports underlines the momentum that H2 has gained the past twelve months and the now unquestionable development of hydrogen ecosystems in the years to come.

Structuring the field's analysis: The role of Hydrogen within electrification and energy transition

Hydrogen has now been widely recognized as an unavoidable part of future economies' ecosystems and of the ecological transition more broadly. What can its 'contours' be?

We argue that the structure of future hydrogen ecosystems, which will be plural and not singular as we will demonstrate, will depend on the interplay between private, mostly industrial, players and public policies. If hydrogen national strategies will structure the regulatory framework and provide investments, credibility, and readability to the different H2 ecosystems, it is their interaction with industrial player's needs, aspirations, and interests that will be crucial.

Specific national and local characteristics will need to be taken into account, going beyond an overly simplified macroeconomic which is blind to the granularity of each system. Exemplifying this dialectic, as we will elaborate on, will be the question of the retrofitting of gas pipelines for hydrogen transport, which might favour, or impede, depending on government and private players understanding, the scaling up of hydrogen in our economies.

All in all, we see three –relatively independent- trends, or dimensions, of analysis, for hydrogen development in the years to come. These trends will partly combine and partly have independent business models and siloed industrial ecosystems.

- First, hydrogen must be approached around the establishment of its specific ecosystem and the industrial problematics that surround its development. One of the decisive dynamics will be the interaction between industrial players (both new upcoming players and old industrial fossil fuel players, such as gas utilities) and government public policies which will shape the regulatory environment. Hydrogen will be a crucial part of the energy transition as it allows for some amount of grids integration. Indeed, it permits energy storage of renewable energy capacities, thus optimising and improving the stability of the power grid. Moreover, hydrogen allows sector coupling, meaning the interconnection and integration of energy sectors. Finally, and maybe most notably regarding the government-industry dialectic, it appears as a useful transitioning vector from fossil-based economies to carbon neutral ones. Indeed, hydrogen can be transported through retro-fitted gas pipelines[1] [2], allowing to involve major gas utilities and corporations in the transition, whereas power and gas utilities had long been rivals. Seen from a private perspective, having the chance to value their assets, these actors will impede all the less a transition to a hydrogen economy. Seen from a public/societal perspective, retrofitting these assets allows avoiding prior investment in these to become "stranded assets", and consequently permits an optimization of the need for new grids.

- Second, Hydrogen, in the years to come, will most probably become an object of trade between countries with abundant RES and those with scarcer ones in the years to come, through a hydrogen backbone of pipelines at a regional level, or, at an international level, stored and transported in the form of ammonia for instance[3]. Such initiatives are already arising: Germany is multiplying memorandum of understandings with countries such as Morocco (January) or Portugal (February) for future hydrogen imports while Japan has signed cooperation agreements with Australia or the United Arab Emirates in January. Both countries indeed lack sufficient renewables capacity to answer their future domestic needs. But we argue that for a long time to come this will not at all take the magnitude nor the forms of standardized transactions, such as oil or natural gas. Rather than a market, long term industry and trade agreements will prevail. The amount of hydrogen that will be traded in a "commodity way" will remain limited[4].

- Third, hydrogen's place in the energy transition must be clearly stated and thought out. It is to be noted that transitioning through direct electrification will remain the priority whenever possible because of the efficiency limitations of hydrogen (following the principle of additionality which states that electrification should always be conducted first if possible because of the great conversion energy losses of hydrogen under the laws of thermodynamics). Electrification, just like hydrogen, is an energy carrier, which can be used to replace fossil fuels applications in many instances, gas for heating or oil for combustion engine for example, therefore enabling to

[1] *Hydrogen act, Towards the creation of the European hydrogen economy.* Hydrogen Europe, April 2021.
[2] No-regret Hydrogen. Charting early steps for hydrogen infrastructure in Europe. Agora Energiewende, Jan.uary 2021.
[3] *Hydrogen insights*. Hydrogen Council, February 2021
[4] Antoine Goutaland and Joël Ruet. L'hydrogène, nouvelle commodité, vecteur énergétique 'magique', ou prescripteur de politiques publiques exigeantes? The Bridge Tank, 2021.

advance the ecological agenda and to decarbonize several energy uses. Based on the assumption that this very electricity is produced in a decarbonized manner (and not from fossil fuel plants). Electricity is prioritized compared to hydrogen as it requires much less conversions for final energy use and therefore less losses.

Thus, the 2020 EU Strategy on "Energy System Integration policy" has declared that hydrogen should be considered « for end-use applications where direct heating or electrification are not feasible, nor efficient or have higher costs » and the Florence School of Regulation highlights that hydrogen will be a complementary vector where « electrification is either (currently) not technically feasible or not cost-competitive »: what we call « hard-to-electrify », or « hard-to-abate » sectors[5]. It is in those sectors (such as long distance transport or industrial uses: steelmaking; refineries, ammonia production) that hydrogen will likely prove to be the more « ecologically-fitted » response[6] [7].

All in all, if hydrogen will be an indispensable tool for the transition, favouring sector coupling and grid stability, it will however not be central to it. Hydrogen must be seen as a complementary energy vector, that completes the limitations of electrification, and provides stability to intermittent renewables, as well as answering the need for energy in hard-to-abate sectors. It is why it is coherent to approach hydrogen not as *one* but as *hydrogens* in the plural, answering inherently different qualitative needs.

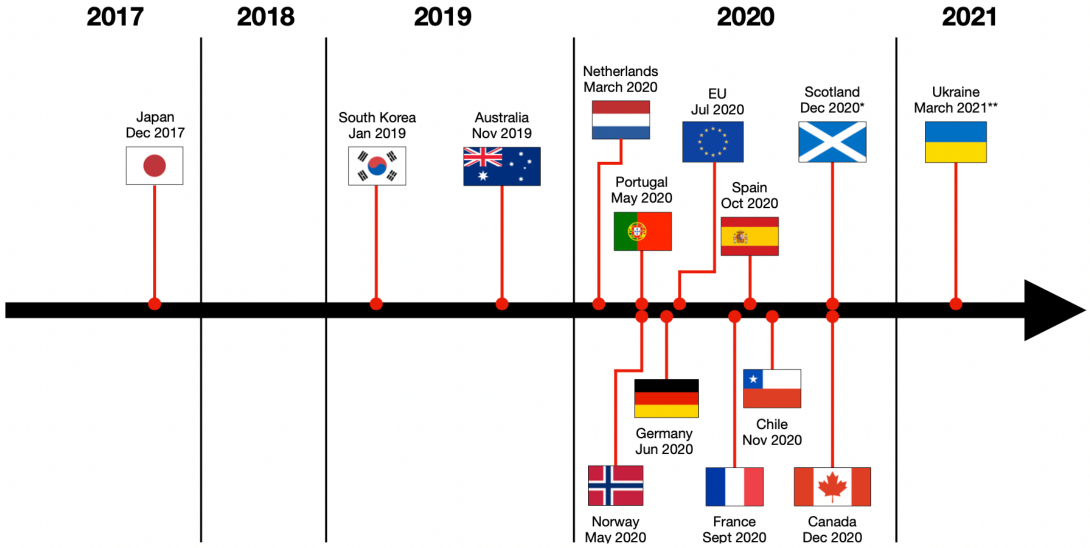
Towards trends (1): The technopush - Mapping Governments' national strategies to long-term hydrogen development

In July 2020, the EU officially recognized the importance of hydrogen by publishing its hydrogen strategy, « A hydrogen strategy for a climate-neutral Europe »[8]. Since then, NGOs' hydrogen reports and national hydrogen strategies have multiplied. For instance, since summer 2020, France, Norway, Spain, Canada, Chile and Germany have each published their own national hydrogen strategy, while some had already been published earlier in the year and many remain in preparation (e.g. Colombia announced it will present its roadmap in the first half of 2021).

In the EU's footsteps, many member States governments followed suit and published their own national hydrogen strategy shortly before or after, and others are preparing to do so. In 2020 alone six strategies were published: those of the Netherlands, Portugal, Germany, Norway, France, and Spain. Among the common traits of the different national strategies that we can put forward is an installed electrolysis capacity objective for 2030. Such a target has been inscribed in almost all national strategies, European's as well as non-European ones. These targets range from 2 GW for Portugal in 2030 to as much as 25 GW for Chile, whose national strategy positions as a future world leader in green hydrogen production thanks to a considerable renewable energy generation potential.

In the long term (at a deadline between 2030 and 2050), green hydrogen (i.e. hydrogen produced from a renewable source of energy) is the main, if not the only, mode of hydrogen production considered by the different governments. However, some countries (the UK, Scotland, the Netherlands, Canada) include blue hydrogen (hydrogen production from fossil fuels with carbon sequestration) as an intermediary medium-term solution to transition to a hydrogen economy and scale-up production. France is in a unique position with the importance of nuclear production in its electricity mix (70% of the country's electricity production in 2019) which might prove to be a real comparative advantage in the race to low-carbon hydrogen production leadership. If nuclear is not explicitly mentioned in the French strategy, the « hydrogen opportunity », if we can call it so, might actually relaunch the nuclear industry in France which seemed to slowly direct itself towards its dismantling.

[5] Hydrogen in the energy transition. Florence School of Regulation, November 18th, 2020.
[6] No-regret Hydrogen. Charting early steps for hydrogen infrastructure in Europe. Agora Energiewende, January 2021.
[7] Hydrogen insights. A perspective on hydrogen investment, market development and cost competitiveness. Hydrogen Council, February 2021.
[8] A Goutaland & J Ruet. *Analysis of the EU H2 strategy, of the EU energy integration strategy and of the clean hydrogen alliance launch*. The Bridge Tank, July 2020.



*Scotland published its Hydrogen Policy Statement in December 2020
**Following a request from Ukraine's Ministry of Energy, UNECE published a « draft roadmap for the production and use of hydrogen in Ukraine » in march 2021

Figure 1 : Timeline of national hydrogen strategies
Source : Our analysis

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[9] Antoine Goutaland and Joël Ruet. *Analysis of the EU H2 strategy, of the EU energy integration strategy and of the clean hydrogen alliance launch*. The Bridge Tank, July 2020.

Finally, in the short term, hydrogen production is mostly considered for industrial use (refineries, steel, ammoniac) and long-distance transport by the governments 'national strategies, in one word, in hard-to-abate sectors.

This priority usage of green hydrogen as an industrial composite underlines the qualitative difference between the three trends characterized in the introduction.

If decarbonizing industrial uses will undeniably be necessary and be carried through using green hydrogen in the years to come, the two additional trends present more uncertainty regarding their true importance in the future.

Hydrogen as a complementary vector providing grid stability and enabling sector coupling will appear to be its principal second usage in case of a massing scale up. Finally, green hydrogen used for exports will likely have the lesser importance between those three trends, as it will remain difficult, costly and risky to transport on long-distances (requiring further conversions, to ammonia for instance) and cannot be assimilated to commodities such as oil or minerals.

	Portugal	Spain	UK**	Germany	Scotland	France	Chile	EU	Netherlands	Norway	Canada
Announced target of installed electrolyser capacity by 2030	2GW	4GW	5GW	5GW	5GW*	6,5GW	25GW	40GW	3-4GW	-	****
Planned H2 investments by 2030	7Mds€ in H2 p° project 900M€ in support of investment and p°	8.9Mds€ during the 2020-2030 period	-	-	100M£ between 2021 and 2026	7Mds€	-	Needed investments would total up to 458Mds€	-	-	-
Plans to use hydrogen for exports	-	-	✓	✗	✓	✓	✓	✗	✓	***	✓
At which sectors is H2 primarily aimed at	Industrial uses & transport	-	-	Industrial uses, transport & heat market	Industrial uses & transport	Industrial uses & transport	Industrial uses, transport & blending with gas infrastructures	Industrial uses & transport	Industrial uses, heavy-duty transport & storage	Industrial uses & transport (maritime and heavy-duty)	Industrial uses, transport, storage & heat market
H2 production modes considered	Green H2	Green H2	Mostly green H2 and blue for transition	Grenn H2	Green H2 and blue H2 (in the medium-term)	Decarbo-nized H2 p° using electrolysis (green and possibly blue H2)	Green H2	Mostly green H2 and blue for transition	Mostly green H2 and blue for transition	Green and blue H2	Green and blue H2

* « an ambition of at least 5GW of renewable and low-carbon hydrogen by 2030 » (https://www.gov.scot/publications/scottish-government-hydrogen-policy-statement/)
** No official national strategy has been published by the UK but announcements have been made and credible expectations can be made with high certainty, especially drawn from the Prime Minister's Ten Point Plan for a Green Industrial Revolution (national strategy will be published in 2021)
*** In the Netherland's « Government strategy on Hydrogen », it is declared that : « Large scale, natural gas-based hydrogen export from Norway is not currently regarded as a realistic option. However, this may be possible in the longer term »
**** Contrarily to other countries, the Canadian government hasn't announced an electrolysis capacity objective but a hydrogen production target : 4Mt/y in 2030 and 20Mt/y in 2050

Table 1 : National hydrogen strategy detailed composition
Source : Our analysis based on published governmental strategies and governmental publications.

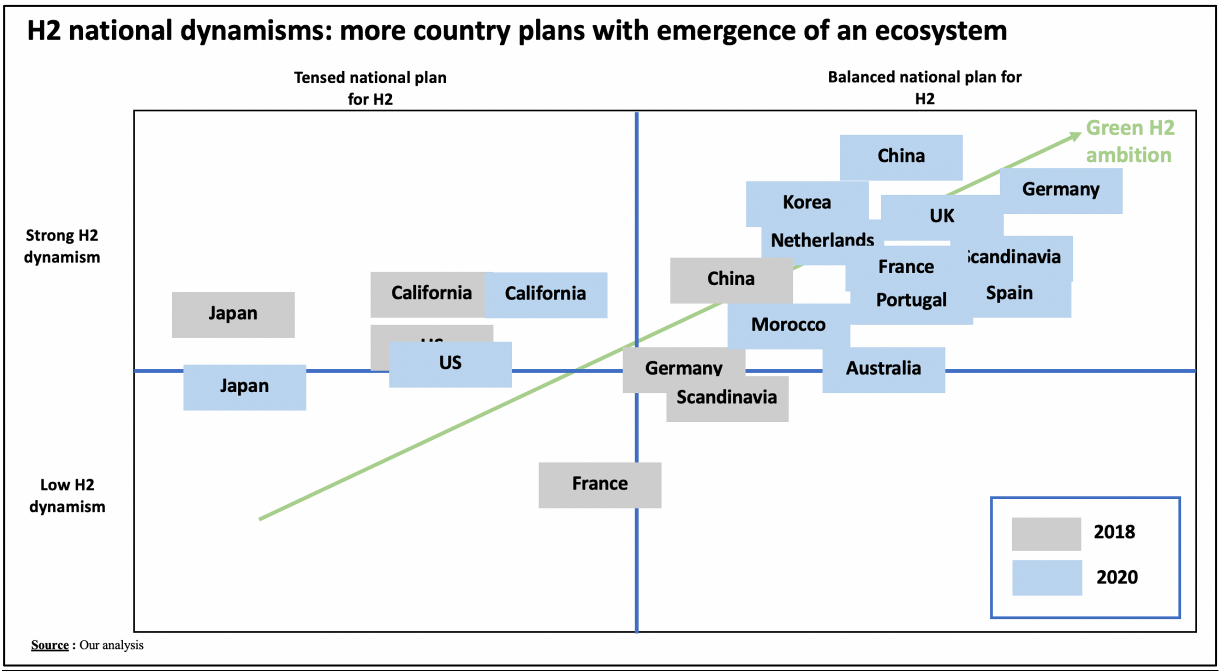
If China hasn't published an official hydrogen strategy per say so far, the leading Asian economy is still investing heavily into hydrogen and perceives it as an essential part of its energy transition, as it aims to reach carbon neutrality by 2060 following President Xi Jinping's engagement. Hydrogen is seen as one of the six industries of the future in the CPC's 14th Five-Year Plan (2021-2025) while 16 provinces and cities have launched their own five-year plans involving hydrogen development. If China mostly puts forward hydrogen for light mobility uses, in reality, it is investing in all possible usages of the hydrogen economy and notably hopes to valorize its enormous renewable (wind and solar) capacities using hydrogen conversion.

The United States, that had seemed to be lagging behind under the Trump and Obama administrations finally seems willing to catch up and invest massively in the hydrogen ecosystem. If their approach is hardly integrated so far (with different vision for hydrogen development between federal states), President Biden has undeniably shown willingness to promote the molecule and recently disclosed the Hydrogen Energy Earthshot.

Finally, it is to be noted that emerging powers and especially MENA countries are not ready to be left behind in this emerging economy and are pushing investments to establish and strengthen their position in the future hydrogen ecosystems. Saudi Arabia hopes to become a green hydrogen exporter and is developing FCEVs manufacturing lines and GW electrolyzers plants in the country. Morocco which detains considerable renewable resources is also emerging as a potential major player and has signed bilateral cooperation agreements regarding hydrogen with Germany and Portugal (in February). The United Arab Emirates (UAE) is also positioning itself: since the beginning of the year, it has inaugurated the first solar-based hydrogen facility in the region, signed a MOU with Japan for the development of an international hydrogen supply chain and three major state owned enterprises (SOEs) signed an MOU eager to turn the emirate into a substantial green hydrogen economy and an exporter of blue and green hydrogen[10].

We see that governments' implication is gradually taking importance and great amounts of investments have now been committed for the development of hydrogen ecosystems all over the world. Governments national hydrogen strategies are indispensable since they communicate clear messages to private players that hydrogen will have long-term importance and they give clarity to the phases of its scale up.

Nevertheless, what will actually shape the hydrogen ecosystems will be industrial players response to those public policies and investments. If indispensable, government commitments are therefore insufficient and industrial player's own interests, perspective and needs must be apprehended.



Source: our analysis

Towards trends (2): Deep Influencers - Recent hydrogen publications from NGOs and private players

Besides governments publishing their national strategies, nongovernmental organizations (NGOs) have also been very active and many hydrogen reports have been published in the last few months. We analysed as much as 20 reports of importance on this subject: 13 published since January 2021 on the subject, against 7 in 2020[11].

We divided these reports into three categories we stylise as such: Area focused reports (11 reports), Breakthrough reports (4

[10] For more details, turn to the Bridge Tank's monthlies hydrogen highlights.

[11] See in the annex.

reports) and Knowledge sharing reports (5 reports). The former designates reports that focus on one specific trait of the hydrogen ecosystem, one technology, one sector, one regional perspective, the second concerns reports that provide new insights and understanding of the hydrogen ecosystem that hadn't been shared or talked about previously, finally, the latter, so far restricted to 5 reports concerns reports that allow a broader understanding and knowledge of the issues and opportunities linked to hydrogen by sharing to a further audience information that was already being discussed beforehand.
Additionally, The Bridge Tank recently released a report pertaining to the knowledge sharing and breakthrough categories that notably contests the qualification of hydrogen as a new "commodity".

Hydrogen: a quantitative photography

As a quantitative recap of the current state of affairs, 120 Mt of hydrogen are produced each year globally with an installed electrolyser capacity of around 200MW in 2021, while fossil fuels account for 95% of production (IRENA, May 2021). 75% of hydrogen consumption is used for oil refining, ammonia, and methane synthesis. IRENA estimates in its World Energy Transition Outlook that green hydrogen will have reached about 400 Mt of production annually (49 exajouls) by 2050, which would require a 5TW installed electrolyses capacity (IRENA 2021). To achieve such a number, the agency estimates that by then, the global manufacturing capacity will need to be around 130 to 160GW a year. On the other hand, the Hydrogen council in its « scaling up » report envisioned 79 EJ of hydrogen production (for a 10 TW renewable capacity).

The Hydrogen Council, in a report titled « Hydrogen Decarbonization Pathways: Potential Supply Scenarios » elaborated three theoretical pathways towards a ten-fold build-out of H2 supply by 2050 with decarbonized sources. It established a green only scenario (only using green H2 by 2050), a blue H2 scenario (only using blue H2) and a hybrid scenario (using both). It established that from 2020 to 2050, achieving the green only scenario would induce the emission of approximately 10 Gt of CO2, 8 of which would come from the progressive phase out from grey H2, while the blue only scenario would induce 20 to 25 Gt of CO2 over the same time period.

A couple of reports, besides the national strategies we had mentioned, defend a hybrid pathway at the beginning with blue hydrogen being regarded as a medium-term transition tool towards a mature hydrogen economy (Oxford Institute of Energy Studies, March 2021 ; UK HFCA, February 2021 ; OPECST, April 2021).

Overall, a few recurring key points can be taken away from the newly published reports.

Public Affairs reports: policy making recommendations and policy stages categorization for the establishment of a hydrogen ecosystem

A couple of reports provide policy making recommendations (Hydrogen Europe, April 2021 ; IRENA, November 2020 and may 2021 ; IRENA, December 2020). Hydrogen Europe puts forward the establishment of a « hydrogen act » composed of a hydrogen infrastructure act as well as a hydrogen market act. It would enable the establishment of a framework that would allow a clean hydrogen market to emerge and would stimulate hydrogen production and demand through political measures.

IRENA in a report titled « Green hydrogen cost reduction » tautologically focuses on cost reduction policies specifically. Four strategies are identified: increasing the module size, investing in R&D, scaling up the manufacturing of electrolysers and finally « learning by doing ». More broadly, in its « guide to policy making » (IRENA, May 2021), the agency provides an overarching view of the useful policies in order to develop the hydrogen economy and scale up production. The policies presented are for instance the establishment of a guarantee of origins, that would certify the « quality » of the hydrogen produced (green, blue, grey etc.),

the creation of standards, the establishment of capacity targets, fiscal incentives…
Most of these reports share a ternary vision of stages that enable the progressive establishment of a mature hydrogen ecosystem. These « steps », or categories, are useful tools for any policy maker to envision a long-term planification in order to act in favor of the development of a hydrogen economy.

- The first is a kick-start phase that aims at establishing the foundations of the hydrogen economy, at achieving hydrogen's technology readiness, demonstrate scalability, insure market establishment.

- The second is a market penetration phase, or ramp up phase, where hydrogen supply is scaled up.

- A third and final set of policies corresponds to a market growth phase where the hydrogen market expands beyond domestic borders, reaches maturity and starts exporting its product, possibly becoming a global market. Such an achievement however will require the establishment of a coordinated and mature hydrogen ecosystem beforehand[12]. Moreover, as was underlined in the quoted report, this set of policies tend to adopt to easily a mistaken understanding of hydrogen as a "commodity" that could establish itself as the "new oil".

A few more area focused reports defend the establishment and development of a « hydrogen backbone » in Europe (Gas for climate, July 2020; Agora Energiewende, January 2021; Hydrogen Europe, April 2021). These reports defend the necessity, or even the opportunity, of establishing a backbone pipeline infrastructure in Europe to favor the transport and storage of hydrogen between European countries. The Agora Energiewende report titled « No-regret Hydrogen. Charting early steps for H2 infrastructure in Europe » establishes the opportunity for a no-regret backbone in Europe, meaning one that will be economically viable and pertinent « no matter what » (no matter the assumptions, the variables).

The interest of a hydrogen backbone is that it can largely reuse the existing gas infrastructures. For instance, in its report, Gas for climate ambitions a 22,900 km backbone for 2040, a total of which 75% would be repurposed natural gas pipelines. According to the report, total investment costs would range from €27 to €64 billion. The 75% retrofitted pipelines would represent only 50% of the required investment, underlying the economic opportunity enabled by the reuse of former gas infrastructures. Similarly, Hydrogen Europe, through its infrastructure act mentioned earlier, defends the establishment of a pan-European backbone infrastructure by converting former natural gas infrastructures. North-western Europe would be one of the main nod of the network as the IEA discusses extensively in its report[13].

Overall, we believe these reports adopt an approach that tend to have an insufficient understanding of the structuring issues specific to each hydrogen ecosystem locally, and on the contrary adopt a vision of one homogenous hydrogen ecosystem globally that ignores the specificities of each national or subnational economy. Such analyses align themselves it in the continuity of a classical economic analysis that treats hydrogen as a standardized commodity, with common specificities.

As highlighted in a previous repor[14], hydrogen should actually be approached in its diversity, as ***hydrogens*** in the plural, and similarly, energy system dynamics should be approached specifically for each economy[15].

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[12] Antoine Goutaland and Joël Ruet. L'hydrogène, nouvelle commodité, vecteur énergétique 'magique', ou prescripteur de politiques publiques exigeantes?. The Bridge Tank, 2021.
[13] Hydrogen in North-Western Europe, A vision towards 2030. International Energy Agency, April 2021.
[14] Antoine Goutaland and Joël Ruet. Op. Cit., 2021.
[15] System dynamics analysis in decarbonizing economies: from national Energy systems to Energy trajectories, The Bridge Tank, 2021.

into account the specifies of each system's inertias and structuring issues.

Prospective reports focusing on costs expectations

Finally, a couple of reports also provide a specific focus on costs expectations for hydrogen in the years to come (Florence School of Regulation, April 2021; The Oxford Institute of Energy Studies, March 2021; UK HFCA, February 2021). The FSR provided the most detailed work with a paper title « A snapshot of Clean hydrogen Costs in 2030 and 2050 ». It recognizes that 2050's prices are mostly speculative but 2030's prices provide a stronger information. By 2030, low carbon hydrogen cost is expected to range from €0.9/kg (for the cheapest solar PVs and electrolysis combination) to €2.8/kg (for the most expansive steam methane reforming using natural gas). As a comparison, conventional hydrogen prices in October 2020 averaged $1.25/kg in the US Gulf Coast versus $2/kg in California (refer to table 2 below).

Most hydrogen reports begin to agree that blue hydrogen (fossil-based hydrogen using carbon capture) will remain a viable investment until no longer than 2030. Afterwards, green hydrogen will outcompete blue hydrogen almost everywhere, even without carbon pricing (however it is to be noted that without carbon pricing, companies have no incentive to use carbon capture). Green hydrogen based on solar plants will be the most competitive compared to the slightly more expensive wind-based electrolysis infrastructures. Most notably, Italy and Spain will have the cheapest solar-based renewable energy in Europe.

The Hydrogen Council (« Hydrogen insights », February 2021) highlights that without carbon pricing, hydrogen will be competitive in four sectors: buses, trains, trucks, and SUVs. In one-word, long-distance and heavy-duty transport. A 100$ carbon price would be required in order to make green hydrogen competitive for ammonia and steel production as well as refinery use.

The tarification of carbon is a more and more talked-about subject and is given great importance regarding future hydrogen development prospects in many reports (Hydrogen Council, February 2021; Hydrogen Europe, April 2021 ; Energy transitions commissions, April 2021 ; UK HFCA, February 2021 ; OPECST, April 2021). Research conducted by BNP Paribas Asset Management suggests that for the EU to credibly meet its 2050 Net Zero goal it must impose a carbon tax of between €79 - €103 per ton by 2030. The OPECST (France's Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques) however states that a price of €250 per ton would be necessary for green and yellow hydrogen (nuclear-based hydrogen) to compete with grey hydrogen, while a price of between €100 and €200 would be required to at least incentivize the use of Carbon Capture and Storage (CCS).

Technologies	Electrolyser & solar PV	Electrolyser & offshore wind	SMR + CCS & natural gas
Costs – 2030 (Note: LHV used for conversion)	0.9-2.3 EUR/kgH2 27-70 EUR/MWh	1.7-2.8 EUR/kgH2 52-85 EUR/MWh	1.2-2.8 EUR/kgH2 36-85 EUR/MWh
Cost driver 1	Electricity price 10-25 EUR/MWh	Electricity price 36-46 EUR/MWh	Natural gas price 3–32 EUR/MWh
Cost driver 2	Efficiency- LHV 69-75%		Efficiency-LHV 69%
Cost driver 3	Full load hour factor 15%-38%	Full load hour factor 40%-57%	CAPEX 1155 EUR/kW-H2
Cost driver 4	Electrolyser CAPEX 98-200 EUR/kWel		CO2 transport & storage 1-55 EUR/tCO2

Table 2 : Shows 2030 costs and four key cost drivers (free of any « regulatory » cost or subsidies).
Sources : Florence School of Regulation, April 2021.

CONCLUSION – An issue to look out for: public-private interactions for the establishment of hydrogen ecosystems

Our previous analysis[16] established that building ecosystems lies at the heart of building a hydrogen economy, or more accurately *economies*, integrated into the transitions paths of national energy systems. A singular, archetypical economic market does not exist for hydrogen but need to be constructed both by governments using public policies in order to frame and structure these ecosystems, and by private actors, at the center of the equation, that will respond to these actions.

Within this framework, we argue that one of the main force that will determine how the future hydrogen ecosystem will set out in the years to come will be the interaction between government policy objectives and industrial players well-understood economic interests which might well contradict the former. In the case of hydrogen, this dialectic has particular significance: indeed, fossil fuels industrial players, that would at first appear to belong to the « world of the past », could actually have a role in the hydrogen ecosystem.

For instance, the place blue hydrogen (i.e. hydrogen produced from fossil fuel plants with CCS) needs to be given in the hydrogen ecosystem is subject to intense debate. Some countries advocate for green hydrogen right away while others such as the UK or Canada consider blue hydrogen as a useful, quick to deploy way of scaling-up hydrogen production and developing the hydrogen economy in the midterm. Evidently, natural gas players are lobbying for the promotion of blue hydrogen, hoping it will enable them to keep exporting their resources and to expand the life span of their gas infrastructure investments. The European Parliament has recently exemplified this tension. On May 19th, MPs voted the European Strategy for Hydrogen, acknowledging the usefulness of « low-carbon hydrogen » (including blue H2) in the midterm to favor the deployment of hydrogen in our economies. As a consequence, the Greens voted against the text defending a « green H2 only » position.

Additionally, gas industrial players have constituted consortiums in order to defend what they considered to be NG's place in the energy transition. In 2017, the Gas for Climate initiative was initiated by ten companies including Enagás, GRTgaz or Snam. They wish to « create awareness about the role of renewable and low carbon gas in the future energy system ». They published several reports underlying the opportunity for the constitution of a hydrogen backbone mostly constituted of retrofitted gas pipelines for hydrogen transportation. As a matter of fact, the European Network of Transmission System Operators for Electricity (ENTSO-E) and the European Network of Transmission System Operators for Gas (ENTSOG) have published an electricity and gas joint Scenario Report in close collaboration underlying this interconnexion between the two networks[17]. Through power-to-gas (conversion of excess power to a renewable gas, most likely hydrogen), the two networks will in fact need to become more integrated, leading to the establishment of a new hybrid energy infrastructure. With the development of hydrogen, utilities can contemplate, in the case of massive centralised production of hydrogen at certain points of the network, bringing an element of stability in an environment where renewable energies are often decentralised. In addition, retrofitting gas pipelines and infrastructures clearly has a certain social value, given the massive investments that were previously made in these networks.

It will be necessary to find the right but uneasy balance between on one hand integrating those industrial gas players in order to facilitate the development of a hydrogen ecosystem in the short to medium term and on the other hand making sure their influence does not go as far as impeding the necessary the effectiveness of the ecological transition and the likely complete abandon of natural gas long-term.

[16] Antoine Goutaland and Joël Ruet. L'hydrogène, nouvelle commodité, vecteur énergétique 'magique', ou prescripteur de politiques publiques exigeantes?. The Bridge Tank, 2021.
[17] ENTSOG, ENTSE. TYNDP. Scenario Report, June 2020.

Annex 1 - National hydrogen strategies

AUSTRALIA

- national strategy approved in November 2019 (https://hydrogenrenewablesaustralia.com/wp-content/uploads/2019/12/australias-national-hydrogen-strategy.pdf)
- **Five out of six Australian states published their own hydrogen strategy**
    - **Queensland** (https://www.statedevelopment.qld.gov.au/__data/assets/pdf_file/0018/12195/queensland-hydrogen-strategy.pdf)
    - **South Australia** (https://research.csiro.au/hyresource/policy/australia-and-new-zealand/south-australia/)
    - **Tasmania** (https://www.stategrowth.tas.gov.au/__data/assets/pdf_file/0003/207705/Draft_Tasmanian_Hydrogen_Action_Plan_-_November_2019.pdf)
    - **Victoria** (https://www.energy.vic.gov.au/__data/assets/pdf_file/0021/513345/Victorian-Renewable-Hydrogen-Industry-Development-Plan.pdf)
    - **Western Australia** (https://www.wa.gov.au/sites/default/files/2020-10/wa_renewable_hydrogen_strategy.pdf)
- between 2015 and 2019, the Australian government invested over 146 million dollars in hydrogen (67 million in R&D, 68 million in pilot)
- World first fully integrated hydrogen supply chain => the hydrogen energy supply chain (HESC) pilot project: production, transport to Japan.
- Geoscience Australia estimates about 11% of Australia (872,000 square kilometres) could be highly suitable for renewable hydrogen production (7)
- 3% of Australia's land (262,000 square km) are identified as highly suitable coastal areas for renewable hydrogen production by electrolysis => they estimate it could be used to make more than the global demand predicted by the Hydrogen Council for 2050
- They also consider using carbon capture (CCS)
- Int the national strategy, says Australia intends to build hydrogen hubs in order to benefit from economies of scale.
- The plan establishes a timescale with goals associated:
    - 2025
        - Ideally clean hydrogen production projects are at 100-300MW
    - 2030
        - Clean hydrogen production project is at 500-1000 MW
        - Hydrogen has become cost competitive for most hydrogen applications
- Australia considers that one of the 2030's measure of success would be to be among the top three exporters of H2 to Asian markets

FRANCE

- announced its national hydrogen strategy in September 2020 => "national strategy for the development of low-carbon hydrogen in France
    - (https://www.entreprises.gouv.fr/files/files/secteurs-d-activite/industrie/decarbonation/dp_strategie_nationale_pour_le_developpement_de_l_hydrogene_decarbone_en_france.pdf)
- The hydrogen strategy is based on four types of issues:
    - environmental / ecological,
    - economic (create an industrial ecosystem),
    - energy sovereignty (reduce dependence on hydrocarbons),
    - technological independence
- 2 billion euros investment for H2 within the recovery plan
    - Trajectory up to 2030 => objective of a total of €7bn of public investment
    - 3.4 billion over the period 2020-2023:
        - 54% for the decarbonisation of industry,
        - 27% to develop professional H2 mobility,
        - 19% for R&D support.

- In industry, 900kt/year of carbonated hydrogen is produced. Decarbonising H2 production would therefore contribute to the objective of reducing CO2 emissions by 2030.
- Hydrogen has been identified as a priority among the 11 key markets selected by the Innovation Council on which future investments will focus

- 3 objectives of the strategy
    - Increase the number of electrolysers installed => France has set an objective of 6.5 GW of electrolysers installed by 2030
    - Develop clean mobility, particularly for heavy vehicles (commercial vehicles and trucks, buses, hydrogen trains, and also in the longer term for ships and aircraft) => objective is to save 5 Mt of CO2 by 2030.
    - Build an industrial sector => generate between 50k and 150k direct and indirect jobs in France
- At the end of 2020, call for projects (AAP) "territorial hydrogen hubs" by ADEME with €275M by 2023
- In 2021, following the example of the European battery project, construction of a IPCEI (important project of common European interest)
    - France will reserve an exceptional financial allocation of €1.5 billion for this action

JAPAN

- Published the Basic Hydrogen Strategy in December 2017
    - (https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf)
    - (https://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf)
- issued a New Strategic Roadmap for Hydrogen and Fuel Cells in march 2019 that renewed the Basic Hydrogen strategy:
    - (https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf)

NORWAY

- published the Norwegian hydrogen strategy in June 2020
    - (https://www.regjeringen.no/contentassets/40026db2148e41eda8e3792d259efb6b/y-0127e.pdf)
- Speaks both of electrolysis and CCS for clean hydrogen
- Recognizes that H2 is not competitive currently compared with fossil energy sources => mentions emission pricing (carbon pricing) as a way to promote low emission solutions
    - The electricity used to produced H2 through electrolysis is moreover exempt from the consumer tax on electricity in order to improve its competitiveness
- Among the 52Mt of CO2e Norway emitted in 2018, 27% came from oil and gas extraction
- Norway currently meets around 3 per cent of the global demand for natural gas and its exports exports represent around a quarter of European gas consumption
    - In consequence, even though they say it is not a economically viable solution for now, Norway remain very attentive to blue hydrogen prospects in the long term
    - It says that « The Norwegian authorities will work to ensure that natural gas reforming combined with CCS can compete on equal terms with hydrogen from water electrolysis in the European energy market »
    - Blue hydrogen can be an alternative to natural gas once the hydrogen infrastructures will have developed and demand increased

PORTUGAL

- Approved its National Hydrogen Strategy in May 2020 (« Portugal national hydrogen strategy (EN-H2). A new ally for the energy transition in Portugal ») (https://kig.pl/wp-content/uploads/2020/07/EN_H2_ENG.pdf)
- Portugal has high level of renewable penetration
    - RES represents 30.3% of final energy consumption with a 47% 2030 target
- H2 is seen as an « element of incentive and stability for the energy sector », as a « sustainable pillar »
- Transport and industry are the two main sectors the Portuguese hydrogen strategy focuses on
- Portugal appears to present very favorable conditions for the development of clean hydrogen via electrolysis
    - Proximity to off take with the existence of industries
    - Access to water sources

  - High availability of renewable sources
  - Land availability

The EN-H2 objectives for 2030 are the following:

- 7000M€ investment in H2 production projects
- 900M€ support to investment and production
- 300 to 600M€ reduction in natural gas imports
  - By having installed a 2GW electrolyser capacity by 2030

SPAIN

- On the 6th of October 2020, the Spanish government approved the « Hoja de ruta del hidrogeno: una apuesta por el hidrogeno renovable » (« Hydrogen Roadmap: a commitment to renewable hydrogen »)
  - Roadmap in spanish: (https://www.miteco.gob.es/images/es/hojarutahidrogenorenovable_tcm30-525000.PDF)
  - Executive summary in English: (https://www.miteco.gob.es/images/es/h2executivesummary_tcm30-513831.pdf)
  - Hydrogen roadmap October 2020 (ppt presentation): (https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/presentations/02.03.02_mf34_presentation-spain-hydrogen_roadmap-cabo.pdf)
- H2 is presented as part of the solution to achieve climate neutrality
- H2 is seen as mostly relevant in the following sectors:
  - long distance transport
  - hydrogen-intensive industrial sectors
  - Decarbonization of industrial sectors that are using gaz and coal to produce hydrogen (grey and brown H2) by adopting green H2 capacities (through electrolyses) is seen as having great potential in the short term
  - for sector coupling and energy storage
  - For the heat sector (where electrification is not the most competitive solution)
- the Spanish government mostly sees H2 as an alternative solution to electrification when it is not possible in the short to middle-term
- the Spanish roadmap provides two visions: Vision 2030 and 2050
- Vision 2030:
  - Aims at a 4GW installed electrolyser capacity (with an intermediate goal of 300 to 600 MW of electrolyzers by 2024)
  - Mobilization of €8,9 billion of investment during the 2020-2030 period
  - In the industry => By 2030, the Spanish government has an objective of at least 25% of all H2 used in industries to be renewable H2
  - In the transport sector => aims at 100 to 150 public access hydrogen stations ; 150 to 200 fuel cell buses ; 5,000-7,500 light and heavy-duty fuel cell vehicles for freight transport
- In November 2020, the Government announced that it would allocate €1.5bn to boost the use and production of renewable hydrogen by 2023 through the European Recovery Instrument ("Next Generation EU")
- The hydrogen roadmap intends to identify the challenges and opportunities for robust development of renewable hydrogen in Spain

CANADA

- released its first hydrogen strategy report in December 2020 (« Hydrogen strategy for Canada. Seizing the opportunities for hydrogen. A call to action ») (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf)
- Canada is one of the top 10 H2 producers in the world today
- Estimate that clean hydrogen has the potential to deliver up to 30% of Canada's end use energy by 2030
- The three main end-uses of H2 mentioned by the strategy are:
  - Fuel for transportation
  - For power production (H2 providing storage and providing stability to the grid)
  - For heat
  - As feedstock for the industry
- they also explicitly mention H2 as an export product

By 2050 Canada aims:

- To produce 20Mt of low carbon intensity H2 per year (4Mt/year in 2030)

- To have up to 30% of Canada's energy delivered in the form of H2 (6.2% in 2030)
- to be one of the top 3 global clean H2 producers
- To have more than 50% of the energy currently supplied by natural gas being supplied instead by H2 in NG pipelines through blending and in dedicated H2 pipelines
- 5 million fuel cell EVs on the road
- To have 350k sector jobs

CHILE

- Published its nation hydrogen strategy in November 2020 (« Chile's national green hydrogen strategy. Chile, a clean energy provider for a carbon neutral planet »):
    - (https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf)
- Chile has a natural comparative advantage for renewable resources. The country has:
    - 509+GW of concentrated solar power
        - North Chile has the most powerful solar radiation on the planet
        - Solar generation in the central part of Chile is already more competitive than fossil-powered electricity generation
    - 191+GW of onshore wind
- according to the IEA, **Chile has a potential for 160Mton of green hydrogen production each year** (for scale, in its New energy outlook 2020, BloombergNef anticipates that H2 could represent up to 25% of 2050's final global energy demand, which would amount to 800 Mton of H2).
- McKinsey and Company estimates:
    - that green hydrogen produced in the Magallanes Region will achieve the lowest levelized cost of production on the planet by 2030.
    - The consulting firm adds that by 2050, Chile could generate $24 billion in exports and $9 billion in domestic applications (with a cumulative necessary investment of $330 billion and 300GW of associated renewable capacity (for scale the 19 nuclear power plant in France have a 60,6GW capacity)).

Chile's national hydrogen strategy is cut in 3 waves:

- **Wave 1 => From 2020 to 2025**: will include domestic usage with existing domestic demand (for energy and H2)
    - Local hydrogen will be kickstarted locally by investing in 6 prioritized H2 applications: oil refineries, ammonia, mining haul trucks, heavy-duty trucks, long-range buses, blending into gas and grids
        - The goal is especially to substitute grey hydrogen production for refineries with green hydrogen and to replace ammonia imports by local production
    - Chile wants to have reached a 5GW electrolysis capacity
- **Wave 2 => from 2025 to 2030**: Chile will start export activities and extend local uses by leveraging the domestic base it created
    - Establishment of an industry of green ammonia production and exportation
    - Chile wants to have reached a 25GW electrolysis capacity
- **Wave 3 => 2030 onwards**: opening of new export markets in the long term. Chile becomes a global supplier of clean fuels.
    - As other nations operate their ecological transition, demand for green H2 will ramp up and Chile will be able to proceed to a massive scale-up of production.
        - Europe is seen as the main market size for green ammonia exports in 2050
        - both Japan, Korea on one side and Europe on the other are seen as the biggest market sizes for green H2 exports in 2050

The EU

- A hydrogen strategy for a climate-neutral Europe, July 2020
    - French (https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:52020DC0301&from=EN)
    - English (https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf)

- Hydrogen EU roadmap:
    - **First phase => from 2020 to 2024**: install 6GW renewable electrolysers capacity in the EU and the production of up to 1Mt of renewable hydrogen
        - Decarbonize existing hydrogen production
        - Infrastructure for carbon capture and use of CO2 will additionally be required to facilitate certain forms of low carbon hydrogen
    - **Second phase => from 2025 to 2030**: H2 needs to become part of an integrated energy system
        - Strategic objectif of at least 40GW of renewable electrolysers capacity in the EU
        - Produce 10 Mt of renewable hydrogen
        - Expected applications are: steel-making, trucks, rail, maritime transport, and other transport modes
        - Hydrogen will start having a stabilizing role and bringing flexibility => balancing a renewable-based electricity system
        - Hydrogen to store electricity
        - Development of local hydrogen valleys => hydrogen clusters / hubs
    - **Third phase => from 2030 towards 2040**: renewable H2 should reach maturity and be deployed at large scale
        - A massive scale up of renewable electricity will be necessary => a quarter of renewable electricity might be used for renewable H2 by 2050 (based on the 1.5 TECH long-term decarbonisation scenario COM (2018))
- the EU hydrogen strategy estimates that investments in electrolysers could range between €24and €42billion by 2030.
- Additionally, €220-340 billion would be required to scale up and directly connect 80-120 GW of solar and wind energy production
- €11 billion will be needed to install carbon capture and storage on existing plants
- €65 billion for hydrogen transport, distribution, storage, refueling stations

=> All of these investments would total up to €458 billion by 2030.
=> From now to 2050, investments in production capacities would amount to €180-470 billion in the EU

Furthermore, investments will also be required to adapt end-use sectors to H2 consumption and H2-based fuels:

- converting a steel installation to hydrogen costs between €160 to 200 million
- rolling out an additional 400 small-scale hydrogen refuelling stations (compared to 100 today) could require investments of €850-1000million

Part of the hydrogen EU strategy is also the establishment of the European Clean Hydrogen Alliance will play the role of facilitating and implementing the strategy's actions as well as supporting investments.
Moreover, the Alliance will help establishing IPCEI projects (Important Project of Common European interest) along the value chain.

Carbon pricing with the Emission trading system (ETS) is seen as a supportive policy framework in order to favor the scaling up of H2.

GERMANY

- Germany's national hydrogen strategy was approved in June 2020: (https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6)
- Germany's hydrogen strategy's first step is the establishment of a strong hydrogen domestic market
- The Federal Government expects that around 90 to 110 TWh of hydrogen will be needed by 2030
    - to cover part of this demand, Germany plans to establish up to 5 GW of generation capacity which correspond to 14TWh of green hydrogen production => will require 20 TWh of renewable based-electricity
- has the objective to add 5 GW of capacity for no later than 2040
- Recognises that most hydrogen consumption will have to be imported

- the aim is like usual to use hydrogen in hard to electrify sectors such as air and maritime transport, some industrial products, heavy-duty transport.
    - Around 55TWh of H2 is used for industrial purposes in Germany (with 7% of demand met by electrolysis)
        - Industrial demand for H2 should increase by 10TWh by 2030
        - It is estimated that 80 TWh of green H2 will be needed to completely decarbonize steel production by 2050.

The German national hydrogen strategy is targeted at:

- hydrogen production => to enable the market penetration and export of H2 technologiques, developing a domestic market is indispensable
- Industrial sector
- Transport
- Heat market

- Action plan:
    - **Phase 1 => 2020-2023:** start domestic market ramp-up
        - For this first phase, 38 mesures are layed out concerning
            - hydrogen production ;
            - fields of applications (transport, heat, industrial sector) ;
                - They intend to have a 2GW installed electrolyser capacity
                - €3.4 billion in grants for the construction of a refuelling and charging infrastructure from the Energy and Climate Fund (ECF)
            - infrastructure / supply ;
            - research, education, innovation ;
            - action at European level ;
            - international H2 markets ;
            - external economic partnerships.
    - **Phase 2 => 2023-2030:** strengthen market rap up domestically and extend internationally

SCOTLAND

- Scotland published its first Hydrogen Policy Statement in December 2020: (https://www.gov.scot/publications/scottish-government-hydrogen-policy-statement/)

- The UK will publish its H2 strategy in 2021 with a 5GW objective of low carbon hydrogen by 2030
- Scotland will publish its H2 action plan in 2021
    - will be supported by 100 million pounds in investment between 2021 and 2026.
    - Has an ambition of 5GW of renewable and low carbon hydrogen by 2030 and at least 25GW by 2045

- the policy statements lays out three steps:
    - In the 2020s => accelerating market demand (for transport and industrial applications most notably) and establishing the policy network. Develop low carbon hydrogen
    - In the 2030s => develop production at scale, develop the value chain for renewable H2
    - By 2045 => global expansion => production of lowest cost H2 for domestic use and export. Development of international hydrogen refueling hubs. A north sea hydrogen pipeline infrastructure must connect Scotland to Europe

UKRAINE

- In response to a request from the Ministry of Energy of Ukraine, UNECE published a « draft roadmap for the production and use of hydrogen in Ukraine » in march 2021: (https://unece.org/sites/default/files/2021-03/Hydrogen%20Roadmap%20Draft%20Report_ENG%20March%202021_0.pdf)

- Ukraine enjoy some of the most abundant renewable resources in Europe
- one of the significant barriers to the use of hydrogen in Ukraine is the outdated and non-

harmonized regulatory and technical safety regulations

- The Energy Strategy of Ukraine until 2035 stipulates the increase of a share of "green"energy up to 25% in the energy mix of the country
- The geo-strategic national security aspect is crucial in Ukraine's energy strategy + a need to reduce oil imports

Milestones:

- 2019-2021 = preparatory phase
- 2022-2025 = according to the first phase, if possible, scale up to 500MW
- 2026-2030 = attain 3-4GW if possible, installed electrolysis capacity

THE NETHERLANDS

- government strategy on hydrogen: (https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen)
- On 30 March 2020, the Dutch government announced the Dutch national hydrogen strategy (DNHS)
- The primary focus is on green H2 but blue H2 is seen as a contribution to the development of the hydrogen ecosystem at the beginning

NEW ZEALAND

- Published its Vision and Roadmap for Hydrogen in September 2019
- Published a Green paper entitle « A vision for hydrogen in new Zealand »: (https://www.mbie.govt.nz/dmsdocument/6798-a-vision-for-hydrogen-in-new-zealand-green-paper)

Government which have launched projects without them being national plans:

INDIA

- On February first 2021, the Finance Minister Nirmala Sitharman announced launching a National Hydrogen Mission

MOROCCO

- Morocco launched the national green hydrogen cluster GreenH2 Maroc

SOUTH KOREA

- South Korea enforced the world's first hydrogen law from 5th February 2021
- Announced a hydrogen economy roadmap in January 2019

The USA

- US department of energy's hydrogen strategy, « Enabling A Low-Carbon Economy », July 2020: (https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf)
- Department of energy hydrogen program plan, November 2020: (https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf)
- Currently, 99% of U.S. hydrogen production is sourced from fossil fuels, with 95% from natural gas by SMR and 4% by partial oxidation of natural gas via coal gasification.
- Only 1% of U.S. hydrogen is produced from electrolysis.
- The US produces more than 10Mt H2 annually while global hydrogen production is approximately 70Mt.
- hydrogen production using natural gas through gasification and methane reforming with CCUS is seen as the lowest cost source of large-scale H2 for the foreseeable future

ANNEX 2 - Hydrogen reports and articles recently published

IRENA - Green hydrogen supply: a guide to policy making - May 2021
(https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Green_Hydrogen_Supply_2021.pdf)

- each year around 120 Mt of H2 are produced globally (fossil fuel accounts for 95% of global production)
- 75% of H2's consumption comes from oil refining and for ammonia and methane synthesis
- In its World Energy Transitions Outlook, IRENA estimates that, according to the roadmap, by 2050, green H2 will reach about 400Mt (= 49 EJ)
    - That would require a 5Tw installed electrolyser capacity by 2050
- in 2021, installed electrolyser capacity is around 200 MW
- In 2019, the world's electrolyser manufacturing capacity was about 135 MW/year (IRENA, 2020b) and is expected to rise to 3.1GW per year by the end of 2021 (BNEF, 2021).
- To achieve total installed electrolyser capacity of 5 TW by 2050, as projected by IRENA (2021), global manufacturing capacity of 130-160 GW/year will be needed (50 times the expecting manufacturing capacity of 2021).
- electrolysis efficiency is around 66%: therefore to produce 1 MWh of hydrogen (or 30kg) around 1.5 VMWh of electricity are needed
- this report examines the policies needed to support the production of green hydrogen by water electrolysis its transport to locations where it will be consumed, and the options for storage

Structure of the report

- **chapter 1**: examines the main barriers to the advancement of green hydrogen production and the development of the necessary infrastructure for its transport and storage
    - Supply barriers:
        - Cost barriers: Green hydrogen needs to reach cost parity with grey H2, Production costs, Conversion costs, Transport costs, Storage costs
    - sustainability issues
        - There is a challenge to make sur that electrolyser consumption of green electricity does not increase fossil fuel consumption elsewhere or displaces more efficient uses of renewable electricity => **principle of additionality** = « if there are other productive uses for the electricity being generated from renewable sources, that electricity should not be diverted from those uses to produce green hydrogen. Instead, green hydrogen should be produced only from additional renewable energy capacity that would not otherwise be commissioned and electricity that would not be otherwise consumed. »
        - This risk is patent for developing countries
        - Converting and transporting H2 can also create additional CO2 emissions
            - For example, the main source for pipelines is the energy consumption for compression => a pipeline transporting 40 tonnes per day for 400 km would have emissions in the order of 0.1 kgCO2/kgH2 (Wulf et al., 2018)
            - Most of the time, these emissions linked to transport of H2 are not calculated
    - lack of clarity regarding future demand
        - No real demand exists yet for products made using green H2 compared to grey H2
        - For now, demand is irrespective of the origin of the feedstock
        - Moreover, hydrogen is not publicly traded for the moment
    - unfit power systems structures
    - Lack of technical and commercial standards

- **Chapter 2**: policy options => provides a map of the policies needed in the future and the policies options. Presents national examples and case studies.

=> policy options are divided into sectorial targets for which policy options are layed out:

    - Electricity consumption
        - Sustainability assurance measures
    - Electrolysis
        - Capacity targets
        - Manufacturing capacity support
    - Green hydrogen off take
        - For price
            - Fiscal incentives
            - Auctions
        - for demand
            - Virtual blending
            - International agreements
    - Infrastructure
        - Creation of standard
        - Financing

(I wrote some policy measures as examples)

- **Chapter 3**: Policy recommendations are separated into three stages:
    - 1/ technology readiness
    - 2/ market penetration
    - 3/ market growth

IRENA - Decarbonising end-use sectors: Practical insights on green hydrogen - may 2021
(https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Coalition_Green_Hydrogen_2021.pdf)

Summarizes the end uses for H2 and the market projections as well as policies that can be implemented to favor hydrogen's uptake.
It gives recommendations to governments to proceed to the development of H2.
Finally, it present case studies of electrolysers H2 projects.

IEA- Hydrogen in North-Western Europe, A vision towards 2030 - April 2021
(https://iea.blob.core.windows.net/assets/ccbc3b01-7403-4c15-90a2-af11dfb92c62/Hydrogen_in_North_Western_Europe.pdf)

North western Europe appears as strategic region for future H2 development and production:

- concentrates today 5% of global hydrogen demand and 60% of European demand, 82% of water electrolysis capacity, 100% of CCUS projects (2), 88% of FCEVs
- is home to the largest industrial ports in Europe.
- has a developed natural gas infrastructure connecting the ports with industrial hubs => this infrastructure is highly strategical for future H2 transport.
- Moreover, the north sea has underutilized potential in RE, especially offshore wind. Hydrogen will therefore be important as a storage option via electrolysis to keep excess production
    - The north sea has also large underground carbon dioxide storage (an option for CCS)

The IEA defends four ranges of measures:

- develop cooperation on H2 in the region
- Develop an integrated regional market (common regulatory framework and standards, support mechanisms to reduce risk)
- Develop supporting schemes to advance technological frontiers
- Design a strategy to address emissions from existing hydrogen producing assets

=> there is a focus on the different national strategies presented by the north western states (Germany, Danemark, France, Belgium, Netherlands, norway, UK,

Additionally, north western countries have been co-operating a joint strategy for north-western Europe. The joint political declaration of The Pentalateral Energy Forum, signed 11 May 2020, affirmed such international collaboration on hydrogen

The reports estimates that without further governmental action in north western Europe and the establishment of an adapted framework, hydrogen production will remain based predominantly on unabated fossil fuels, accounting for 85% of dedicated production by 2030

- in the current policy landscape (baseline scenario)
    - hydrogen demand in the region will drop slightly from today's level
    - a shift towards new applications in industry and mobility is expected
    - annual demand should be around 400 kt H2 per year by 2030
- however in an accelerated scenario, total hydrogen demand in the region could grow by a third, reaching more than 8.5 Mt per year by 2030

Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques - Les modes de production de l'hydrogène (note n°25) - Avril 2021
(https://www2.assemblee-nationale.fr/content/download/342294/3355536/version/2/file/OPECST_2021_0032_note_hydrogene_.pdf)

- state of play of hydrogen production and possibilities with renewables
- Considers that, apart from electrolysis by renewables, other decarbonised modes of H2 production should not be abandoned
    - Mentions in particular two solutions that are more affordable and more operational:
        - Methane pyrolysis (where the carbon remains in solid form)
        - Production of hydrogen from biomass
- Insists that H2 is not a miracle solution
    - Low efficiency
    - Delicate and expensive distribution
    - Covering the current H2 needs of industry (70Mt or 420GW) with renewable hydrogen would require the commissioning of more than one million new wind turbines or 56 million hectares of photovoltaic panels. Or 400 new 1GW nuclear reactors.

The note recommends the use of CCS for H2 production in addition to the development of hydrogen by electrolysis from renewables and nuclear power plants.
It also recommends thinking about carbon pricing. It speaks of a price of 250€/t to allow green or yellow hydrogen to compete with grey H2. A price between €100 and €200 would at least encourage CCS.
Finally, it advocates support for research.

The note concludes that "a significant increase in our low-carbon electricity production capacity can lead to a revival of the nuclear sector".

Hydrogen Europe - Hydrogen act, Towards the creation of the European hydrogen economy - April 2021
(https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/2021.04_HE_Hydrogen-Act_Final.pdf)

The report proposes a « Hydrogen Act » that, in the context of the EU hydrogen strategy, proposes an umbrella framework in order to harmonize and integrate the different policies and legislations.
=> it focus on infrastructure and market aspects with two parts:

- a **hydrogen infrastructure act** => establishes a framework for the conversion of natural gas infrastructures into multifunctional hydrogen infrastructures
    - Building H2 valleys
    - Building a pan-europeans backbone infrastructure
- a **hydrogen market act** => framework to allow a clean hydrogen market to emerge
    - Stimulation of H2 production and demand through political measures (auctions for the former for example and quotas, investment support for the latter)
    - GOs

=> both acts are themselves organized in **three overarching phases** that are layed out between 2020 and 2050.

- a kick-start phase (2021-2026) =>
    - foundation of a European H2 economy
    - production of 1 million ton of clean hydrogen by the end and at least 6GW of electrolyser capacity
    - The focus is to demonstrate scalability of H2 projects
    - State aid rules must be relaxed temporarily in order to facilitate hydrogen growth
- a ramp-up phase (2025-2035) =>
    - eventually achieve commercial competitiveness of hydrogen.
    - **Hydrogen Guarantees of Origin (GOs)** needs to have been established in order to provide transparency on the GHG foot-print of H2.
    - hydrogen will require some sort of regulatory support, including for example throughtariffs, auctions/tenders, quotas, investment support, tax relief
- a market-growth phase (2035-2050)

Energy transitions commissions - Making the hydrogen economy possible: accelerating clean hydrogen in an electrified economy - April 2021
(https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf)

A big overall summary of the interest of hydrogen, the challenges and required actions and investments for scale up and the policies and industrial plans towards 2030-2050.

3 chapters:

- Chapter 1: A vision for 2050: Hydrogen's role in a zero-carbon, deeply electrified economy
    - Summary of is hydrogen utility, challenges, its part in net zero, the options for net zero production, storage options etc.
- Chapter 2: Scale-up challenges, required actions and investments
    - Comparison costs with fossil fuel produced H2 and paths to 2050, investment needs
- Chapter 3: Critical policy and industry actions in the 2020s
    - For example carbon pricing, demand side and supply side support, hydrogen cluster developments

Florence School of Regulation - A snapshot of Clean hydrogen Costs in 2030 and 2050 - April 2021
(https://cadmus.eui.eu/bitstream/handle/1814/70971/210426%20PB_Snapshot_Glachant&Dos%20Reis.pdf?sequence=1)

- divide the different hydrogens into two:
    - the "dirty hydrogens" – responsible for GreenHouse Gas (GHG) emissions
    - the "cleaner hydrogens" – with no or little GHG emissions
- the relative costs of the hydrogens are a way to gauge their potential
    - But the cleaner hydrogen have not reach maturity
    - Therefore projection costs varies greatly

Horizon 2030 for costs of clean H2:

- two main possibilities:
    - Electrolysers, fed with water and "clean" electricity (for the horizon 2030, the only mature technologies they see here is electrolysis alimented by wind turbines or PVs).
    - Steam Methane Reduction, with Carbon Capture and Storage (CCS), fed with natural gas

=> at horizon 2050, costs are mostly speculative.

NB: *According to Platts hydrogen price assessments, conventional hydrogen prices in October 2020 averaged $1.25/kg in the US Gulf Coast versus $2/kg in California.*
(Dans l'ensemble les prix varient à 2-3€/kg).

Table 2 reports the costs and key cost drivers.

Technologies	Electrolyser & solar PV	Electrolyser & offshore wind	Electrolyser & electricity from regional decarbonised power mix	SMR + CCS & 'sustainable' biomethane	Methane pyrolysis with CCU & 'sustainable' biomethane
Costs – 2050 (Note: LHV used for conversion)	0.6-1.7 EUR/ kgH2 18-52 EUR/ MWh	1.4-2.1 EUR/ kgH2 42-64 EUR/ MWh	1.2-2.7 EUR/ kgH2 36-82 EUR/ MWh	2.4-4.3 EUR/ kgH2 73-130 EUR/ MWh	1.7-2.8 EUR/kgH2 51-85 EUR/MWh
Cost driver 1	Electricity price 4-20 EUR/MWh	Electricity price 30-40 EUR/ MWh	Electricity price 28-62 EUR/ MWh	Biomethane price 30-60 EUR/ MWh	Biomethane price 30-60 EUR/ MWh
Cost driver 2	Efficiency- LHV 74-76%			Efficiency-LHV 69-70%	Efficiency – LHV 55%
Cost driver 3	Full load hour factor 16%-40%	Full load hour factor 45%-60%	Full load hour factor 90%-99%	Overnight CAPEX 1088 EUR/kW-H2	Costs reduction (selling by-product solid carbon) 0.25-0 EUR/kg solid carbon
Cost driver 4	Electrolyser CAPEX 68-110 EUR/kWel			CO2 transport & storage cost 17-55 EUR/tCO2	CAPEX 1261 EUR/kW-H2

Table 1 shows 2030 costs and four key cost drivers (free of any "regulatory" costs or subsidies).

Technologies	Electrolyser & solar PV	Electrolyser & offshore wind	SMR + CCS & natural gas
Costs – 2030 (Note: LHV used for conversion)	0.9-2.3 EUR/kgH2 27-70 EUR/MWh	1.7-2.8 EUR/kgH2 52-85 EUR/MWh	1.2-2.8 EUR/kgH2 36-85 EUR/MWh
Cost driver 1	Electricity price 10-25 EUR/MWh	Electricity price 36-46 EUR/MWh	Natural gas price 3–32 EUR/MWh
Cost driver 2	Efficiency- LHV 69-75%		Efficiency-LHV 69%
Cost driver 3	Full load hour factor 15%-38%	Full load hour factor 40%-57%	CAPEX 1155 EUR/kW-H2
Cost driver 4	Electrolyser CAPEX 98-200 EUR/kWel		CO2 transport & storage 1-55 EUR/tCO2

Institute of Energy Economics at the University of Cologne. The Oxford institute for energy studies - Contrasting European hydrogen pathways. An analysis of differing approaches in key markets - march 2021
(https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/03/Contrasting-European-hydrogen-pathways-An-analysis-of-differing-approaches-in-key-markets-NG166.pdf)

The paper examines the intended hydrogen pathways in six key Western European markets (France, Germany, Italy, Netherlands, Spain, and the UK) and compare the approaches being developed in each of those countries.

Policy drivers
Despite all having hydrogen national strategies, there are differences in the policy drivers that the states are presenting:

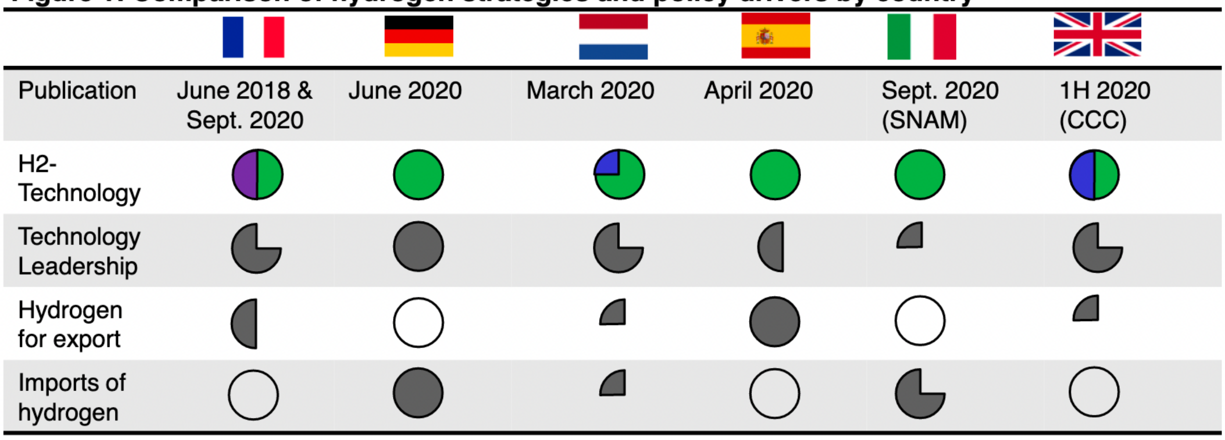
- all countries see a significant long-term role for green hydrogen, made via electrolysis using renewable electricity.
    - Most countries go for full-on green h2 from the start
    - the UK and the Netherlands see blue H2 as important for H2 scale up and making the transition (blue H2 as a partial interim measure).
    - France is in a unique position with the importance of the nuclear produced electricity in its mix that gives great importance to purple h2.

Regarding imports exports:

- Germany intends to be a centre of excellence to export the technology globally. However, it gives great importance to imports to match its demand knowing that it won't have enough capacity to produce h2 domestically to respond to all national demand.

- At the other extreme, Spain, has great potential for large quantities of low-cost solar power and consequently sees itself as a potential significant exporter of hydrogen

Figure 1: Comparison of hydrogen strategies and policy drivers by country



Source: Authors' analysis

The author argues that it will be more important to decarbonise the existing hydrogen production first (most notably refineries and ammonia production) and thereby increase the scale and reduce the costs of low-carbon hydrogen production.

Says it is also important to asses for each sector the real advantage of H2 compared to electrification for example.

Demand

The expected demand for 2030 and even more for 2030 presents high uncertainty but green H2's importance in overall demand by sector remains very law:

- for refinery, green H2 is expected to match 11% of overall refinery demand in France, 5% in Germany, 13% in the Netherlands in the low scenarios and the maximum in the high scenarios is 22% in Spain
- For ammonia production, the highest percentage of demand that will be match be green H2 is 5%
- For steel 13% in Germany (and 2% for all the other countries)

=> we see that even in the sectors that simply have to substitue grey H2 for green H2, green H2 demand will remain very limited in 2030 compared to overall demand of the sector (no more that 1/5th).

Table 1: FCH JU assumed penetration in 2030 of low carbon hydrogen by country and sector

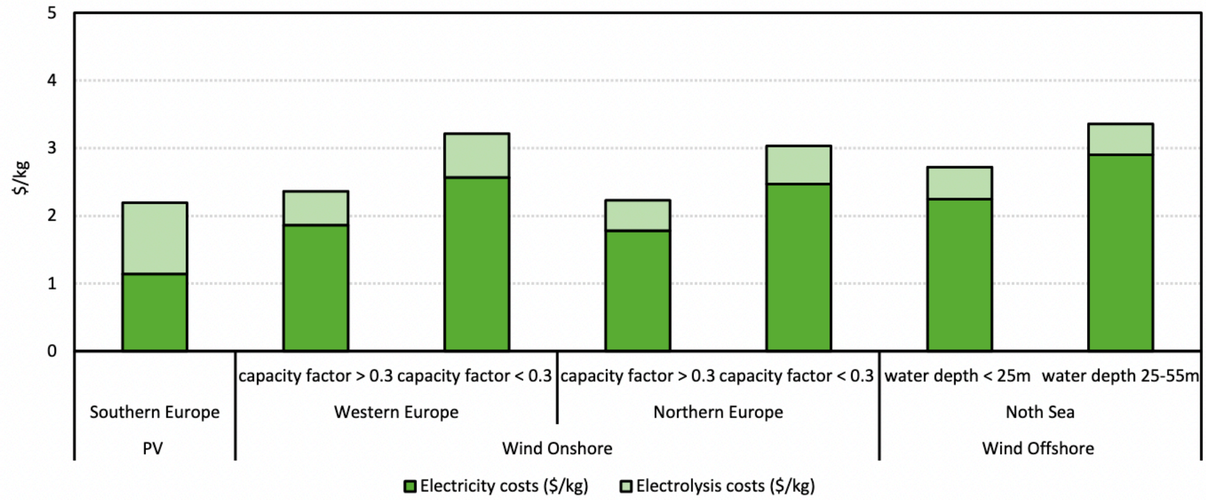
	Refinery	Ammonia	Steel	Other feedstock	Buildings	Road Transport	Power
Low scenario							
France	11%	0%	0		0,75%	1%	0%
Germany	5%	0%	4%		0,75%	1%	0%
Netherlands	13%	0%	0	1%	0,75%	1%	0%
Spain	24%	0%	0		0,75%	1%	0%
United Kingdom	5%	0%	0		0,75%	1%	0%
Italy	7%	0%	0		0,75%	1%	0%
High scenario							
France	19%	5%	2%	1,5%	7,5%	2%	0%
Germany	14%	5%	13%	1,5%	7,5%	2%	0%
Netherlands	20%	5%	2%	1,5%	7,5%	2%	0%
Spain	22%	5%	2%	1,5%	7,5%	2%	1%
United Kingdom	13%	5%	2%	1,5%	7,5%	2%	0%
Italy	16%	5%	2%	1,5%	7,5%	2%	0%

Source: Authors' analysis of FCH JU data

Supply

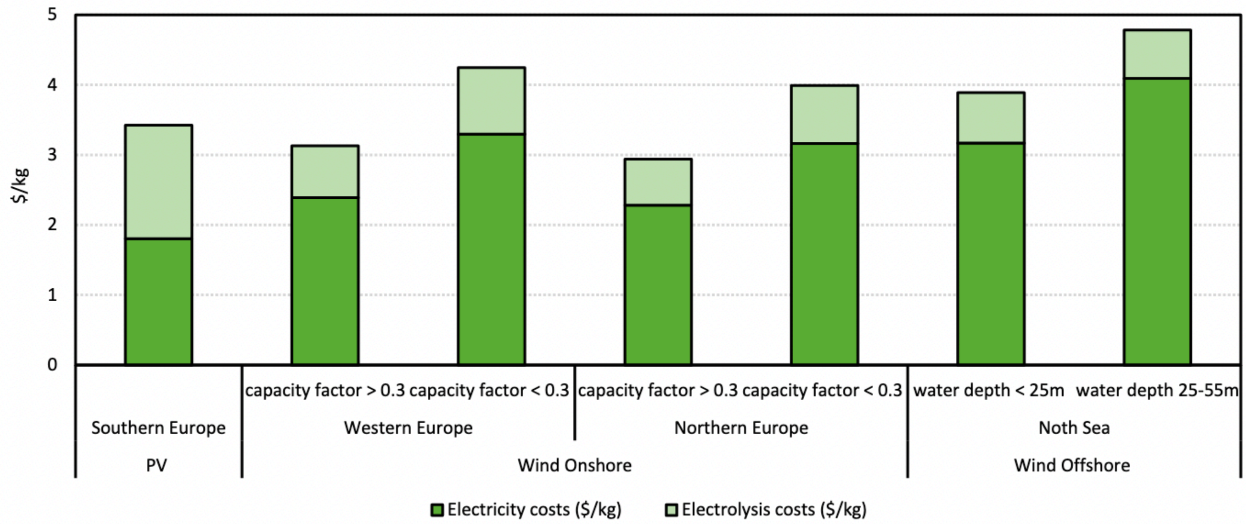
LCOH = levelized hydrogen costs

Figure 5: LCOH for green hydrogen production for selected RES technologies and regions by 2050



Source: Brändle et al, 2020

Figure 4: LCOH for green hydrogen production for selected RES technologies and regions by 2030



<u>Options for supply by electrolysis of water are</u>:

- **electricity supply from dedicated plants**
  - Advantages and disadvantages:
    - main advantage => no electricity grid connection is necessary
    - may help reduce bottlenecks within the electricity grid from volatile RES feed-in

- The main disadvantage is the high production costs or the levelized hydrogen costs (LCOH)
- Costs:
  - Cost of green H2 = levelized cost of electricity generation (LCOE) + costs for the electrolysis (OPEX = dépenses d'exploitation + CAPEX = dépenses d'investissement)
  - Costs of electrolyser plants and of renewable electricity are expected to decline, which will make green H2 more and more competitive
  - LCOE price is expected to be lower for PV but wind has higher capacity factors, especially offshore wind
    - Therefore, electrolysis can be utilized more intensively in combination with wind-based electricity
- geographical perspectives:
  - southern countries (Spain and Italy) ave the best potential to become large-scale producersof RES-based hydrogen, due to a large and comparable low-cost PV-potential
  - In Central European countries (Germany, Netherlands, UK) PV will only play a minor role but have some good locations for onshore wind (but the are potential remains limited)
    - The north sea has high capacity factors and considerable area potential
    - But the LCOH of offshore-based hydrogen is high
  - among the countries examined, France has the highest onshore wind potential + with nuclear may benefit from low cost, nuclear-based H2 production

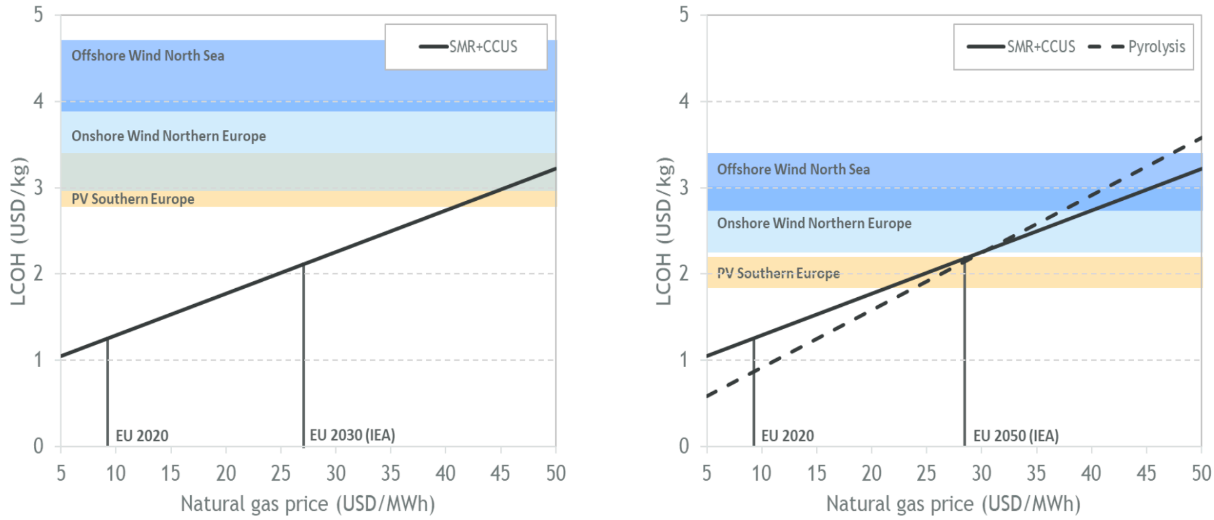
- **Electricity supply from the grid**
  - Advantages:
    - main advantage of this option is that running the electrolysis does not depend on RES capacity factors => the electrolysis can run at higher full load hours, resulting in lower unit capital costs
    - Additionally, H2 production can take place close to demand centres which avoids transportation costs
  - disadvantages
    - Electricity transportation has a lower energy density
    - Furthermore, it is necessary to ensure that grid electricity supply has low carbon intensity, which is not the case for most of the countries under consideration
  - electricity used for H2 production is exempt from taxes and levies in certain countries
    - In Germany, the electricity for electrolysis is free of grid charges for twenty years
    - In France, operators of electrolysis plants do not have to pay electricity tax
    - It will be necessary to create a level playing field within Europe and to guarantee that the electricity used by electrolysis comes from RES or is low-carbon, exemptions should be harmonized and linked to specific requirements, which are similar to those mentioned in the Renewal Energy Directive (REDII)

- **Natural gas-based hydrogen with carbon capture**
  - it is clear that particularly until 2030, RES-based hydrogen will not be competitive if natural gas prices increase as predicted by the IEA
  - In the long run, around 2040, only PV-based hydrogen production in Italy and Spain would be competitive with gas-based, low-carbon hydrogen

  - offshore storage in the north sea is the most likely option

- In addition to the countries covered in this report, other North Sea neighbours like Norway (29,188 $MtCO_2$) or Sweden (14,900 $MtCO_2$) have enormous, identified CO_2offshore storage potential that European countries could use

Figure 6: Comparison of natural gas-based and RES-based hydrogen production in 2030 (left) and 2050 (right) based on Brändle et al.[22]



The authors say that they « remain unconvinced of the logic for significant investment in hydrogen from electrolysis as long as marginal incremental power generation is provided by fossil fuels. It would be more logical to focus on blue hydrogen initially, until around2030 when there should be sufficient large-scale renewable power generation to justify significant investment in electrolysis ».

UK HFCA - The case for hydrogen, UK hydrogen and Fuel Cell association position paper - February 2021
(http://www.ukhfca.co.uk/wp-content/uploads/Green-Hydrogen-final-21-02-21.pdf)

- estimates the UK can deploy 10GW of green H2 by 2030, 80GW by 2050
- Estimates that a price target of 2pounds / kg (2,33€) on average for green H2 is achievable by 2030
- The UK can become a green hydrogen exporter
- Considers methane reforming and pyrolysis have a place in producing low carbon H2 (that the report considers as green H2 even for blue H2 in this case).
- According to analysis conducted by the Hydrogen Taskforce, a commitment to hydrogen by the government and supported by appropriate measures, could create over 74,000 jobs and generate up to £18billion of GVA for the UK per annum by 2035
- According to the National Grid Future Energy Scenario (FES) 2020, UK green hydrogen capacity from electrolysis, and other Net Zero hydrogen, could grow from around 700,000 tonnes to 7.4 million tonnes per year by 2050, which represents a total growth of 90% and 1100% from current installed capacity.
    - An additional 250TWH of renewable electricity will need to be generated to meet this green hydrogen demand in the most ambitious scenario.

- the note provides examples of policies to support development of green h2 in the UKs
    - Research conducted by BNP Paribas Asset Management suggests that for the EU to credibly meet its 2050 Net Zero goal it must impose a carbon tax of between Eur 79 - Eur 103 per ton by 2030
    - Apparently the UK Treasury would be supportive of this type of approach and could support a 75 pounds / ton carbon price by 2030.

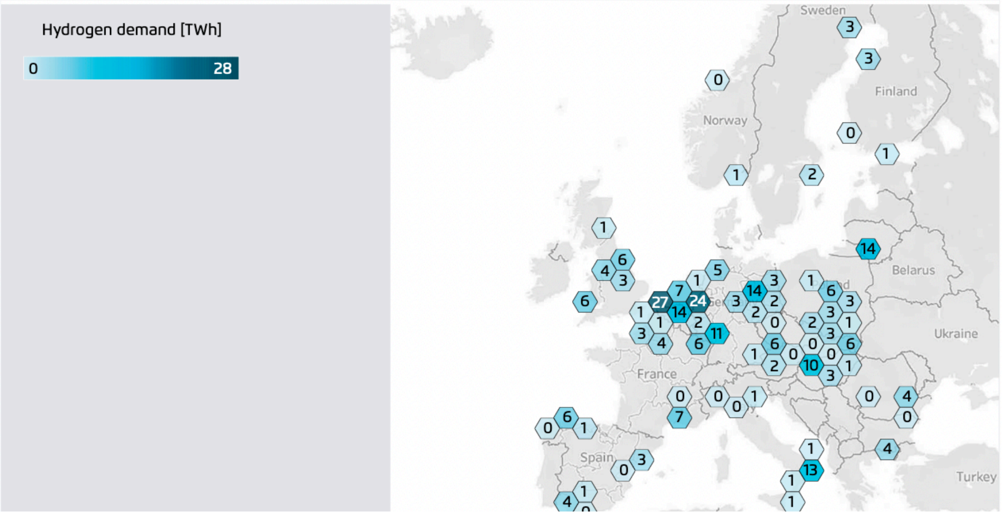
Agora Energiewende - No-regret Hydrogen. Charting early steps for H2 infrastructure in Europe - January 2021
(https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf)

With expectations of rising hydrogen demand (especially green) in the future, there is discussion of the utility of establishing a « hydrogen backbone » in Europe that would permit the transportation and storage of H2. This paper identifies a « no-regret » backbone the can be established that no matter the future assumptions (technical assumptions, of demand, of costs), this backbone will be useful in the future and therefore can be invested in now.

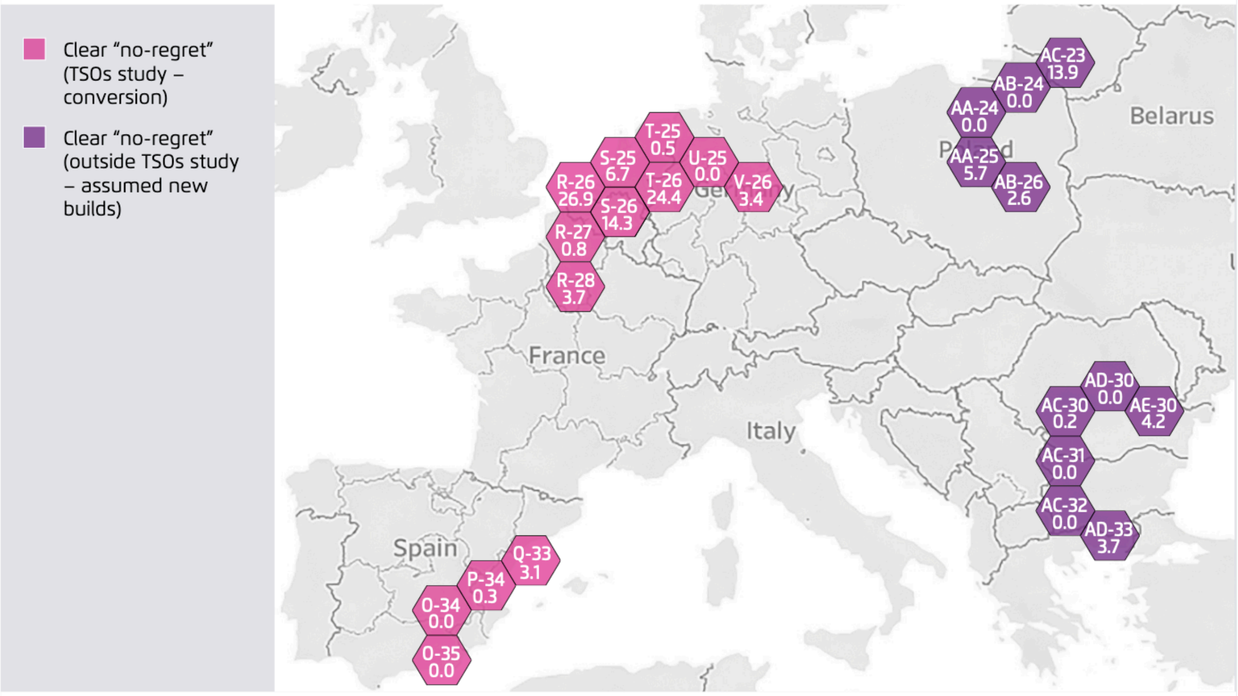
Main conclusions:

- 1/ Hard-to-abate industrial sectors represent a major area of hydrogen demand in the future due to a lack of alternative decarbonization options
    - The report does not consider using H2 for heating indeed:
        - The report shows that 40% of natural gas final energy consumption in the EU industry sector is destined at less than 100°C heating, which can be replaced by heat pumps very well. For the remaining 60% over 100°, the heat pumps are not yet up to the task
        - Electric system designed to generate heat (power-to-heat technologies) exist and appear to be more efficient than hydrogen
- 2/ The investment window for fossil-based hydrogen with carbon capture remains open, but in the long run renewable hydrogen will emerge as the most competitive option across Europe
    - fossil-based hydrogen with carbon capture will remain a viable investment until the 2030s
    - Depending on the scenario, blue H2 will already be uncompetitive by 2030 or between 2030 and 2050 (in 2030, it will have remained competitive in some partes of northern Europe, most notably the UK and Norway, but in most of most of western Europe, solar and wind will have already become more competitive).
- 3/ they identify robust no-regret corridors for early hydrogen pipelines based on industrial demand
    - Pipelines must focus on indispensable demand, robust green corridors in order to reduce the risk of oversizing (any future H2 network will be smaller than the current natural gas network).
    - Some regions were identified as optimal locations for H2 hydrogen infrastructure across continental Europe => would deliver hydrogen to demand clusters at the lowest possible cost, and provides access to hydrogen storage to facilitate flexibility and seasonality => **four no regret corridors were identified:**
        - In Central west Europe (principalement autour des flandres, Belgique pays bas)
        - In Spain
        - In south east Europe
        - In east Europe (autour de la Pologne, mer baltique)
    - => based on their assumptions (they focus solely on industrial demand), they explain that there no justification for creating a larger, pan-European hydrogen backbone
    - Their recognize that if H2 demand extended to other hard to abate sectors such as long range aviation and shipping, then it would amplify the need for connections between supply and demand clusters accros Europe

Distribution of industrial hydrogen demand projected for 2050 in TWh per year — Figure 2



Clear “no-regret” routes (hexagons contain the ID and the demand in 2050 in TWh) — Figure ES-3



AFRY analysis. © 2020 Mapbox © OpenStreetMap.

Hydrogen Council - Hydrogen insights - February 2021
(https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf)

(Cf notes écrites)

58 pages report that summarizes all the issues concerning H2 development and perspectives.

The report broaches the subjects of:

- deployment and investment (current investment and expected investment by 2030 as well as the necessity of government support)
- Hydrogen supply => cost comparison with grey H2 by 2030 (could become competitive in optimal region) etc.

- Hydrogen distribution => what H2 transporting to adopt in function of conditions and cost of H2 global transport
  - **On this point, on the analysis of the cost of transport in function of each carrier, of pipelines, for specific end use, they develop much further that what I have seen in any other report**
  - There is no ideal type of transport for H2, it depends on distance, you have ;
    - Pipelines: for on site transport an regional (remains pertinent until a 1500km distance
      - Are the most cost effective means of distribution
    - Trucking: for regional
    - Shipping: for international
- end applications => cost competitiveness of H2 applications ; the sectors where H2's cost could breakeven: road transport and mining equipment, ammonia, steel, sustainable shipping fuels, aviation
  - Cost competitiveness mostly depends however on the price of the ton of CO2
  - Without carbon pricing, H2 can be competitive in four sectors: buses, trains, trucks, SUVS (FCEV could achieve breakeven with diesel by 2028 if H2's price at the pump is 4,5 USD / Kg
  - With 100$/ton of CO2, H2 is also competitive for production of ammonia, refinery, steel

Hydrogen Council - Hydrogen decarbonization pathways - January 2021
Executive summary: (https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Executive-Summary.pdf)

Consists of two distincts reports:

- **1/ "Hydrogen Decarbonization Pathways: A Life-Cycle Decarbonization Pathways: A Life-Cycle Assessment"**

(https://hydrogencouncil.com/wp-content/uploads/2021/04/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf)

The report intends to establish a life cycle assessment (LCA) of the emissions induced by H2 production, in function of the production (grey or blue or green), in order to evaluate the carbon-saving potential of hydrogen over the life-cycle

To assess hydrogen supply pathways, they take into account a number of sustainability aspects:

- the energy source for H2 production
- Biogenic feedstock => for H2 production, can result in a wide range of GHG emissions.
  - GHG emissions from biogenic wastes most notably
- Capex-related emissions => emission linked the assets necessary for the energy production
  - Emissions are low across the board
  - GHG emissions of renewable power-to-hydrogen pathways are dominated by capex-related emissions
- the impact of metal recycling has been observed
  - All in all, impact is limited
  - Is most pronounced for green H2 production pathways => recycling tends to yield GHG savings of about 30% for the manufacturing of photovoltaic plants and 40% for wind power plants in 2030 versus using virgin material
- gross water demand has also been looked at as a possible sustainability issue
  - It is most pronounced for the cooling of thermal power plants
  - For water electrolysis using PV and wind, water demand is low with 9kg of water per kg of H2
    - Still, at GW scale, water can be an issue and needs to be taken into account

The report LCA analysis has been applied to eight illustrative hydrogen value chains calculating emissions for 2030 and 2050.
=> pathways are established describing mobility and industry applications.
=> across the different pathways and applications, very high (around 90%+) to high (around 60%+) GHG emission reduction can be demonstrated with a transition to green or blue H2

Exhibit 1: Carbon-equivalent emissions by hydrogen production pathways, 2030 and 2050 (resulting figures refer to virgin material use); energy production refers to GHG emissions from the supply of the main input into the H_2 plant (natural gas, coal, electricity), while H_2 production refers to direct GHG emission of H_2 plant, including from plant auxiliary electricity use

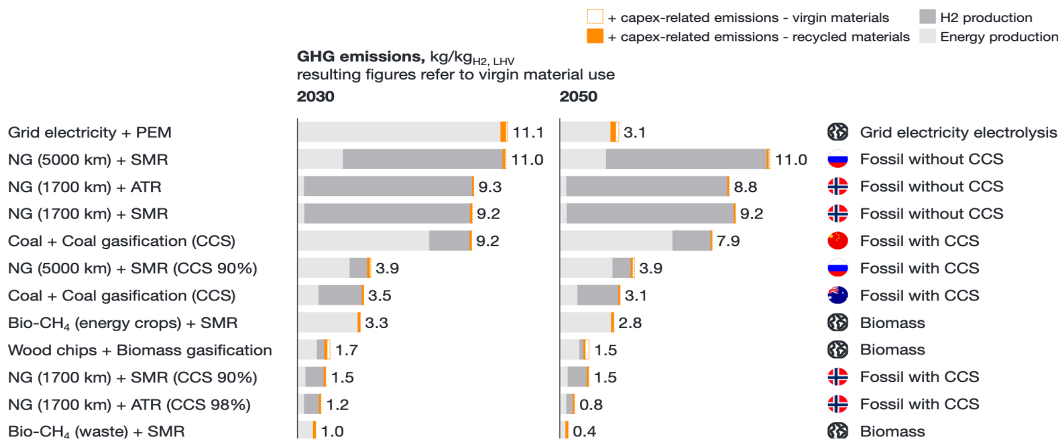


Exhibit 4: Eight illustrative pathways

	Origin region	Destination region	Energy production	H_2 production	H_2 conversion	H_2 transport, distribution	H_2 application	Alternatives
1	Australia	East Asia	Natural gas	ATR + CCS	LH_2	LH_2 shipping (9,000 km)	Light-duty vehicles (e.g., fleets)	Gasoline ICE BEV
2	Scandinavia	Scandinavia	Natural gas	ATR + CSS	LH_2	LH_2 trucking (100 km)	Shipping (e.g., cruise ship)	Diesel ICE
3	North/West Europe	North/West Europe	Natural gas	ATR + CCS	–	H_2 pipeline network	Industrial heat (e.g. boiler/furnace)	Natural gas
4	Middle East	East Asia	Natural gas	ATR + CCS	NH_3 synthesis	NH_3 shipping (12,000 km)	Central power generation	Natural gas
5	North America	North America	Wind + solar	Central EL	NH_3 synthesis	NH_3 shipping (2,000 km)	Fertilizer	Natural gas
6	China	China	Solar	Central EL	–	H_2 pipeline (2,500 km)	Buses	Diesel ICE
7	USA	USA	Wind + solar	On-site/ Decentral EL	–	Refueling station	Trucks	Diesel ICE
8	West/Central Europe	West/Central Europe	Offshore wind	On-site/ Decentral EL	–	–	Steel plant (DRI + EAF)	Steel plant (BF + BOF)

- **2/ "Hydrogen Decarbonization Pathways: Potential Supply Scenarios"** (https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-2_Supply-Scenarios.pdf)

Study lays out different supply scenarios that can achieve a ten-fold build-out of H2 supply by 2050 with decarbonized sources.
FCA

Three theoretical scenarios are considered:

- A green H2 only scenario
- A blue H2 only scenario
- A combined scenario

Findings:

- a decarbonized hydrogen supply is possible regardless of the production pathway => Neither of the scenarios exceed the world's ressources
    - Either regarding RE energy capabilities
        - 78 EJ of H2 production will be necessary by 2050 (estimation based on the « Scaling up » report by the Hydrogen council) which would require 10 TW of renewables capacity equivalent to solar panels covering the area of Italy and wind turbines covering almost half of China's coastal waters
        - however, that is still less than 10% of the estimated accessible global renewables potential
    - Or sequestration capabilities
        - The blue h2 only scenario would require 50 Gt of carbon sequestration capabilities by 2050
        - Which is less than 0.2% of estimated geological storage reserves

- overall emissions reductions would be even lower for the green scenario compared to the blue
    - From 2020 to 2050, the green scenario would induce the emission of approximately 10 Gt of CO2, 8 of which would come from the phasing out of grey H2
    - On the other hand, the blue scenario would induce 20 to 25 Gt of CO2 over the same time period

- a combination of green and blue production pathways appears to result in the least-cost global supply over the entire period of scale-up
    - Makes best use of the near-term cost advantage of blue in some regions while simultaneously achieving a scale-up in electrolysis
    - Allows to achieve very low cost green H2 in the medium / long term
    - It also makes best use of complementary global resources

Bird&Bird& - International Green hydrogen report - 2021
(https://www.twobirds.com/~/media/pdfs/greenhydrogen2021_brochure_v05.pdf?la=en&hash=2B7B1D0A589ECE37A8F344F89DBE07D8AB453CCD)

Has a focus on the different hydrogen strategies and policies put in place by a number of states: Australia ; France ; Germany ; Italy . Poland ; Singapore ; Spain ; the Netherlands ; the UK.
=> each time it analyses the legal framework in place.

It talks about the key legal areas surrounding H2:

- hydrogen and regulations
    - One of the issues would be the double burden of certain levies and charges that still applies in the context of energy storage

  - Another key issue is the development of a hydrogen infrastructure => subsidy laws must be complied to in this context
- hydrogen and contracts
- Hydrogen and intellectual property
- Hydrogen and cooperation

=> report is not that interesting. Provides very general areas of legal interest without any detail and resumes some of the important national trends and policies regarding H2.

Baker McKenzie - Shaping tomorrow's global hydrogen market via de-risked investments - January 2020
(https://www.bakermckenzie.com/-/media/files/insight/publications/2020/01/hydrogen_report.pdf?la=en)

Based on the assumptions that hydrogen is unavoidable for the H2 transition and that global warming makes this transition also unavoidable, the hydrogen sector will have a considerable importance in the future and governments will support hydrogen (just like renewables).
=> Therefore, the report argues that hydrogen is an investment opportunity, and that being a first mover can bring long term benefits.
=> to do so, they must monitor energy policies and profit from government support to de-risk investment

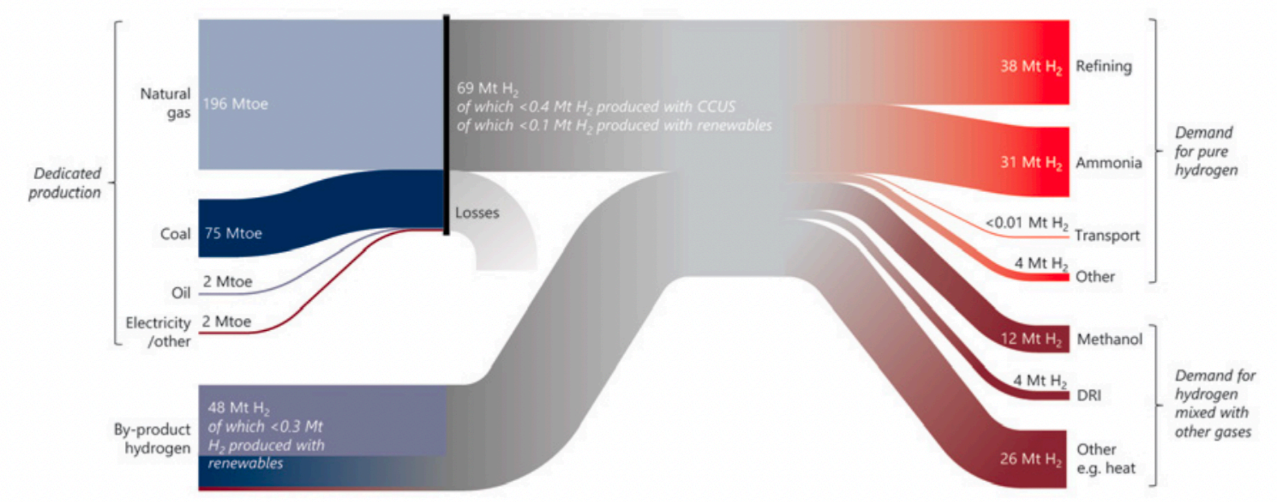


Figure 3. *Today's hydrogen value chains.* Source: IEA (2019), *The Future of Hydrogen.* p. 32. All rights reserved.

Report says that the low-carbon hydrogen market size could reach USD 25 billion by 2030 and grow even further long-term

RTE - The transition to low carbon hydrogen in France. Opportunities and challenges for the power system by 2030-2035 - January 2020
(https://assets.rte-france.com/prod/public/2021-03/Hydrogen%20report_0.pdf)

=> provides an overview of the hydrogen sector and its place in the ecological transition, and more specifically its place in France.

McKinsey&Company - Global energy perspective 2021 - January 2021
(https://www.mckinsey.com/~/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/Global%20Energy%20Perspective%202021/Global-Energy-Perspective-2021-final.pdf)

- As green hydrogen becomes cost competitive in the 2030s, "indirect" power demand for electrolysis accounts for approximately 40 percent of electricity demand growth from 2035 to 2050, primarily in industry and transport.

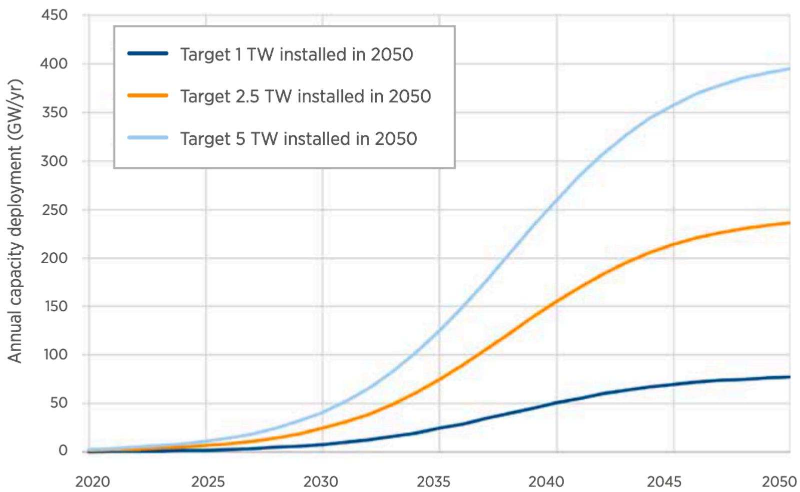
IRENA - Green hydrogen cost reduction - December 2020
(https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf)

In the second part =>
Provides an exhaustive summary of the different electrolyser technologies, the cost of an electrolyser according to each of its specific parts.

The report presents strategies for cost reduction (provides technical advices on the production chain):

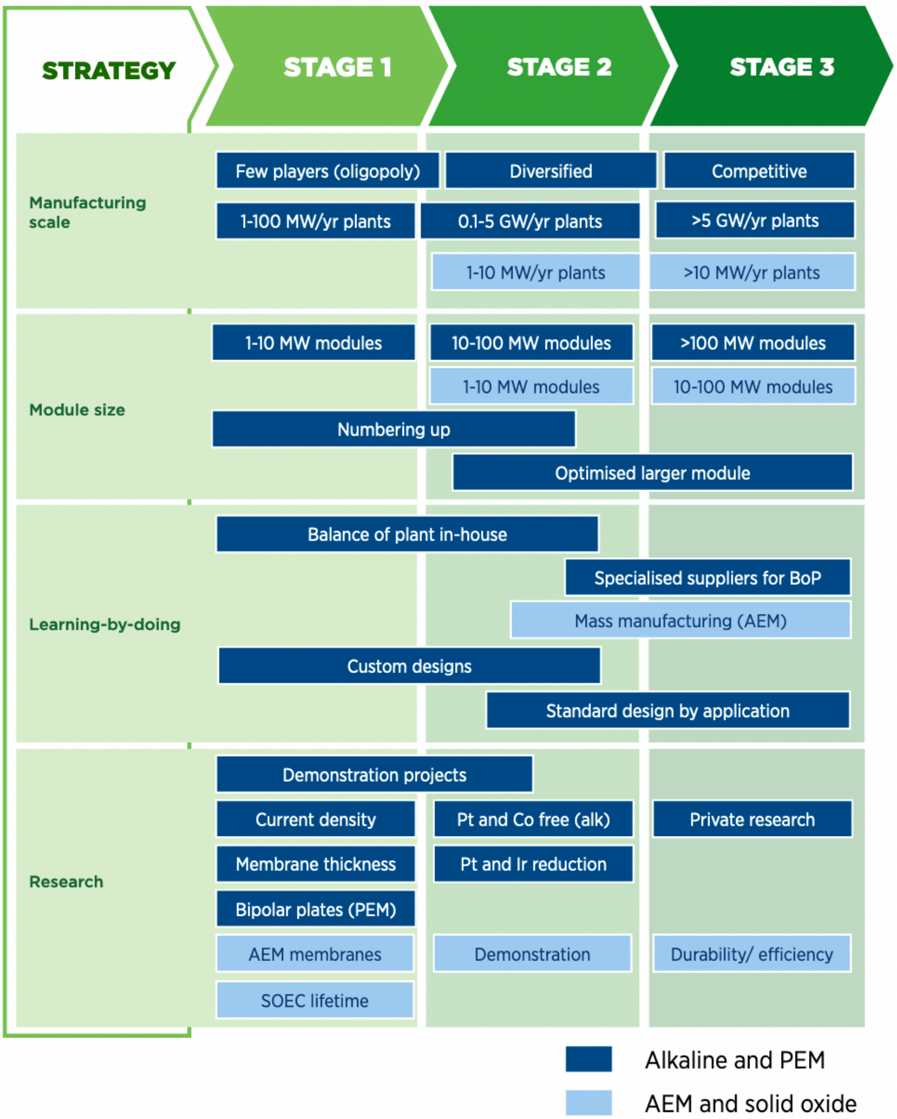
- at the stack level => two strategies: module size ; research
  - Aiming at the stack design and cell composition
    - Reduce the use of critical materials (or even substitute them) because of their cost and criticality
      - Alkaline systems must transition to platinum and cobalt free designs.
      - For PEM electrolysers, further efforts are needed to reduce the platinum and iridium content
    - Achieve higher efficiency of materials and energy
  - Increase the module size to achieve economies of scale
    - Increasing the facility size can have the largest cost reduction effect on the balance of plant
  - government support for r&d is absolutely necessary
- at the system level => two strategies: manufacturing scale of electrolysers ; learning by doing
  - Largest economies of scale for electrolyser manufacturing are reached around the 1GW/year level => government could set manufacturing capacity targets manufacturing tax benefits, grants and loans for capacity expansion
  - A predictable 5-10 year pipeline of electrolysis projects – driven by green hydrogen demand – will be key for manufacturers to invest in new, larger and automated production facilities => incertitude concerning future demand is the key barrier to the scaling up of green H2
  - Government must ensure that costs are communicated transparently because of uncertainty of the future trajectory of electrolyser costs

Figure 32. Estimated necessary electrolyser manufacturing capacity (GW/year) to meet different installed capacity targets by 2050.



Report estimates that a 40% cost decline could be achievable in the short term, with a final 80% cost reduction in the long term when all the targets are achieved

Figure 33. Milestones for four cost reduction strategies across three stages of deployment for electrolysers.

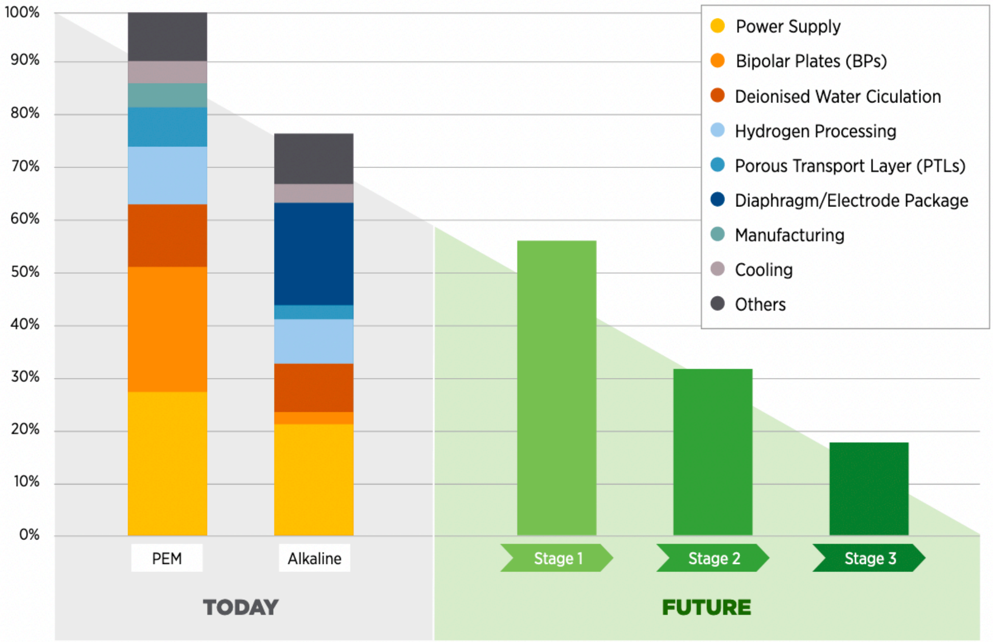


Based on IRENA analysis.

The report distinguishes stages of development => the four strategies presented are each layed out and presented for each specific stage

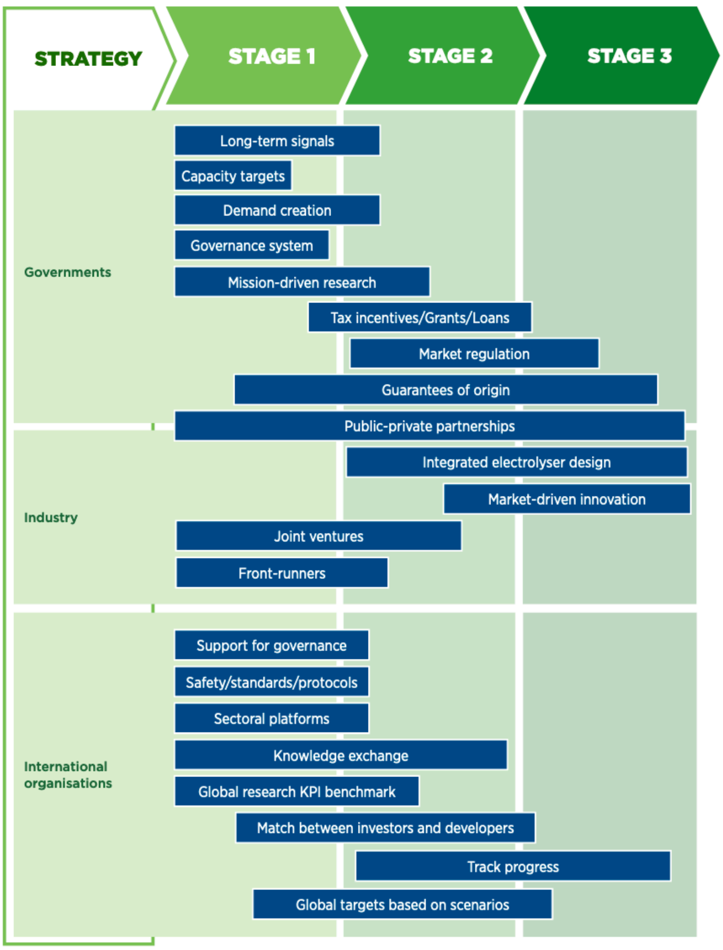
- 1/ market establishment
- 2/ scaling up and improving design
- 3/ a global market

Figure 34. Potential cost reduction by implementing strategies presented in this report across three stages of deployment.



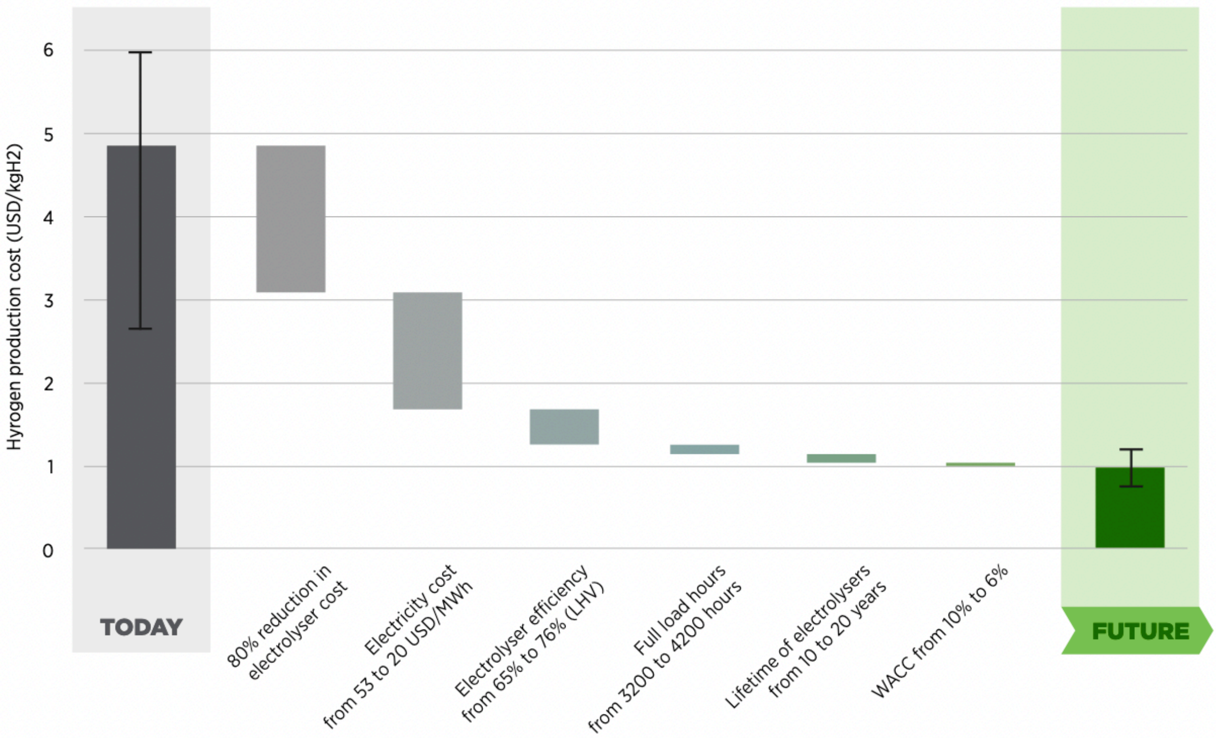
Based on IRENA analysis.

Figure 36. Main actions and functions for key stakeholders influencing the scale up of green hydrogen.



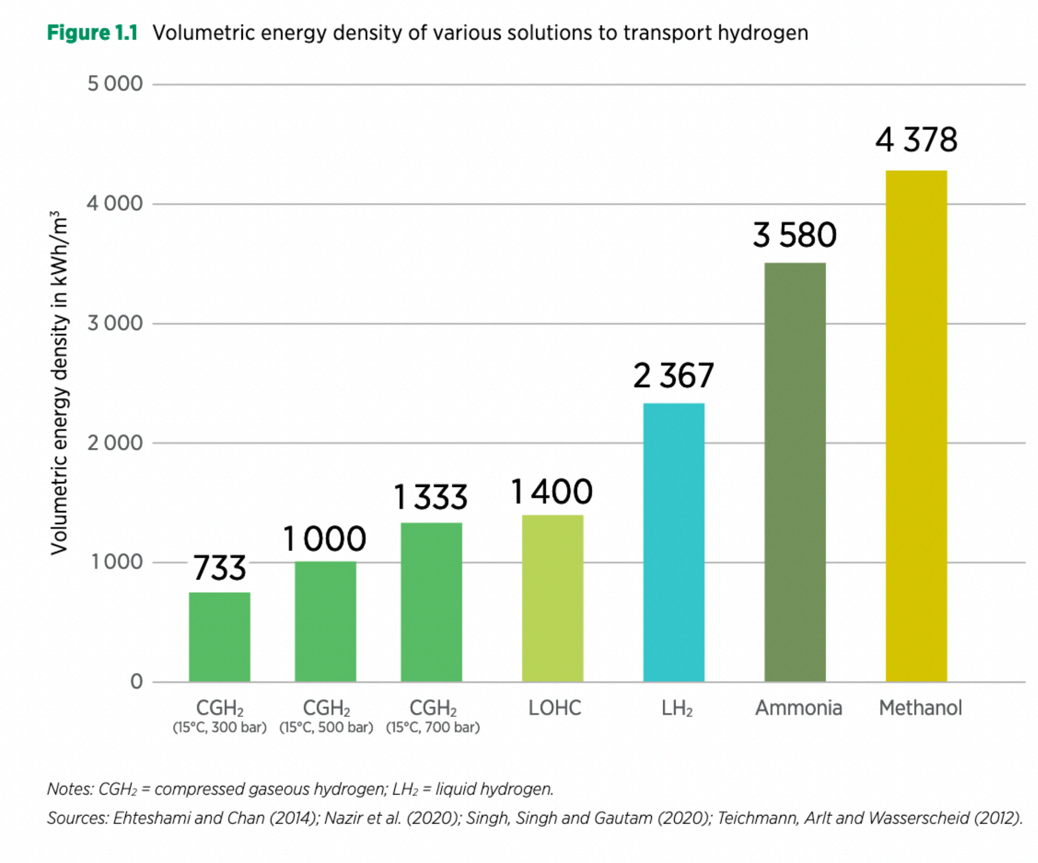
Based on IRENA analysis.

Figure 35. Step changes for achieving green hydrogen competitiveness.



Note: 'Today' captures best and average conditions, with an average investment of USD 770/kW, efficiency of 65% (LHV), an electricity price of USD 53/MWh, 3 200 full load hours (onshore wind), a WACC of 10% (relatively high risk). Best conditions are USD 130/kW, efficiency at 76% (LHV), electricity price at USD 20/MWh, 4 200 full load hours (onshore wind), and WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis.



IRENA - Green hydrogen: A guide to policy making - November 2020 (https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/May/IRENA_Green_Hydrogen_Supply_2021.pdf)

Current state of affairs:

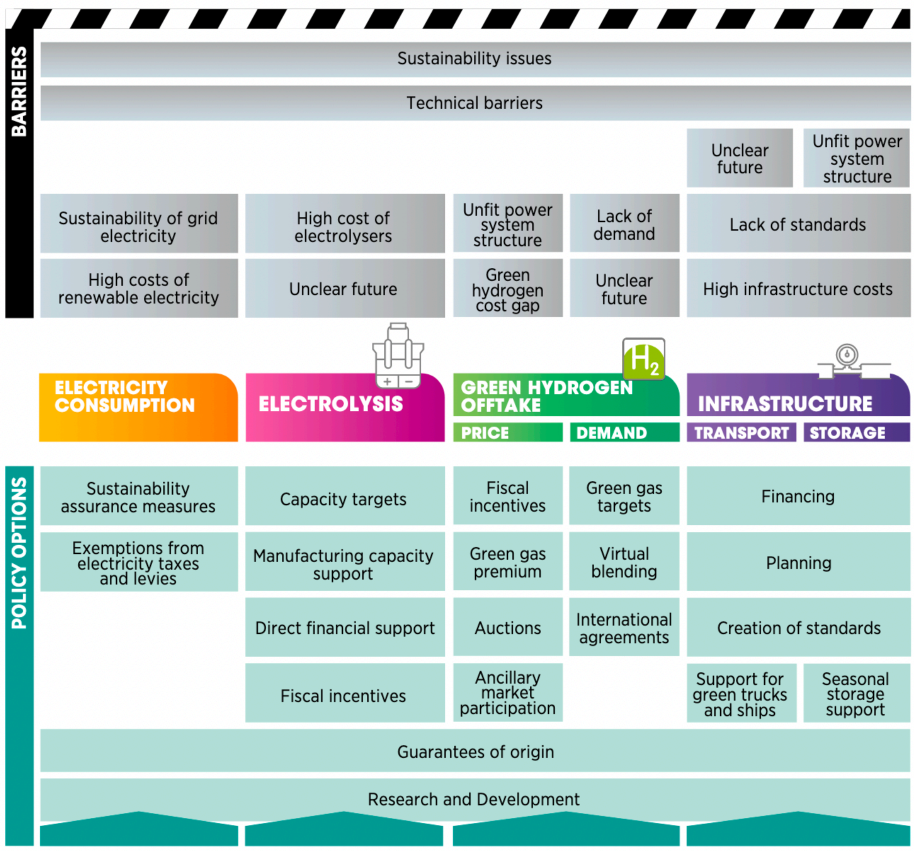
- Current installed electrolyser capacity is around 200MW.
- In 2020, the pipeline for the next five years was estimated to be about 18 gigawatts (GW) but in a few months that changed considerably and it now varies between 33 GW (BNEF, 2021a) and above 90 GW (Hydrogen Council, 2021)
- In 2018 the world's electrolyser manufacturing capacity was about 135 MW/year (IRENA, 2020b)
    - Global manufacturing capacity is expected to rise to 3.1 GW/year by the end of 2021 (BNEF, 2021b).
    - To achieve total installed electrolyser capacity of 5 TW by 2050, as projected by IRENA (2021), global manufacturing capacity of 130-160 GW/year will be needed

Current H2 supply barriers are:

- cost barriers (production, conversion, transport and storage costs)
- Sustainability issues
  - Pbs with grey h2
  - Principle of additionality for H2 production
- lack of clarity regarding future demand
- unfit power system structures
- Lack of technical and commercial standards

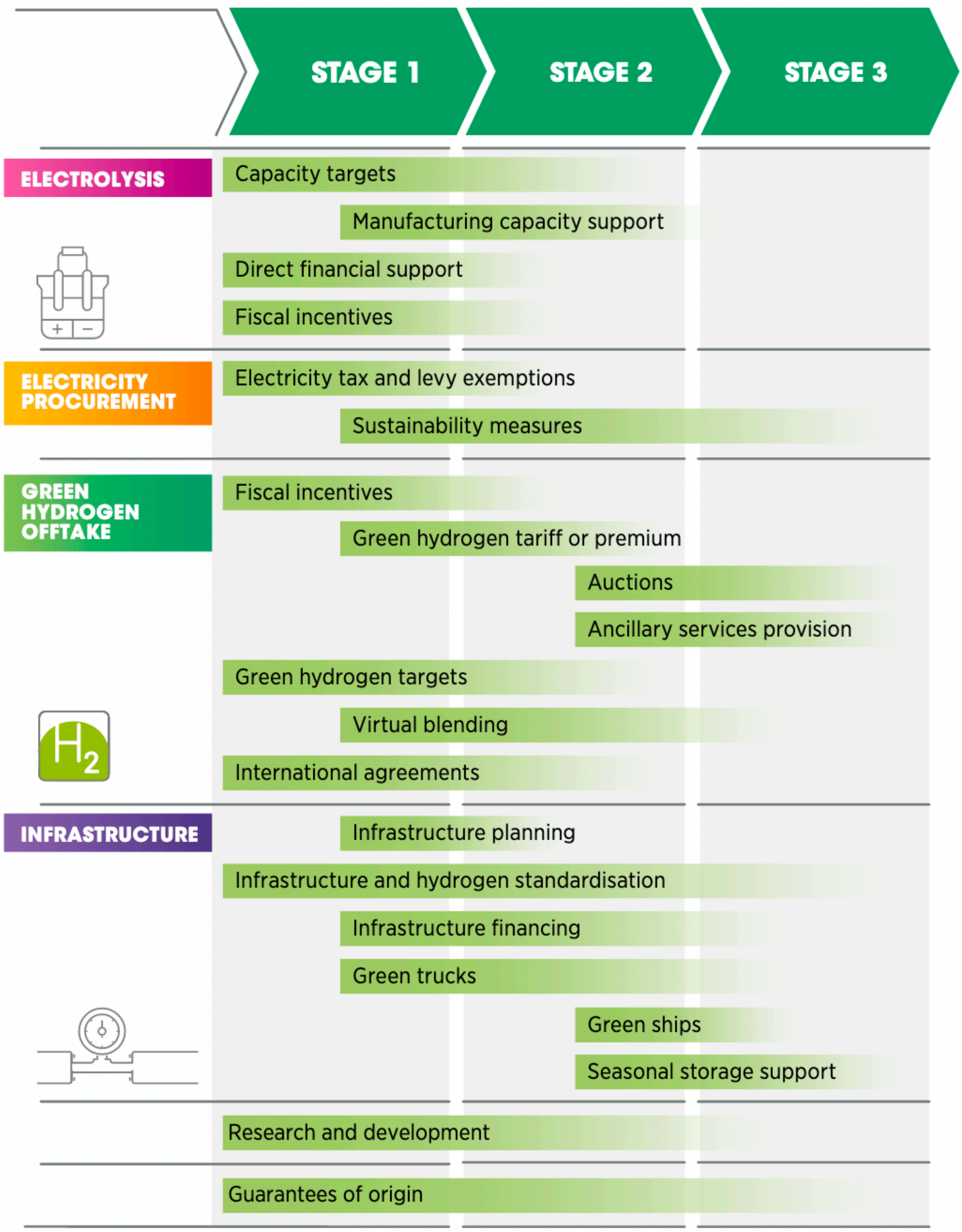
The report presents policy options support green hydrogen supply:

Figure 2.1 Barriers and policy options for the supply of green hydrogen



The report also establishes stages of development:

Figure 3.1 Range of policies to promote electrolysis across three stages of deployment.



Clifford Chance - Focus on hydrogen: a 7.2 billion strategy for hydrogen energy in France - September 2020
(https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2020/10/focus-on-hydrogen-eur-7-2-Billion-strategy-for-hydrogen-energy-in-france.pdf)

=> presents French national H2 strategy

Gas for climate - European Hydrogen Backbone. How a dedicated hydrogen backbone can be created - July 2020
(https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/)

Report defends the establishment of a European pipelines infrastructure. It presents the shared vision of 11 European gas TSOs (transmission system operators). The present report shows a vision for a:

- 39700km hydrogen pipeline infrastructure in 21 countries by 2040, 70% of which would be base on repurposed existing natural gas pipelines
- The 2040 infrastructure has an estimated investment cost of €43-81 billion
- It could transport hydrogen over 1000 km with an average stretch of the backbone cost €0.11-0.21 per kg

The backbone would start with an emerging infrastructure of approximately 6800km of H2 transport pipelines in 2030 and would be mature in 2040. The proposed 2040 hydrogen backbone covers just over 22,900 composed of 75% repurposed NG infrastructures.

Costs of the European hydrogen backbone:

- Total investment costs of the envisaged 2040 European Hydrogen Backbone are expected to range from €27 to €64 billion (covering the full capital cost of building and retrofitting the backbone)
    - Against hundred of billion in investments in green H2 production that the EC hydrogen strategy foresees
    - The retrofitted pipelines that represent 75% of the 2040's European backbone represent only 50% of the total investment
    - Annual operating costs are expected to be between €1.6 and €3.5 billion[26] when assuming a load factor of 5000 hours per year.

TABLE 1

Estimated investment and operating costs of the 22,900 km European Hydrogen Backbone (2040). Input ranges leading to the 'low', 'medium', and 'high' scenarios are presented in Appendix A.

		Low	Medium	High
Pipeline cost	€ billion	17	23	28
Compression cost	€ billion	10	17	36
Total investment cost	**€ billion**	**27**	**40**	**64**
OPEX (excluding electricity)	€ billion/year	0.7	0.9	1.1
Electricity costs	€ billion/year	0.9	1.2	2.4
Total OPEX	**€ billion/year**	**1.6**	**2.1**	**3.5**

TABLE 2

Estimated levelised cost of hydrogen transport through pipeline infrastructure. Input ranges leading to the 'low', 'medium', and 'high' scenarios are presented in Appendix A.

		Low	Medium	High
Levelised cost, 100% new infrastructure	€/kg/1000km	0.16	0.20	0.23
Levelised cost, 100% retrofitted infrastructure	€/kg/1000km	0.07	0.11	0.15
Levelised cost, European Hydrogen Backbone (75% retrofitted)	**€/kg/1000km**	**0.09**	**0.13**	**0.17**

4. Key infrastructure components

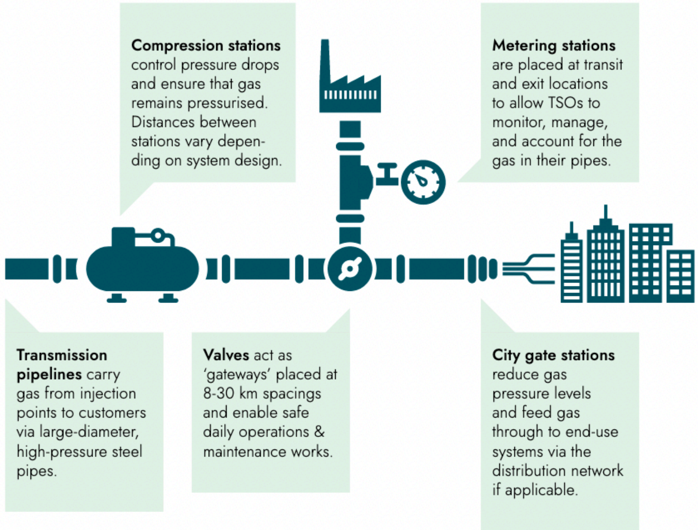


FIGURE 7

Schematic of the physical elements of natural gas infrastructure.