# A Roadmap for the Deployment of EU Hydrogen Valleys

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CLEAN AIR TASK FORCE

# Summary

Clean hydrogen is widely viewed as an important tool for achieving economy-wide decarbonisation, particularly in sectors where complete electrification is infeasible and other climate-friendly fuel alternatives are lacking. For this reason, the European Commission has set ambitious goals for developing supplies of low-carbon and renewable hydrogen and expanding its application in end-uses, such as industry and transportation. Its REPowerEU Plan includes several prominent hydrogen initiatives including a plan to double the number of Hydrogen Valleys operating in Europe by 2025. The term 'Hydrogen Valley' refers to a regionally co-located network of hydrogen production, distribution, and end-use infrastructure, analogous to the terms 'Hydrogen Hub' or 'Hydrogen Cluster' used by other jurisdictions. Clean Air Task Force (CATF), which has conducted extensive analysis of hydrogen production and deployment challenges in Europe and worldwide, provided recommendations to a recent European Commission consultation for input on its forthcoming REPowering the EU with Hydrogen Valleys Roadmap, which will guide and support European efforts to develop Hydrogen Valleys.

This paper reprises CATF's full submission to the European Commission in response to its request for input on Hydrogen Valley development, including the additional analysis, information, and discussion CATF provided in support of the key recommendations listed below.

**Figure S-1: CATF recommendations for EU Hydrogen Valleys**

RECOMMENDATION 1:

**Prioritise 'no regrets' end-use sectors, particularly those sectors that are already producing and consuming carbon-intensive hydrogen today.**

RECOMMENDATION 2:

**Make use of all clean hydrogen production pathways and allocate support based on entire value chain emissions reductions, cost, and scalability.**

RECOMMENDATION 3:

**Site clean hydrogen production close to where hydrogen is consumed, and ensure a constant, reliable supply to end users.**

RECOMMENDATION 4:

**Provide socio-economic benefits to the local community.**

RECOMMENDATION 5:

**Match public funding to the most promising Hydrogen Valley developments that meet the foregoing recommendations, which in turn should spur a final investment decision.**

RECOMMENDATION 6:

**Establish a comprehensive EU Hydrogen Valleys database to promote transparency,accountability, and cross-Valley collaboration.**

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SECTION 1

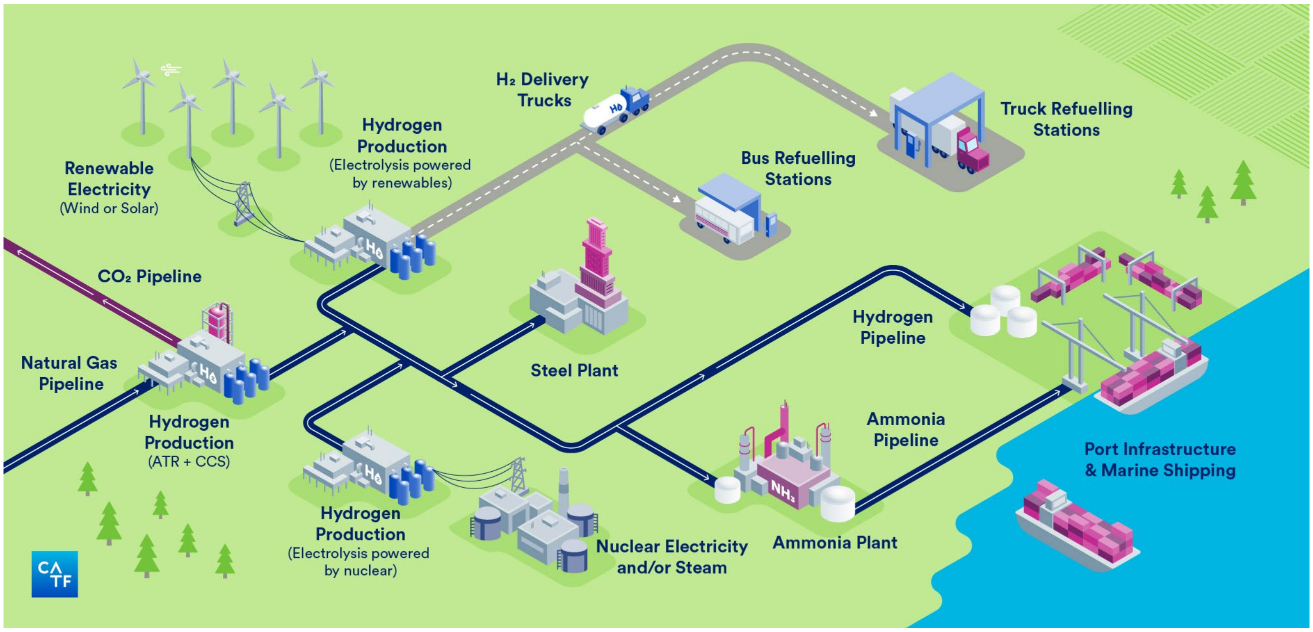
# Context: The hydrogen economy and Hydrogen Valleys

As a critical component of the climate change solution set, low-emissions hydrogen is widely expected to play a major role in achieving full, economy-wide decarbonisation by mid-century. We already know that electrification based on a massive increase in clean power production and transmission build-out can do much of the work of decarbonisation. However, it will be very difficult to eliminate emissions from some hard-to-abate sectors (including oil refining, aviation, maritime, primary steel production, and petrochemical industries) without using clean hydrogen—both directly, as a low-carbon fuel, and as a feedstock for other critical products, such as ammonia and climate-friendly synthetic fuels that are suitable for use in aviation and other applications.

There are also significant barriers to achieving a large-scale increase in clean hydrogen production and use, as other CATF work has highlighted, including major challenges in terms of energy requirements, transportation and storage infrastructure, and adaptations to end-use equipment. Given these challenges, CATF's strong view is that hydrogen deployment should be limited to those applications and sectors where hydrogen is expected to deliver significant climate benefits and where other cost-effective decarbonisation options do not exist. Pursuing hydrogen primarily for energy security reasons, for example, does not make sense given the amount of energy need to produce hydrogen in the first place.

**A 'Hydrogen Valley' (termed a 'Hydrogen Hub' or 'Hydrogen Cluster' in other jurisdictions) is typically understood as a regionally co-located hydrogen network consisting of the production, end-use, and connective infrastructure to build and operate a fully-functioning, regional clean hydrogen ecosystem.** The longer-term goal of developing Hydrogen Valleys is to connect them to form a broader, synergistic hydrogen economy. Valleys would launch with demonstration projects, ideally at large scale, to test and prove out technologies for minimising the greenhouse gas (GHG) intensity of hydrogen production, for using hydrogen in new applications to aid decarbonisation, and for storing and transporting hydrogen to meet the demands of an emerging market.

**Figure 1: Hydrogen Valley design concept**




The concepts of Hydrogen Valleys, Hubs, and Clusters are not new, and governments around the world are seeking to incentivise the development and scale up of regional hydrogen demonstration projects. In the United States, the Infrastructure Investment and Jobs Act (IIJA) of 2021 authorises the Department of Energy to spend 8 billion USD to create 'Regional Clean Hydrogen Hubs'. This first-of-a-kind demonstration program aims to provide a platform and framework for operationalising the advances needed to lower the cost of clean hydrogen production and launch a domestic clean hydrogen industry. The program has attracted significant interest and in October 2023, seven regional Hubs located across the U.S. were selected for funding.[1] CATF is actively tracking these developments and engaging with hub developers in the United States.[2]

Similarly, the concept of Hydrogen Valleys is not new in Europe. The initiative was launched as part of an EU effort to become the first major climate-neutral economy by 2050. The idea is to connect clean hydrogen production to end-use demand sectors at a regional level and on a scale that encourages 'matchmaking' and 'co-investment', as well as links with parties outside the EU, including Norway and the United Kingdom. The objectives of the REPowerEU Plan include doubling the number of Hydrogen Valleys in operation by 2025; these objectives are reiterated in the proposed Net Zero Industry Act (NZIA), which further calls for establishing hydrogen infrastructure interconnections across EU borders. In support of the European Green Deal and the REPower EU Plan, the Clean Hydrogen Partnership has provided funding to nine Hydrogen Valleys so far.

Despite these policy and resource commitments, meeting European goals for hydrogen development, and for decarbonisation more broadly, will be extremely difficult. CATF's recommendations to the European Commission as it develops its EU Hydrogen Valleys Roadmap reflect the magnitude of the challenge and CATF's strong view that only a thoughtful approach, grounded in a clear-eyed analysis of the realities and trade-offs that lie ahead, will result in success. The remainder of this paper provides context and detail for each of these recommendations.

1 https://www.catf.us/2023/10/doe-selections-regional-hydrogen-hubs-mark-critical-first-step-clean-hydrogen-economy/

2 See CATF – U.S. Hydrogen Hubs Map

SECTION 2

# Recommendations

RECOMMENDATION 1:

## Prioritise 'no regrets' end-use sectors, particularly those sectors that are already producing and consuming carbon- intensive hydrogen today.

Most of the Hydrogen Valleys that have been announced on the Mission Innovation Platform thus far are focused solely or primarily on renewable hydrogen deployment in the transportation sector, as a fuel for use in cars, buses, trucks, and trains. Whilst part of the transportation sector may require hydrogen and its derivatives to decarbonise (e.g., in the aviation and marine shipping sectors), other forms of transportation, such as light-duty vehicles, may benefit by prioritising electrification as their primary pathway to decarbonisation, for reasons of cost as well as scalability. Given Europe's limited domestic resources for producing hydrogen (both in terms of natural gas supply and renewable energy capacity), hydrogen should be viewed as a precious molecule and prioritised for use in hard-to-abate sectors where it is needed and where the deployment of other energy- and cost-effective decarbonisation options is not feasible.

Accordingly, the EU should ensure that publicly (co-) funded Hydrogen Valleys focus on deploying clean hydrogen, either as feedstock or fuel, in 'no regrets' sectors. By 'no regrets' sectors, CATF means sectors where hydrogen will be needed to complete industrial processes, or where no other energy- or cost-efficient decarbonisation options are available, such as in oil refining, fertiliser production, methanol production, primary steel manufacturing, and maritime shipping. Specifically, CATF urges focused deployment efforts in the following order of priority: First, to decarbonise existing processes for producing and consuming hydrogen and second to supply emerging end-use applications, as availability allows. Appendix 1 provides more detailed recommendations on how hydrogen deployment should be prioritised and why.

**In sum, clean hydrogen provides an essential tool for reducing emissions in certain sectors but is far from a silver bullet for decarbonisation and should not be deployed indiscriminately to all sectors as if every potential end-use has equal merit.** Rather, policymakers should recognise that hydrogen is a critical chemical for running some of today's industries sustainably, feeding future populations (as a feedstock for ammonia and fertiliser production), and fuelling certain modes of transportation that underpin the global economy.

**As already mentioned, hydrogen itself is not a source of energy but rather a chemical that is energy-intensive to produce. Smart policies will prioritise clean hydrogen deployment to sectors that absolutely require this precious molecule to decarbonise.**

**Figure 2: CATF ranking of potential hydrogen end use sectors**

### First-order priority sectors

- Crude oil refining
- Petrochemicals production
- Ammonia production [fertiliser]
- Methanol production
- Steel & iron production

### Second-order priority sectors

- Renewable fuels production
- Sustainable aviation fuels [aviation sector]
- Marine shipping fuel
- Long-haul trucking fuel

### Likely niche applications

Hydrogen is also being considered as a decarbonisation option for other sectors, but in some of these cases it may not be the most suitable pathway. This is particularly true where other, more energy- and/or cost-efficient options exist, such as electrification, CCS, and heat pump installation.

- Power generation
- Natural gas blending
- Residential heating
- Light-duty vehicles
- Seasonal energy storage

RECOMMENDATION 2:

## Make use of all clean hydrogen production pathways and allocate support based on entire value chain emissions reductions, cost, and scalability.

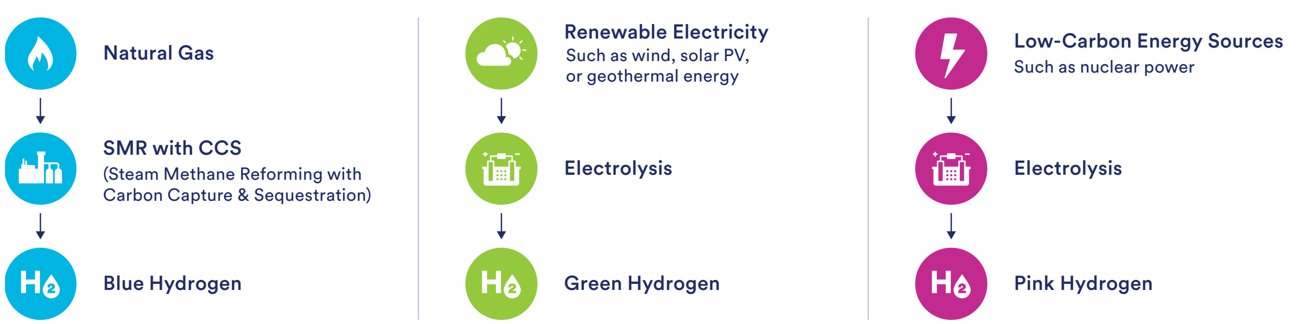
Different pathways exist for producing hydrogen using renewable or low-carbon energy:

- Steam methane reforming (SMR) or autothermal reforming (ATR) with carbon capture and storage (CCS). For this pathway to be considered clean or low-emission, CCS systems must be installed and operated to ensure a high carbon dioxide ($CO_2$) capture rate (greater than 90%) and strict controls must be in place to limit upstream methane emissions. Hydrogen produced subject to these conditions is known as 'blue' hydrogen.
- Hydrogen production via electrolysis[3] using electricity generated from renewable sources (such as onshore wind, offshore wind, solar photovoltaics, or superhot rock geothermal). Hydrogen produced in this manner is known as 'green' or 'renewable' hydrogen.
- Other forms of hydrogen production from low-carbon energy sources (such as nuclear power). This production pathway is also known as 'pink' hydrogen.

In Europe and elsewhere, available renewable energy (e.g., wind and solar) is unlikely to be sufficient, by itself, to satisfy demand for clean hydrogen over the next several decades, both because of resource and capacity constraints and because of competing demands (e.g., to decarbonise the electricity grid). **Using scarce, renewable power to produce hydrogen in the short- to medium-term, while the European grid has not yet been fully decarbonised, would be counterproductive from a resource deployment perspective, particularly at a time when electricity consumption is still increasing in other sectors of the economy.** In fact, the share of electricity in final European energy demand is expected to increase from 20% in 2019 to 50% in 2050[4]—eventually, the European Commission expects that electricity will account for as much as 65% of final energy consumption. Put another way, grid decarbonisation must be prioritised ahead of 'green' hydrogen production, otherwise hydrogen production could delay the decarbonisation of other emissions-intensive sectors whose primary decarbonisation pathway is heavily or entirely dependent on the availability of clean electricity, such as electric vehicles.

Since renewable hydrogen will not be available in the quantities needed to fully meet Europe's forecasted demand, efficient production and deployment of hydrogen to suitable applications, based on proven technologies (e.g., SMR or ATR with installed CCS), should be considered a key intermediary solution to rapidly ramp up hydrogen production capacity and bridge any gaps. **CATF advocates for openness to all forms of clean hydrogen production, so long as they are compatible with the European Commission's 'do no significant harm' principle.** This means that hydrogen

**Figure 3: Hydrogen production pathways**




3 In electrolysis, an electric current is used to split molecules into their constituent elements. For purposes of hydrogen production, this method generally involves splitting water molecules to generate hydrogen and oxygen.

4 Data from DNV Pathways to Net Zero Emissions Energy Transition Outlook 2021 report

production incentives should not be based on arbitrary colour-coding but on GHG emission reduction merits based on rigorous emissions accounting.

Comparisons between different hydrogen production pathways must consider GHG emissions[5] across the entire lifecycle/value chain. In certain cases, emissions from 'blue' hydrogen production can be as low as those from 'green' hydrogen production, if the process ensures high carbon capture rates and if strict measures are implemented to reduce upstream methane leakage. On the other hand, much of the equipment needed to harness wind and solar energy is manufactured today in China, where 60% of the electricity grid is powered by unabated fossil fuels. The carbon intensity of renewable energy also strongly depends on resource availability, which varies considerably between EU Member States. More information on these issues, based on CATF analysis of 'blue' and 'green' hydrogen production pathways, can be found in Appendix 2.

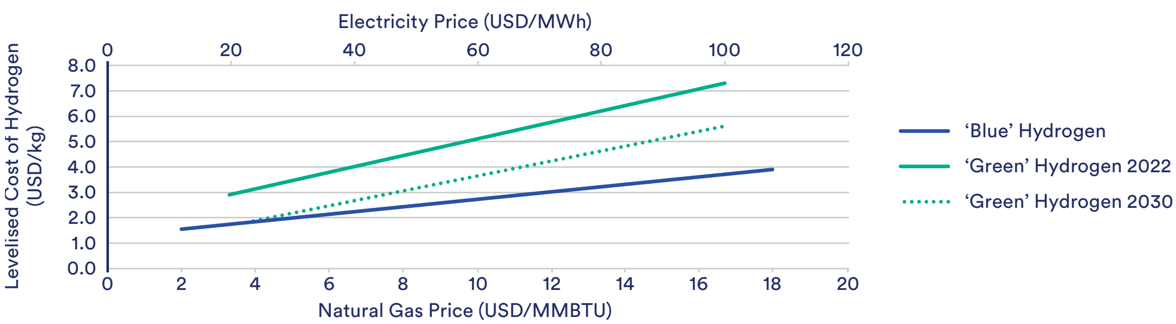
'Blue' hydrogen can also be scaled more quickly, at a lower cost and with higher capacity factor and utilisation rates compared to 'green' hydrogen, because the technology is more developed. It also requires significantly less upfront capital investment. For instance, the estimated installed cost for a 300-megawatt (79 kilotonnes-per-annum) 'blue' hydrogen facility using ATR with a 97% carbon capture rate, similar to the facility that has been proposed for the UK-based HyNet project, is currently around 330 million USD.[6] According to 2020 report from the Institute for Sustainable Process Technology (ISPT),[7] the estimated cost for a 'green' hydrogen electrolysis plant with similar output is 621 million USD today and projected to fall to 300 million USD in 2030. Importantly, the electrolysis facility would need to be matched with an equally extensive upfront capital investment in renewable electricity sources, whereas the 'blue' hydrogen facility would have higher ongoing operating costs primarily in the form of natural gas procurement.

To ensure that the EU can supply sufficient volumes of clean hydrogen to meet its decarbonisation goals, all forms of clean hydrogen production should be considered in EU plans and initiatives. While the EU Hydrogen Strategy references low-carbon 'blue' hydrogen as a transitional option, several other key EU policy initiatives (including REPowerEU, the EU Hydrogen Bank, and the NZIA) do not fully consider this pathway. Many publicly announced Hydrogen Valleys projects focus solely on local production of 'green' hydrogen.

Member States and European companies must be empowered to make use of a full array of clean hydrogen production pathways, to rapidly ramp up hydrogen production capacity and bridge gaps in hydrogen demand. Considering and incorporating all forms of clean hydrogen production in the EU Hydrogen Valleys framework would reduce hydrogen costs and enable the scale-up of clean hydrogen production faster than if production is dependent on renewables generation alone.

**Figure 4: Levelised cost of hydrogen**

*Source: CATF*




5 See CATF Assessing hydrogen emissions across the entire life cycle (2022)

6 IEAGHG report estimate for a plant in NL. Estimates provided in EUR; EUR/USD conversion rate of 1.15 is assumed.

7 ISPT report provided cost estimates for GW-scale PEM electrolysis plants. A 300MW plant would probably cost more given the smaller scale. Estimates provided in EUR; EUR/USD conversion rate of 1.15 is assumed.

RECOMMENDATION 3:

## Site clean hydrogen production close to where hydrogen is consumed, and ensure a constant, reliable supply to end users.

Where possible, Hydrogen Valleys should locate clean hydrogen production close to consumption and set up infrastructure to connect the entire value chain. Due to its physical properties, hydrogen is a difficult molecule to transport, so any hydrogen transport should (a) be limited to cases where hydrogen serves a very specific need and (b) use the most energy- and cost-efficient methods, such as via pipeline.

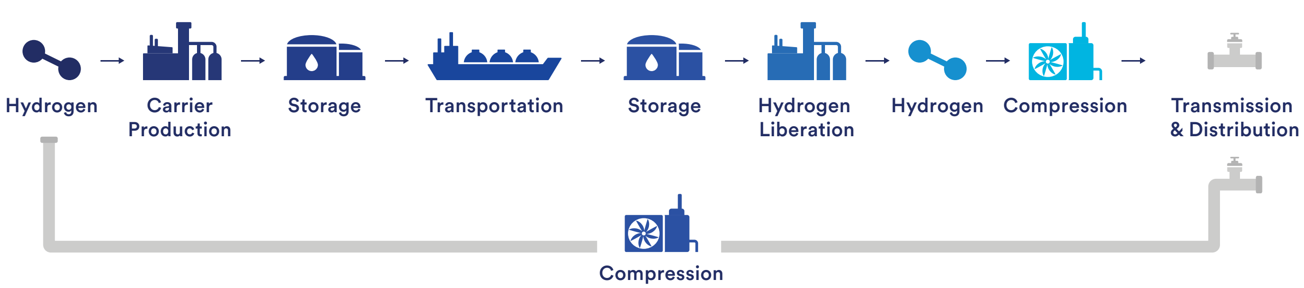
Where connecting hydrogen infrastructure across Member State borders is feasible and needs-driven, it should be pursued as a way to facilitate larger-scale collaborative projects and the creation of a common hydrogen market. If hydrogen must be transported over longer distances, new infrastructure for this purpose should be carefully planned and streamlined, utilising existing assets and the most efficient transportation methods.

Recognising limits to domestic production within the bloc, REPowerEU sets a target of 10 million tonnes per year of renewable hydrogen imports from third countries. Importing hydrogen and its derivates from distant suppliers and delivering it to demand centres will require significant infrastructure build-out. The EU and its Member States must approach this challenge carefully, considering the logistics and cost-effectiveness of large-scale hydrogen imports, and taking into account where and how hydrogen will be imported, and where it is needed for deployment.

A CATF report, Techno-Economic Realities of Long-Distance Hydrogen Transport: A Cost Analysis of Importing Low-Carbon Hydrogen to Europe, explores pathways for importing hydrogen to Europe from various potential producing regions. **The report concludes that importing large quantities of hydrogen over long distances into Europe will be expensive and relatively energy inefficient due to hydrogen's inherent properties, particularly its ow volumetric energy density.** Of the transport options available, pipeline is the most cost-effective method, ideally over the shortest distances possible, followed by maritime transport of ammonia for direct use. 'Cracking' ammonia to liberate pure hydrogen incurs significant energy penalties, making the process even less efficient and costly. Hence, CATF recommends prioritising imported ammonia for use in industry applications that specifically require ammonia, in sectors such as agriculture and maritime shipping, for example. Compared to pure hydrogen, ammonia is much cheaper and more stable to transport via ship and truck.

Developers must carefully forecast hydrogen demand for each Hydrogen Valley, identifying what share can be met with domestic production as well as the size of the remaining gap that needs to be covered by imports, preferably via pipeline from neighbouring countries. To avoid costly but ultimately unsuccessful ventures and stranded assets, Member States must carefully assess and select the most efficient pathways for importing hydrogen and ammonia and coordinate closely on international projects before any significant investments are made.

**Figure 5: Hydrogen transportation and storage**



RECOMMENDATION 4:

## Provide socio-economic benefits to the local community.

Developers must consider the benefits of their projects for local communities, including benefits to the local workforce and economy. As a minimum, CATF recommends that plans for a Hydrogen Valley should:

- Create structures and processes for local community engagement that allow for meaningful citizen input throughout the full planning and development process.
- Create local, sustained jobs that meet prevailing wages and support local workforce development efforts throughout the full clean hydrogen value chain.
- Incorporate results from a comprehensive environmental and health assessment ahead of project implementation.

**Hydrogen Valley developers should also ensure that their projects deliver regional benefits in terms of environmental indicators, such as improved air quality and water availability.**

At an absolute minimum, the net environmental impact of a Hydrogen Valley should be neutral. Developers should also be encouraged to undertake a lifecycle analysis (LCA) of GHG emissions across the entire hydrogen value chain[8] to demonstrate that their projects are truly low-carbon and will deliver climate benefits.

Providing maximum environmental and socio-economic benefits and imposing minimum costs on local communities will help ensure that Hydrogen Valleys are successfully integrated into local economies and make a sustainable contribution to local communities.

RECOMMENDATION 5:

## Match public funding to the most promising Hydrogen Valley developments that meet the foregoing recommendations, which in turn should spur a final investment decision.

Any use of public funds (EU, national, regional, local) to leverage the development of Hydrogen Valleys should be allocated to the most promising projects, specifically to those projects that prioritise off-takers in 'no regrets' sectors, produce clean hydrogen through the most energy- and cost-efficient means possible, plan and use infrastructure in an energy- and cost-efficient manner, and provide benefits to the local community.

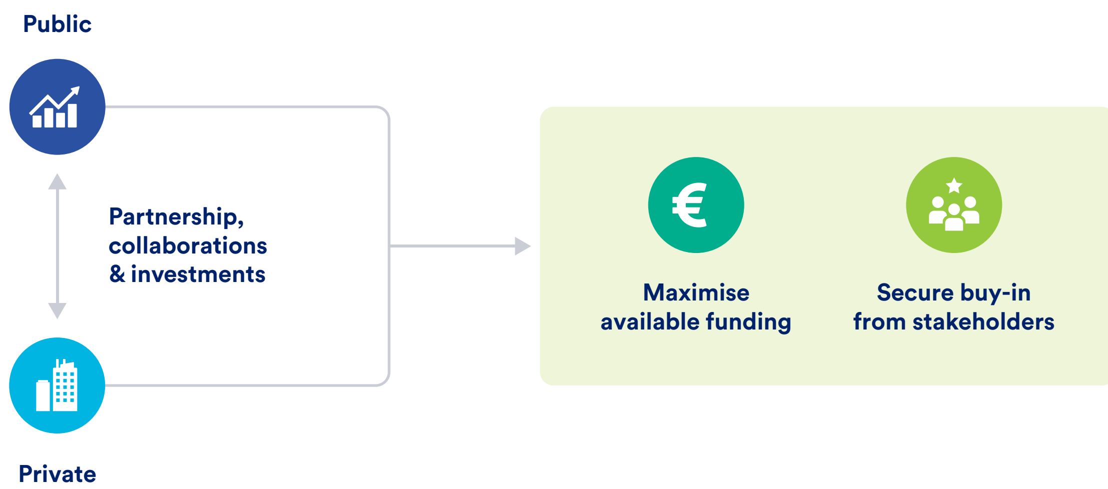
As mentioned previously, CATF recommends that the EU open any funding mechanisms relevant to the development of Hydrogen Valleys (including the Hydrogen Bank and Innovation Fund) to all forms of clean hydrogen, including 'blue' hydrogen, so that project development is not held back by technology and resource limitations. Similarly, any national funding schemes to support Hydrogen Valleys should not be limited to 'green' hydrogen alone.

Policies should also be designed to speed support for the most promising demonstration projects and pilots and to streamline pathways to a final investment decision (FID).

**Finally, public-private partnership collaborations and investments should be encouraged, both to maximise available funding in light of constraints on public resources and to help secure buy-in from stakeholders that need the clean hydrogen the most.**

8 See CATF – Assessing hydrogen emissions across the entire life cycle (2022)

**Figure 7: Maximising financial potential for Hydrogen Valleys**




RECOMMENDATION 6:

## Establish a comprehensive EU Hydrogen Valleys database to promote transparency,accountability, and cross-Valley collaboration.

To promote knowledge-sharing and cross-Valley collaboration, and to ensure that project developers are fully transparent and accountable to their funders and local communities, the EU should further build on its database of Hydrogen Valleys. The database can provide a one-stop source of information about current proposals and developments, including what stage projects are at, who is involved, the method of hydrogen production, and identified off-takers. While the Mission Innovation Platform is a notable first step in this direction, it could benefit from the inclusion of additional information and from incorporating other Hydrogen Valley initiatives. Additionally, the platform as currently configured does not capture all EU developments, only those that have launched official development proceedings (e.g., feasibility studies, planning, engineering, de-risking). The European Commission (and the Clean Hydrogen Partnership) is well placed to set up and promote a single official, comprehensive information platform for EU Hydrogen Valleys.

SECTION 3

# Conclusion

Hydrogen Valleys hold promise as an effective strategy for accelerating the commercialisation and scaleup of clean hydrogen ecosystems that efficiently link hydrogen production and distribution capacity with end-use opportunities. Nonetheless, nurturing a robust clean hydrogen industry in Europe on a scale that meaningfully advances key climate goals is an objective that still faces significant barriers in terms of cost, energy requirements, infrastructure buildout, and customer demand. Adding to the overall challenge, these barriers will need to be tackled in a context where pressure on scarce public resources and policy attention to pursue other critical avenues for decarbonisation will be high.

CATF commends the European Commission's efforts to develop a thoughtful roadmap for Hydrogen Valleys. Our central recommendation to the Commission and Member States is to ensure that any public funds leveraged for the development of Hydrogen Valleys are allocated to the most promising projects, prioritise off-takers in 'no regrets' sectors, support clean hydrogen production through the most energy- and cost-efficient means possible, build and use infrastructure in an energy- and cost-efficient manner, and provide benefits to the local community. Applying these guidelines will increase the odds of program success and maximise the long-term economic and climate benefits that Hydrogen Valleys can deliver.

APPENDIX 1

# Hydrogen end-uses and recommended prioritisation for deployment

## First-order priority sectors for hydrogen deployment include:

### Crude oil refining

Almost 50% of all hydrogen produced today is consumed in petroleum refineries. Refineries produce a wide array of products critical to the functioning of today's economy and hydrogen is a critical feedstock in their production. For example, hydrotreating transportation fuels to remove impurities, such as sulphur, nitrogen, oxygen, olefins, and heavy metals, in order to meet government, technical and safety requirements. Hydrogen is also used to hydrocrack fuel to increase the product yield. Using low-carbon hydrogen to replace unabated hydrogen production in refineries could reduce the industry's emissions by 240-380 MT/year, equivalent to the total emissions of the UK.[9]

### (Petro)- chemicals production

Hydrogen is used as an essential feedstock in the production of chemicals and products that are commonly used by households and businesses on a day-to-day basis. These include plastics, pharmaceuticals, detergents, pesticides, dyes, paint, fabrics, fibres, adhesives, construction materials, and more. Whilst some of these products may be phased out over time in favour of more sustainable alternatives, new products will take time to test, demonstrate and scale. Other products may lack sustainable alternatives; in these cases, decarbonising their production and operation is a priority to reduce associated greenhouse emissions as much as possible.

### Ammonia production

Ammonia is a critical ingredient in nitrogen fertilisers, where 70% of global ammonia goes to fertiliser production. This plays an essential role in providing a secure food supply for human populations worldwide. Other important uses include the production of synthetic fibres (e.g., nylon), explosives in the mining sector, and other speciality applications. Hydrogen is an intermediate input and is reacted with nitrogen in the atmosphere to create ammonia. Given the critical role ammonia plays in underpinning our modern agricultural system, decarbonising the carbon-intensive hydrogen feedstock used in its production should rank high on the priority list for low-carbon deployment.

### Methanol production

Methanol is a critical industrial chemical used to produce certain chemicals (e.g., formaldehyde, acetic acid) and plastics (methanol to olefins). Methanol and its derivatives are also used as fuel additives to improve combustion properties. Hydrogen is an intermediate input and is reacted with a carbon to produce methanol. Given the importance of methanol in industrial sectors, lowering the carbon intensity of its production by replacing the carbon-intensive hydrogen feedstock should rank high on the priority list for low-carbon deployment.

### Steel and iron production

Hydrogen currently plays a role in steel manufacturing via the direct reduced iron-electric arc furnace (DRI-EAF) process, where hydrogen from a synthetic gas (mainly H2+CO) is used to remove oxygen from DR-grade iron ore. The idea of using low-carbon hydrogen in existing DRI applications has been proposed as a pathway for reducing emissions from steel manufacturing.

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9 See: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147372/2022_Provisional_emissions_statistics_report.pdf

## Sectors classed as second order of priority for hydrogen deployment, due to their nascent status, include:

### Renewable diesel and sustainable aviation fuels

Hydrogen must be used to produce renewable diesel and kerosene - known more commonly as sustainable aviation fuels or SAF - by hydrotreating biomass feedstocks, oils, and fats of biogenic origin. These types of fuels continue to draw interest as an alternative to electrification of certain segments of transportation as they offer compatibility with existing infrastructure and engines, hence often referred to as 'drop in' fuels. Using hydrogen to develop such fuels could help reduce emissions of heavy-duty vehicles, aviation, and marine transport. Note that these fuels are different to 'e-fuels', which are not included as part of this sector categorisation.[10]

### Long-haul transportation fuel

Recent CATF analysis[11] shows that long-haul hydrogen fuel cell vehicles (FCEVs) outperform battery electric vehicles for heavy-duty trucks in terms of the number of stops required, (re-)fuelling time, and available cargo room. The role that FCEVs play will ultimately be influenced by other factors, such as total cost ownership and well-to-wheel life cycle emissions.

### Marine shipping fuel

Ammonia is a strong contender as an alternative marine fuel, although it would need to be made using low-carbon hydrogen to be considered a zero-carbon fuel. Health, safety, and environmental concerns attributed to ammonia combustion would also need to be thoroughly examined before any wide-scale sectoral applications. Furthermore, developing a low-carbon ammonia fuel market should not draw away from any efforts to decarbonise existing ammonia production for present day applications, in particular for making fertilisers. Another potential low-carbon marine shipping fuel is methanol and many cargo ships being built today incorporate dual fuel capability to handle a future mix of marine oil and low-carbon methanol. However, unlike ammonia, methanol emits carbon at the point of combustion, so to produce a low-carbon fuel, 'sustainable' carbon atoms would need to be sourced for the methanol production process.

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10 E-fuels' specifically refer to transport fuels produced using a combination of electrolytic ('green') hydrogen and CO2 that is either sourced from biogenic feedstocks or captured from the atmosphere. Presently there is no consensus on what e-fuels are and CATF is exploring further analysis on the topic. However, early assessments indicate that e-fuels for some transport applications (such as light-duty vehicles) are unlikely to deliver any real climate benefits. Thus, its deployment should be limited to sectors where no other viable decarbonisation options, such as electrification, are available.

11 See: https://www.catf.us/resource/zero-emission-long-haul-heavy-duty-trucking/

**Hydrogen is also being considered as a decarbonisation option for other sectors but in some of these cases it may not be the most suitable pathway. This is particularly true where other more energy- and/or cost-efficient options exist, such as electrification, CCS, and heat pump installation. Examples include:**

### Power generation

There has been increasing interest in using low-carbon hydrogen as a replacement to natural gas for power production since it emits no carbon when burned. However, numerous technological, infrastructure, and system challenges would need to be addressed, for example the quantities of hydrogen needed would likely necessitate geologic storage and dedicated transmission and distribution pipelines. Where hydrogen could play a limited role in power generation, it would be important to focus on the carbon intensity of the hydrogen used: either produced from natural gas ('blue' hydrogen) or renewable / nuclear energy ('green' or 'pink' hydrogen). When combusting 'blue' hydrogen in a simple-cycle power plant, you can reduce emissions by approximately half compared to natural gas combustion. However, this method would be significantly more expensive than other available abatement options, with $CO_2$ abatement well above USD 400 / tonne. Using 'green' hydrogen is unlikely to be any more appealing, since the round-trip efficiency (RTE) of the energy input is only 19%. Put in another way, where a grid is not fully decarbonised, five units of clean electricity will be diverted from further grid decarbonisation to deliver one unit of clean electricity, effectively losing four units of clean electricity that could be used to serve other direct electricity end uses. One role that 'green' hydrogen could usefully play is the option for grid balancing at times when renewable energy generation would otherwise exceed demand and be curtailed. However, this role is likely to be relevant only when the grid is fully decarbonised.

### Natural gas blending and residential use

Blending low-carbon hydrogen into the gas grid, such as for deployment in home heating, would dilute the environmental benefits of a scarce commodity. Several independent studies have concluded that decarbonisation alternatives for home heating, such as heat pumps, solar thermal systems, and district heating, are more economic- and energy-efficient, and have a smaller environmental impact than hydrogen. Though routinely used in industrials applications, its use in residential settings present potentially serious safety hazards, both due to hydrogen's susceptibility to leakage and its ignition rage, which is six times that of natural gas.

### Light-duty vehicles

FCEVs require up to three times as much energy as electric vehicles and their costs per kilometre are even higher. There is growing market consensus over the pathway forward for light-duty vehicles, given the trivial sales of hydrogen vehicles over the past decade and rapid growth in electric vehicle purchase. All but few auto manufacturers have discontinued their efforts of developing hydrogen light-duty vehicles.

### Seasonal energy storage

Production costs are not cost-competitive with other options for energy storage and generation, and additional infrastructure is needed to support the transportation and storage of hydrogen. Moreover, gas pipeline systems have been optimised to transport methane; therefore, introducing hydrogen at a large scale requires addressing regulatory and technical barriers that may persist when distributing hydrogen in existing natural gas pipelines or developing a new, hydrogen-specific distribution system. Other challenges with using hydrogen for seasonal energy storage include the lack of scalable and commercial options for storing large volumes of hydrogen beyond salt caverns, which are geography dependent. Additionally, any electrolysis units used to capture curtailed renewable electricity would likely be vastly underutilised, contributing to high production costs that would call into question whether a viable business model exists for such facilities, given that developers and investors would have to rely on a variable and to some extent unpredictable cash flow stream.

APPENDIX 2

# Life cycle analysis of greenhouse gas emissions for 'blue' and 'green' hydrogen

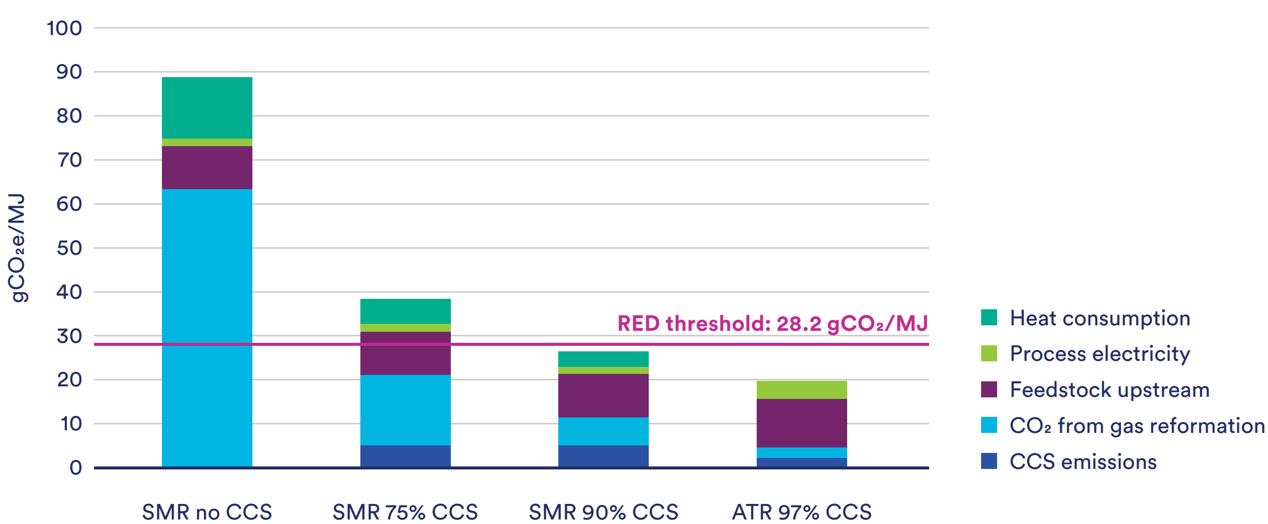
Figure 8 shows emissions from the production of 'blue' hydrogen at different carbon capture rates, assuming the typical mix of natural gas in Europe with a reported methane leakage rate of 0.7%. The Renewable Energy Directive (RED) emissions threshold (28.2 $gCO_2/MJ$) is also represented for reference. With a carbon capture rate of 75%, 'blue' hydrogen would have a carbon intensity equal to 38 $gCO_2e/MJ$. A carbon capture rate of 90% would reduce the carbon intensity of hydrogen production to 27 $gCO_2e/MJ$. Increasing the carbon capture rate further, to 97% (using an ATR), would reduce emissions further, to 20 $gCO_2e/MJ$ (e.g., the UK "HyNet LCH" project). These results are calculated assuming the GWP100 for methane.[12] If the GWP20 is used, $CO_2$-equivalent emissions for 'blue' hydrogen production would be higher due to the higher climate impact assigned to methane leakage.

Aside from applying very high carbon capture rates, it is important to highlight that strict measures need to be implemented to limit methane leakage in the natural gas supply chain when producing 'blue' hydrogen.

For countries that regularly export gas to Europe, such as Russia, Algeria, and the U.S., average leakage rates of 2% have been recorded. Further afield, in places such as Libya, Iraq, or some oil-heavy regions of the U.S., leakage rates of up

**Figure 8: Emissions from hydrogen production via SMR/ATR with different carbon capture rates.[13]**

*Source: CATF*




12 Global warming potential (GWP) describes the relative potency of a greenhouse gas, such as carbon dioxide, methane, and nitrous oxide, taking account of how long it remains active in the atmosphere. It is a measure of how much energy 1 tonne of a greenhouse gas in the atmosphere will absorb over a given period, relative to 1 tonne of $CO_2$. The notation GWP100 and GWP20 indicates GWP over 100- and 20-year time horizons, respectively. We use GWP values for methane from the sixth IPCC Assessment Report: GWP100 = 29.8; GWP20 = 82.5.

13 Based on CATF – Hydrogen Lifecycle Analysis Tool

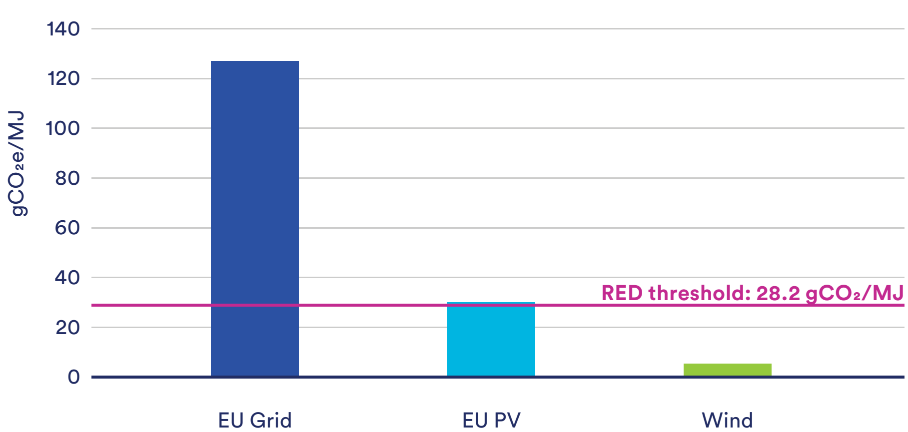
to 8% have been recorded. In parts of Norway, recorded leakage rates were as low as 0.003%–1.3% in 2019.[14] CATF has documented feasible and cost-effective leakage standards that can be implemented to significantly reduce methane emissions in Europe and the U.S.[15]

Hydrogen production via electrolysis using renewable energy sources, such as wind or solar PV, is currently considered as having zero emissions in the RED, since upstream emissions from materials extraction and manufacturing of renewable energy plants are neglected. Although upstream carbon intensity for this pathway is expected to decline in the future as countries decarbonise their energy systems, it is worth mentioning that today, most solar PV and many wind turbine components are manufactured in China,[16] a country in which coal accounts for 60% of the grid electricity mix. Wind turbines are made of at least 70% steel,[17] which requires considerable amounts of energy and is today produced mostly with unabated fossil fuels. In the future, the NZIA is expected to support the decarbonisation of upstream emissions from solar PV and wind energy by strengthening European manufacturing capacity such that it meets at least 40% of the EU's annual deployment needs by 2030.

The carbon intensity of solar PV or wind energy strongly depends on resource availability. This means, for instance, that the carbon intensity of a solar PV panel installed in Iceland (89 $gCO_2/kWh$), can be double than the same PV panel installed in Spain (44 $gCO_2e/kWh$). Therefore, it is important to evaluate where PV and wind installations should be deployed to deliver low-carbon electricity. To illustrate this, Figure 9 compares the carbon intensity of proton exchange membrane (PEM) electrolytic hydrogen production using the EU grid mix in 2020 (264.96 $gCO_2/kWh$), the EU solar PV average (61.92 $gCO_2/kWh$), and wind (11 $gCO_2e/kWh$). The carbon footprint of hydrogen produced using solar PV is 30 $gCO_2/MJ$ – a result that is of the same order of magnitude as the estimated carbon footprint of 'blue' hydrogen with a 90% carbon capture rate (note that the EU PV carbon intensity used in these calculations is from 2011). The carbon footprint of hydrogen from wind is 5 $gCO_2/MJ$, depending also on the availability of wind resources.

**Figure 9: Emissions from hydrogen production via PEM electrolyser using different electricity sources[18]**

*Source: CATF*




[14] A. Foulds et al. – Methane emissions from offshore oil and gas facilities (2022)

[15] See CATF – Smart methane policy to reduce EU emissions (2021); CATF – Reducing Methane from Oil and Gas (2022)

[16] IEA – Solar PV Global Supply Chains (2022)

[17] CATF – Why Europe's wind industry needs decarbonised steel (2022)

[18] Based on CATF – Hydrogen Lifecycle Analysis Tool

# About Clean Air Task Force

Clean Air Task Force (CATF) is a global non-profit organisation working to safeguard against the worst impacts of climate change by catalysing the rapid development and deployment of low-carbon energy and other climate-protecting technologies. With 25 years of internationally recognised expertise on climate policy and a fierce commitment to exploring all potential solutions, CATF is a pragmatic, non-ideological advocacy group with the bold ideas needed to address climate change.

For more information, please visit cleanairtaskforce.org and follow @cleanaircatf.