Coordination and Support Action SET4H2

Report on mapping value chains, infrastructural and industrial scale-up

Enablers and challenges identified in the frame of the SET Plan

D3.4

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Executive summary

In line with the EU Strategy for Energy System Integration and drawing from a ten-year experience in different SET Plan IWGs, namely on IWG 6 – EE in Industry, this deliverable aims to assist a structured and systematic approach to hydrogen and its derivatives. Its goal is to promote the transition to a climate-neutral energy system by developing clean technologies and added value solutions in a fast and cost-effective way in the frame of the Power-to-X strategies and technologies, about which the European Commission is recognising an instrumental role as well as the need to be improved in order to meet energy goals during the next decade.

Having that said, this report aims:

i. To acknowledge the role of hydrogen as a system facilitator in both the molecule and electron forms, depending on system efficiency in each case, from the access to and integration of clean energy sources at competitive costs, to the circular economy of each value chain, and including along the chain namely reliable suppliers, carbon leaks avoidance, qualified job creation, risk management and strategic investments.
ii. To assist a structured and systematic non-nuclear approach to hydrogen and its derivatives by building on the value chain concept for hydrogen, as the hydrogen molecule can be converted into other useful compounds with variable roles in the product design: end use products, intermediate products, industrial commodities or industrial process heat.
iii. To promote a transition process to a climate-neutral energy system by a combination of both new and existing elements on the wider system – which are enablers of disruption effects that lead to developing cleaner technologies in a fast and cost-effective way.
iv. To provide insight on a hydrogen approach at a system level, which enables to design an innovate IWG addressing hydrogen to integrate the SET Plan framework.

Considering the three main roles hydrogen has either as a molecule or electron, they are addressed in different sections, each impacting specific markets: end use products, intermediate products, industrial clean commodities or energy source. Biofuels and e-Fuels are examples of H2 derivatives namely contributing via the reduction of GHG emissions to the transition of the energy system towards a particular end-use sector: sustainable mobility. Besides the production of cleaner fuels, the production of H2 to decarbonize chemicals and materials production processes is also addressed, as well as selected end use sectors such as the hard to electrify heavy, energy intensive industry and heavy-duty transportation (i.e. long-distance trucking, shipping and aviation).

Having such delivery challenge at scale, there is an ongoing effort across the Union to provide a competitive playing field for both renewable and low-C H2, where it is key to avoid just producing grey H2 followed by an abatement technology like CCU, as GHG emissions have to be adequately managed under clear thresholds – which are about to become well defined in the frame of the EU Low Carbon Delegated Act. The effective carbon abatement on the one hand and need for carbon dioxide as a commodity on the other, calls for the need to build a sustainable supply chain for carbon. It is a major challenge, particularly given that to achieve cost efficiency, cheap renewable electricity for hydrogen production and a sustainable and scalable carbon source would need to be available.

List of abbreviations and acronyms

List of abbreviations

Abbreviation	Long form
AC	alternating current
AFIF	CEF Transport Alternative Fuels Infrastructure Facility
Biofuels	liquid or gaseous transport fuels, such as biodiesel and bioethanol, made from biomass
CAPEX	Capital Expenditure
CCU	Carbon Capture and Utilization
CCS	carbon capture and storage
CCUS	Carbon Capture, Use and Storage
CEF-E	Connecting Europe Facility for Energy
CEF-T	Connecting Europe Facility for Transport
CH4	methane
CHP	Clean Hydrogen Partnership
CINEA	European Climate, Infrastructure and Environment Executive Agency
CO_2	carbon dioxide
CRMA	Critical Raw Material Act
CSA	Coordination and Support Action
DAC	Direct air capture
DC	direct current
EC	European Commission
ECA	European Court of Auditors
e-fuels	synthetic fuels, or electro fuels

ERA	European Research Area
e-SAF	electro Sustainable Aviation Fuels
ETIP	European Technology and Innovation Platform
EU	European Union
EUR	Euro
EV	Electrical vehicle
FCH-2 JU	Joint Undertaking
FTL	Fischer–Tröpsch Liquid
G20	‘Group of 20’ is an intergovernmental forum comprising 19 sovereign countries, the European Union (EU), and the African Union (AU)
GHG	Greenhouse gas
GW	Gigawatt
H2	Hydrogen
HEU	Horizon Europe
HRS	Hydrogen Refuelling Station
HVO	Hydrotreated/ hydrogenated vegetable oil
IEA	International Energy Agency
IF	Innovation Fund
IPCEI	Important Projects of Common European Interest
IWG	Implementation Working Group
kg	kilogram
l/L	litres
Low-C	Low carbon
MJ	Megajoule

Mt or Mton	Million ton
MWh	Megawatt per hour
NG	natural gas
NZIA	Net-Zero Industrial Act
OPEX	Operational Expenditure
PtX/P2X	Power-to-X: X= final products/applications on energy
PV	Photovoltaic
R&I	Research and Innovation
RED	Renewable Energy Directive
REDIII	EU Renewable Energy Directive III (2023)
RES	Renewable energy sources
RFNBO	Renewable Fuels of Non-Biological Origin
P2X	Power to X (Hydrogen and derivatives)
SAF	Sustainable Aviation Fuels
SET Plan	Strategic Energy Technology Plan
SMR	steam methane reforming
SRIA	Strategic Research and Innovation Agenda
TA	topical area
TCP	Technology Collaboration Platform (IEA related)
TWG	Temporary Working Group

Acronyms of CSA SET4H2 consortium partners

AEA: Österreichische Energieagentur - Austrian Energy Agency

BGH2A: Balgarska Asotsiatsia za Vodorod, Gorivni Kletki I Sahranenie na Energia (Bulgarian Hydrogen, Fuel Cell and Energy Storage Association)

EUREC: Association of European Renewable Energy Research Centers

DGEG: Direção-Geral de Energia e Geologia (Directorate General for Energy and Geology)

DLR: Deutsches Zentrum für Luft- und Raumfahrt e.V.

HER: Hydrogen Europe Research

MUR: Ministero dell'Università e della ricerca

UNIBO: Alma Mater Studiorum – Università di Bologna

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1. When H2 matters: From H2 to P2X applications - An introduction

Following to our first proposal on this subject by early July 2024, which is in line with the EU Strategy for Energy System Integration[1], and with the upcoming Clean Industrial Deal that will provide a joint roadmap for decarbonization and competitiveness, as well as by drawing from our experience in different SET Plan IWGs and in the first stages of the Net-Zero Industry Act implementation, this deliverable aims to assist a structured and systematic approach to hydrogen and its derivatives to promote the transition to a climate-neutral energy system by developing clean technologies and added value solutions in a fast and cost-effective way in the frame of the Power-to-X strategies. This approach aims to be proposed a working proposal to include the Implementation Plan of the Implementation Working Group on Hydrogen (IWG H2), which is currently under preparation in the frame of the SET Plan.

1.1 Why a systemic and holistic view?

Hydrogen has a wide range of applications that leverage its molecular and electronic properties. By taking a hydrogen and derivatives approach, on the basis both of molecules and electrons, using systemic and holistic views is key for different reasons namely if one needs to avoid a one-size-fits-all strategy, like electrification in hard to abate sectors.

Addressing complexity.

Having into consideration that hydrogen has three main roles impacting different markets, as: an end use product, an intermediate product or an industrial commodity, it enables to encompass the complexities of the Hydrogen economy, namely on the production, storage, distribution, and utilization stages of its value chain. And it will ensure conditions for:

- A sustainable and efficient approach.
- Building on its flexibility, the optimization of its leveraging role at a European system level in the energy transition process towards a net-zero target.

Two main features of complex challenges are how the challenge is framed by different actors and the nature of the knowledge base and its uncertainties. The knowledge base and its degree of uncertainty are again dependent on how the challenge is framed, that is on how the boundaries and the dynamics of the problem are characterised.

Adopting a holistic perspective.

By adopting a holistic perspective, organizations and business units can gain insights into the entire hydrogen and derivatives value chains - included in the P2X value chains approach, and the development of a more robust understanding of their relative contribution to the low-carbon Economy on a comprehensive basis. This includes (European and international) partnerships, cooperating and collaboration along the value chains, understanding the markets (upstream,

[1] EC (2020). Powering a climate-neutral economy: An EU Strategy for Energy System Integration, COM(2020) 299 final, Brussels, 8.7.2020

downstream), pricing dynamics, long-term contracts, cluster/hub strategies, and import/export strategies, especially where the domestic potentials for renewable energy generation and for hydrogen production or derivatives are limited.

1.2 Enablers and barriers of the clean energy transition.

In the context of the clean energy transition, different factors can act as both enablers and barriers, depending on how they are managed and implemented. The following factors have a key role:

Policies and regulatory framework:

Effective policies can drive the energy transition by setting clear targets, providing incentives, and creating a stable regulatory environment. However, inconsistent, poorly designed or unharmonized policies between Member States, as well as complicated or uncertain regulatory frameworks can hinder progress and lead to delays or cancellations of renewable or low-carbon hydrogen production projects.

Infrastructure:

Modern and resilient infrastructure is crucial for integrating renewable energies and clean hydrogen ensuring reliable and sustainable clean energy supply. The slow development of the infrastructure for transport, storage and import of hydrogen prevents the connection of clean hydrogen suppliers and industrial consumers. Furthermore, a quality infrastructure to ensure safety and performance standards and methods related to metrology should enable traceable validation and performance assessment of gas quality, along with methods to assess measurement uncertainty, applied along the entire clean hydrogen value chain. There is also a need to develop and update standards for hydrogen distribution, storage and transmission to the end user.

Skills and Capacities:

A skilled workforce is essential for developing, deploying, and maintaining of new energy technologies in the clean hydrogen ecosystem to achieve the EU ambitious targets and implement the strategies of Member States and regions. The main challenges for education and training in the field of hydrogen include the lack of accessible infrastructure and available equipment for practical training, the lack of established training standards on hydrogen, the lack of sustainable funding for the establishment of a comprehensive training programme for education and training, and the lack of flexibility in educational pathways for the introduction of new topics such as hydrogen.

Funding and Financing:

Access to funding and affordable financing is crucial but also critical for investing in renewable energy and clean hydrogen projects and infrastructure. EU funding is limited and complex while national level funding can be dispersed and not effectively supporting market uptake. Some countries still lack a clear funding scheme for clean hydrogen deployment. The EU needs to increase public funding for hydrogen to keep up with other international players, such as China, Japan or the USA. The main drivers of EU-funding are the Innovation Fund (including the EU Hydrogen Bank) and the Clean Hydrogen Partnership (Horizon Europe). However, infrastructure funding remains limited, with only EUR 360 million spent so far on hydrogen infrastructure by CEF-E and CEF-T. Regarding infrastructure funding, competition is high, with AFIF funding for HRS far smaller than for EV charging stations.[2]

However, a new EU guarantee facility - as is being currently proposed, aims to boost investments in net-zero technologies, which is a significant step towards achieving climate neutrality. Some pros and cons should be part of that discussion, although overall, while the new EU guarantee facility presents some challenges, its potential benefits for the environment, economy, and energy security is likely to make it a promising initiative[3].

Table 1: Towards a discussion on new EU guarantee facility

Pros	Cons
Increased Investment: The facility is designed to attract more private and public investments into net-zero technologies, helping to scale up production and deployment.	High Initial Costs: The upfront investment required to develop and deploy these technologies can be substantial
Job Creation: By fostering the growth of the clean tech sector, it is expected to create quality jobs within the EU.	Technological Uncertainty: There is always a risk associated with investing in new technologies, which may not perform as expected or may become obsolete.
Energy Independence: Enhancing the EU's capacity to produce its own clean technologies reduces dependency on imports, increasing energy security.	Market Dependencies: The success of these investments heavily depends on market conditions and global demand for clean technologies.
Regulatory Simplification: The facility includes measures to streamline administrative processes, making it easier for companies to innovate and expand.	Regulatory Challenges: Despite efforts to simplify regulations, navigating the new framework can still be complex for some businesses.
Environmental Benefits: Accelerating the deployment of net-zero technologies will significantly contribute to reducing greenhouse gas emissions.	

[2] Clean Hydrogen Monitor 2024, Hydrogen Europe

[3] EU is proposing a new guarantee facility aimed at boosting investments in net-zero technologies.
That is an initiative, which is part of an approach on building synergies between the NZIA - Net-Zero Industry Act and the STEP - Strategic Technologies for Europe Platform (European Council, 2024) namely to streamline the funding access for companies involved in deep and digital technologies, biotechnologies, and net-zero technologies – which is the STEP framework. Though it builds on previous initiatives, this new EU facility introduces several key improvements. It will leverage existing funding programs such as 'InvestEU', the 'Innovation Fund', 'Horizon Europe', the 'Recovery and Resilience Facility', and Cohesion policy funds. The aim is to accelerate investments in NZ-technologies following a path on the EU's progress towards its 2030 climate and energy targets and the transition to climate neutrality.

International Collaboration:

International trade cooperation is important to ensure sustainable market growth and encourage technology development and innovation. By setting ambitious targets for renewable hydrogen supply in 2030 and beyond in the REPower EU plan, the European Commission has facilitated large-scale imports of clean hydrogen, recognising that renewable resources will face intense sectoral competition and deployment barriers.

1.3 Hydrogen in EU – Quo vadis?

The EU Strategy on Hydrogen was adopted in 2020 and suggested policy actions in five areas: investment support; support production and demand; creating a hydrogen market and infrastructure; research and innovation, and international cooperation.

The EU is making considerable advances in the development and implementation of hydrogen as a key component of its energy decarbonisation strategy. The ultimate goal being to reduce greenhouse gas emissions and achieve climate neutrality while ensuring sustainable development.

Hydrogen is expected to play an active and key role in Europe's energy strategy. The EU's hydrogen strategy[4] and the REPowerEU plan[5] have put forward a comprehensive framework to support the uptake of renewable and low-carbon hydrogen. In 2022, hydrogen accounted for less than 2% of Europe's energy consumption and was primarily used to produce chemical products, such as plastics and fertilisers.[6] However, of this present hydrogen consumption levels, 96% was produced from natural gas, resulting in significant amounts of CO_2 emissions. The consolidated priority for the EU is to develop renewable hydrogen, and the REPowerEU plan published May 2022 introduced the 'hydrogen accelerator' concept to scale up the deployment of renewable hydrogen, with the ambition to produce 10 million tonnes and import 10 million tonnes of renewable hydrogen in the EU by 2030.

By 2023 the Renewable Energy Directive specified the Renewable Fuels of Non-Biological Origin (RFNBOs, such as electrolytic hydrogen) and setting the targets of 1% for transport and 42% for the industry by 2030 for the Union and its Member States.[7] Also supplemented by the Commission Delegated Regulations the conditions under which hydrogen is accounted as

[4] The EU strategy on hydrogen (COM/2020/301) was adopted in 2020 and suggested policy action points in 5 areas: investment support; support production and demand; creating a hydrogen market and infrastructure; research and cooperation and international cooperation. The Fit-for-55 package, presented in July 2021, put forward several legislative proposals to translate the European hydrogen strategy into concrete European hydrogen policy framework. During 2023 and 2024, that legislation came into force, respectively. Two delegated acts, adopted in June 2023, complemented this policy framework applicable to renewable hydrogen under the RES directive. RFNBOs are addressed in one of those delegated acts, which sets the criteria for products that fall under the renewable hydrogen condition. The other one puts forward a detailed scheme to calculate the LC emissions of renewable hydrogen and recycled carbon fuels to meet the greenhouse gas emission reduction threshold set in the directive.

[5] EC, 2022

[6] EC: acceded in July 2024 (https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en)

[7] EC, 2023

renewable.[8] In addition, the revised Renewable Energy Directive (RED) laid down specific minimum binding targets for the use of renewable fuels of non-biological origin in industry and transport. REDIII, besides simplifying and shortening permitting procedures in a comprehensive and structural manner, has adopted guidance on several areas including renewable fuels of non-biological origin (RFNBOs)[9], namely by clarifying the targets on the consumption of RFNBOs in the industry and transport sectors, and by explaining the calculation of those targets, their scope and the interlinkage between the two targets for industry and transport. The guidance is instrumental to help countries transpose the main elements of the directive into national law by 21 May 2025. It is also key for large scale RFNBO hydrogen production projects or import facilities for conversion of renewable hydrogen (carriers) and will provide more clarity to companies that need to adjust their industrial processes as to include renewable hydrogen.

The Recovery and Resiliency Facility for clean energy was created in 2021 as a temporary instrument made available to EU countries to invest in hydrogen projects across the value chain. Investment support has also been provided through the IPCEI on Hydrogen, which includes four waves. The first 'IPCEI Hy2Tech' was approved in July 2022, aiming at developing innovative technologies for the hydrogen value chain to decarbonise both industrial processes and the mobility sector, with a focus on the end-use including 41 projects on technologies for electrolysers, fuel cells, storage, transmission and distribution, and end user technology. The second wave 'IPCEI Hy2Use' was approved in September 2022, aiming at supporting the construction of hydrogen-related infrastructure and sustainable innovative technologies for the integration of hydrogen into the industrial sector, to deploy 3.5 GW of electrolysis and to support the development of several hydrogen applications in the industry. The third wave 'IPCEI Hy2Infra' was approved in February 2024, aiming at supporting the development of electrolysers, hydrogen transmission and distribution pipelines, large-scale hydrogen storage facilities and handling terminals. The fourth and final wave 'IPCEI Hy2Move' was approved also in 2024, aiming at supporting the development of a set of technological innovations in the frame of mobility.

The EC has presented an ex-ante impact assessment for the EU's 2040 climate target. This recommends reducing the EU's net greenhouse gas emissions by 90% by 2040 relative to 1990. The modelling also includes projections for potential future hydrogen production and demand. In other words, the required volumes of hydrogen could increase in conjunction with decarbonisation beyond what was set out in the REPowerEU Plan.

In addition, the industrialization approach along the hydrogen value chain should be addressed as well. The Green Deal Industrial Plan aims at strengthening the industrial and manufacturing basis of the European Union, decreasing import dependency of the fossil fuels, and increasing resilience and sustainability. The proposal for the Regulation on the Net-Zero Industry Act ('NZIA', adopted on 27 May 2024) and a Critical Raw Material Act ('CRMA', adopted on 11 April 2024) are the key elements of this plan. The NZIA aims at ensuring that the manufacturing

[8] EC: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/renewable-hydrogen_en#:~:text=The%20Delegated%20Act%20on%20a,%2Dbiological%20origin%20(RFNBO).
[9] REDII, Articles 22a, 22b and 25

capacity in the Union of strategic net-zero technologies (which includes electrolysers and fuel cells) approaches or reaches at least 40% of the Union's annual deployment needs by 2030. Large parts of the hydrogen industry already aim to go beyond this. Furthermore, it will accelerate permitting for setting up manufacturing facilities, support a market for more sustainable and resilient net-zero technologies, enhance upskilling and reskilling of the qualified workforce, and foster better coordination between Member States. Meanwhile, the CRMA aims to strengthen the accessibility, and the value chain of critical raw materials used in the production of hydrogen via electrolysis, with a particular focus on circularity.

The Hydrogen Bank launched the first EU-wide auction awarded nearly €720 million to 7 renewable hydrogen projects across Europe under the Innovation Fund (IF). CINEA evaluated 132 bids submitted to the auction between November 2023 and February 2024, from which the successful projects were selected and announced in April 2024. Together, the winning bidders plan to produce 1.58 million tonnes of renewable hydrogen over ten years, avoiding more than 10 million tonnes of CO_2 emissions. The Commission plans to launch a second European Hydrogen Bank auction by the end of 2024 and has published in April and performed a public consultation in June, on the Draft Terms and Conditions of the IF24 auction.

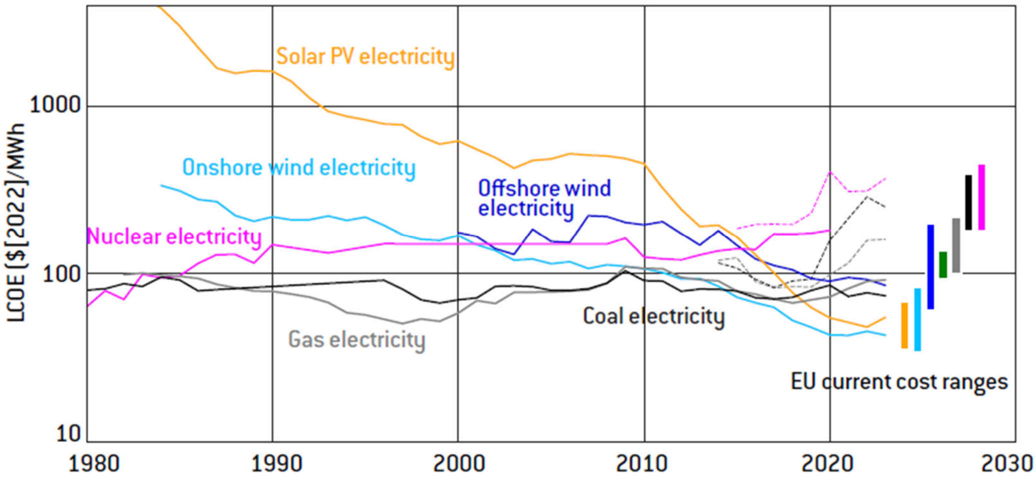
The Clean Hydrogen Partnership (2021-2027) succeeds to the FCH-2 JU, which transferred its legacy portfolio as of 30 November 2021. The core of this Partnership is based on the European Clean Hydrogen Alliance, a joint public-private partnership that was launched alongside the EU hydrogen strategy in 2020, as part of the new industrial strategy for the EU. Bringing together industry, national and local authorities, civil society and other stakeholders, this CH Alliance has a Multiannual Work Programme on that period, and a funding programme under Horizon Europe (2021-2027) of EUR 1.2 billion, aiming at:

- Achieving an ambitious deployment of hydrogen technologies by 2030, by bringing together renewable and low-carbon hydrogen production, hydrogen demand in industry, transport and other sectors, and hydrogen transmission and distribution.
- Launching and exploring the Hydrogen Valleys Platform initiative, under Mission Innovation.

As referred in a previous paragraph, on early 2024 the European Commission recommended that the European Union should cut GHG emissions by 90% by 2040, compared to 1990. The EC modelling showed this target is feasible technically[10] and in line with social acceptability and global fairness objectives. As the result of dedicated support policies and technological advancements, the deployment of clean technologies is underway, and the EU is seeing a significant upscaling of renewables. All pathways to a net-zero economy rely to a certain extent on novel or evolving technologies that so far are unproven at large scale, and this creates risks for decarbonisation, but also potential upsides. In the case of wind and solar power, they have become economically viable and are now the preferred choice for new energy investments.

[10] Based on the REMIND modelling, the EC published results in 2024 on the positive impact up to 2040 of several immature technologies, including e-fuels, electrolysis and, importantly, widespread deployment of carbon-management technologies.

Fig. 1: Wind and solar PV power generation costs are falling at unprecedented rates[11]



However, according to Bruegel think tank[12], different risks – geo-economic instability, technological progress, socio-economic inequities, policy quality and credibility - need to be addressed requiring a robust and resilient designed framework to answer those risks. In the case of technological advances, different technologies are becoming more efficient and affordable at different rates in the long run (fig.1), because of their inherent characteristics such as size, modularity, design complexity, need for customisation and the type of manufacturing or construction processes required.

In the meantime, the European Court of Auditors (ECA) addressed in the summer of 2024 the EU's industrial policy on renewable hydrogen, its plans, legal framework and the measures that were taken so far. It was recognised that the EC policy field of work has created conditions for the emerging renewable and low-C hydrogen markets and has deployed an almost complete legal framework in the same field within a short space of time. Adding to that, it also provided the legal certainty that is necessary for a new market, and the definition of its objectives. However, this EU strategy is likely exhibiting excess of focus on the hydrogen itself, and much less to its derivatives, which will be the real system facilitators in complex systems – providing the flexibility needed in variable chemical forms and contexts of use (e.g. ammonia, SAFs, e-methane, FTL incl. e-SAFs and methanol, and other chemicals and/or applications such as green steel production). The EU's industrial policy on renewable hydrogen has also to solve a problem of consistency in its planning when referring to the ambition of installing 40 GW of electrolysis capacity by 2030 to enable the production of 4.4 megatons of hydrogen, when according to the REPowerEU-Plan the target is to supply 6.6 megatons of hydrogen. The estimates on EU domestic demand based on regulation for the year 2030, would on the other hand amount according to the ECA (2024) to a range between 3.8 and 10.5 Mt, where most of them lie significantly under 10 Mt.

Thus, for a majority of the 20 Mt envisaged in the REPowerEU Plan – 10 Mt from domestic European production, plus 10 Mt imported – there are therefore no significant markets and

[11] Heussaff et al, 2024, based on Way et al, 2022
[12] Heussaff et al, 2024

customers yet. In the market, the uncertainty is mainly in the form of the well-known chicken-and-egg problem: No industrial company will bank on hydrogen if it is not safely available, and no company will invest in expensive infrastructure before customers are ready. It is also likely that the Member States, according to their regional contexts, have different ambitions that do not always coincide with those of the EC decision taking.

The ERA pilot action Agenda Process on Green Hydrogen R&I, launched in 2021, follows to the EU Competitiveness Council conclusions of December 2020[13], in which the Council invites the Commission and Member States interested to conduct an agenda process focusing on a green hydrogen research and innovation pilot action, while ensuring consistency with other related initiatives and without prejudice to the relevance of a broader hydrogen R&I policy approach beyond this ERA pilot action. Being a pilot measure, its goals included as well to strengthen the new European Research Area by generating more commitment, dedication and scope for action from the Member States side. The Strategic Research and Innovation Agenda (SRIA)[14] that was prepared and published in 18 March 2022 as result, is the departure line for the agreement between representatives of the European Commission Services, representatives of the EU Member States and SET Plan countries on setting-up a new Implementation Working Group (IWG) on Hydrogen, within the revamped SET Plan and on setting targets for hydrogen technology development to build a hydrogen economy in Europe by 2050, in accordance with the European Green Deal and in close cooperation with the Clean Hydrogen Partnership (including links to other European Partnerships) and other SET Plan IWGs. The IWG on hydrogen within the SET Plan will coordinate efforts by Member States and stakeholders, help ensure optimal alignment of EU, national and regional initiatives, capitalising on and expanding the existing research and technology infrastructures, namely the Member States' support for Hydrogen Valleys in their national programming. The IWG H2 SRIA is also intended to serve as an orientation and impulse for countries that have not yet developed their own hydrogen strategy or who are revising or updating their national strategies.

From previous work, worth referring to the significant momentum that has been built both by the Hydrogen Council (2017) with its seminal figure (fig.2) on the hydrogen seven roles in decarbonizing major economy sectors (ibid. pg.5), and by Hydrogen Europe namely by the Hydrogen Act[15].

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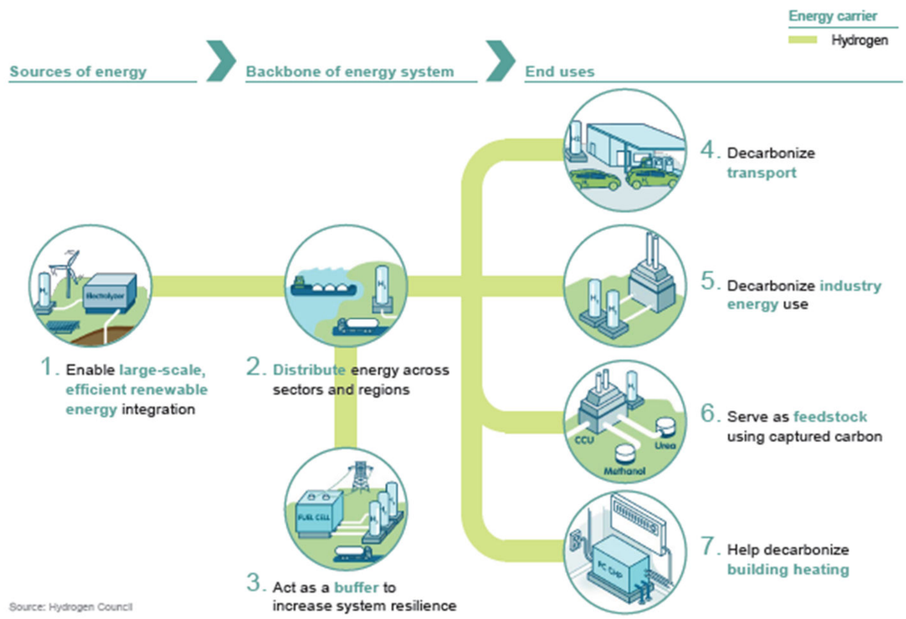
[13] EU Competitiveness Council conclusions of December 2020 13567/20

[14] Expert groups of the agenda process (2022). Strategic Research and Innovation Agenda. Key findings and conclusions of the agenda process for the European research and innovation initiative on green hydrogen. Final version

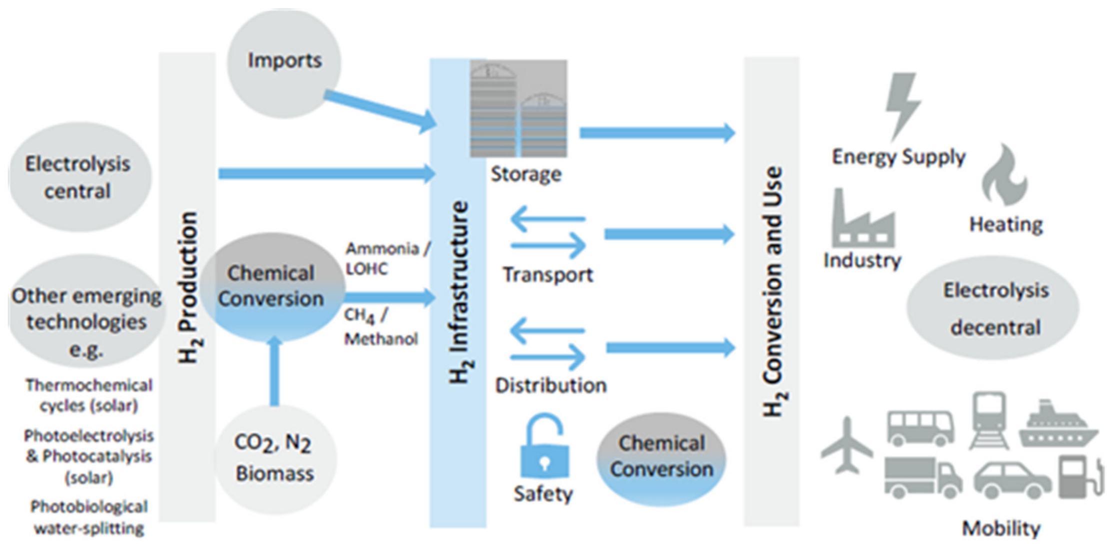
[15] Chatzimarkakis et al, 2021

Fig. 2: Hydrogen roles as a powerful enabler for the energy transition[16]



This proposal 'When H2 matters: From H2 to P2X applications - sources, technology and utilizations', in the frame of the Coordination and Support Action (CSA) SET4H2, draws from experience gathered with the SRIA elaborated in 2022, under the 'Agenda Process for the European Research and Innovation on Green Hydrogen' referred above, and is deeply aware of the envisaged complementarity that should exist with the Clean Hydrogen Partnership Multiannual Work Programme.

Fig.3 - The value chain of green hydrogen, elaborated in SRIA of the 'Agenda Process for the European Research and Innovation on Green Hydrogen' (2022).



[16] Hydrogen Council, 2017:5

Building on the value chain concept for green hydrogen that was elaborated in the SRIA under the ERA Agenda Process (fig. 3), the 'When H2 matters: From H2 to P2X applications - sources, technology and utilizations' is a framework proposal (fig.4 based on four main facts:

a) Hydrogen is a central product of P2X strategies, and a key intermediary in the processes implemented for renewable electricity conversion.
b) Power-to-X (P2X): where 'X' = final products/applications on energy including but not limited to gaseous fuels (hydrogen, methane), liquid and synthetic fuels (gasoline, kerosene or diesel, e-SAF), ammonia and other chemicals (methanol), and value chains that integrate electricity conversion, energy storage (power, heat), and reconversion pathways that use surplus renewable energy.
c) The Hydrogen Economy, and the energy transition towards a net-zero condition by 2050, is already using and will benefit from an integrated approach to all the P2X value chains.
d) Within a comprehensive P2X strategy to serve the Hydrogen Economy, such integration requires flexibility enough to inspire the approach to the different contexts at a country level, where each P2X value chain is designed, planned, promoted and implemented to evolve along time on different perspectives (e.g. technology, markets, and other). Such flexibility strongly suggests on the other hand that modular-oriented 'fit-for-purpose' design should have a key role on each national system's architecture.

This framework proposal should require further elaboration by the SET Plan TWG H2, as specificities and requirements at the Member countries are likely to be integrated.

Last but not the least, the European Commission's impact assessment report[17] accompanying the working document "Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society"[18] points to the need to improve the role of P2X technologies in meeting energy goals in the next decade.

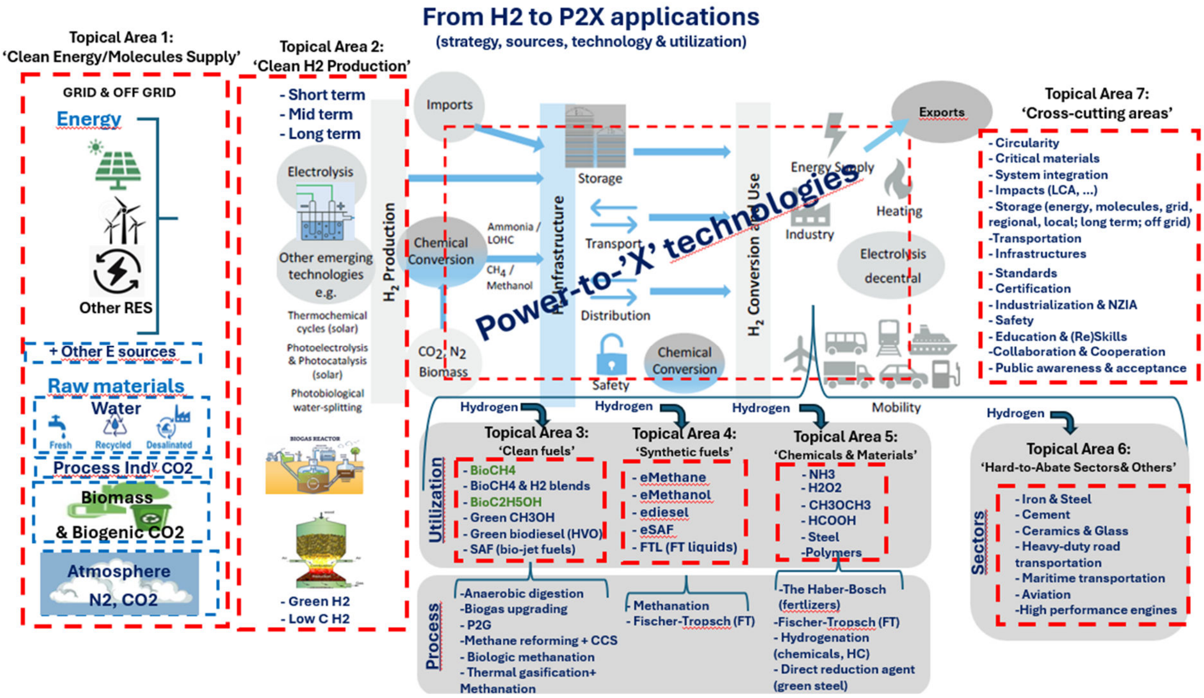
Adding to that, evidence also shows that there is more beyond what IEA is stating as "Technologies needed are not there yet fully developed or widely available"[19] is just partly true as the transition process we are currently experiencing is carrying a combination of both new and existing elements to the system – which are enablers of disruptive effects just like Hydrogen alone has been showing as well since 2020.[20]

Having that said, to assist the delivery of the R&I implementation plan of the new SET Plan IWG H2, the proposal 'When H2 matters: From H2 to P2X applications - sources, technology and utilizations' herewith aims - after discussion for coherency and consistency checking, to

[17] CE 'SWD(2024) 64 final'
[18] EC, 2024
[19] The International Energy Agency (IEA) recently highlighted the challenges in the global energy transition in their World Energy Outlook 2024 report. They emphasized that clean energy technologies are advancing rapidly, as well as that the necessary technologies to fully achieve a clean energy transition are not yet fully developed or widely available. This underscores the mixed need for: stronger policies namely on the promotion of markets creation and business models, on greater investments to accelerate the development and deployment of these technologies, but as well on the literacy of strategic innovation management and on strategic energy modelling – to be ready for emerging technologies.
[20] According to Partidário et al (2020)

be further elaborated at the TWG Hydrogen level. The span of this analysis includes the H2 and derivatives value chains perspectives – from power and feedstock supply to the 'X' production, till the end-use markets, as well as to the exports of commodities where applicable. Finally, building on the result, if existing redundancies, when compared to the Clean Hydrogen Multiannual Work Programme, must be minimized.

Fig. 4: The framework proposal: if adopted, it requires further elaboration by the SET Plan TWG H2

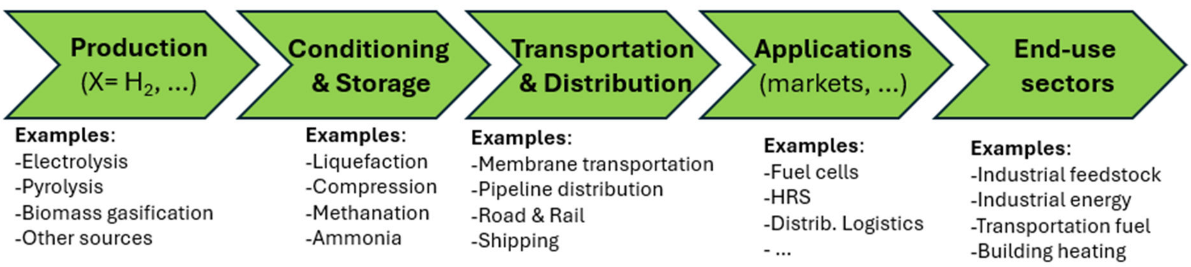


1.4 An integrated approach proposal, based on the role of H2 & P2X

What does it mean?

Taking a P2X based bottom-up approach, this framework proposal refers to a range of scientifically and technologically accepted technologies that convert electricity, particularly from renewable sources, into other forms of energy or products, primarily driven by the production of hydrogen through electrolysis - a process in which water is split into hydrogen and oxygen using electricity (fig. 5). The produced hydrogen, known as green or clean hydrogen when produced using renewable electricity, can either be used directly or as a base reactant to produce a variety of energy carriers, raw materials and other products.

Fig. 5: Hydrogen and its value chain: A primary product of P2X



Why is P2X important?

Power-to-X (P2X) technologies will play an increasingly crucial role in our path towards a sustainable and carbon-neutral future. By changing the form of renewable energy from electricity to molecules, it becomes better suited to decarbonizing industries that cannot be directly electrified fully and at scale. P2X technology is one of these key solutions, providing alternatives of indirect electrification solutions. By providing carbon-neutral alternatives to fossil fuels, P2X offers a viable pathway to significantly lower carbon emissions in carbon-intensive sectors that are difficult to electrify and account for around 30% of global emissions. Adding to that, besides being instrumental to the effective implementation of the Renewable Energies Directive and to the application of circular economy concept, P2X technologies provide:

(i) a flexible and efficient way to store and use excess renewable energy, and

(ii) a versatile solution due to their ability to produce a variety of energy carriers and products,

thus contributing significantly at a system level to the global energy transition. P2X technologies are expected to serve as the backbone of a resilient, decentralized, and carbon-neutral energy system.[21]

Power-to-X (P2X) technologies are versatile. That versatility of P2X is integrated in the variable 'X', which represents the various energy carriers or raw materials produced from green hydrogen, because they can convert electricity into various forms of energy or products. This includes gases (e.g. hydrogen or methane), liquids (e.g. synthetic fuels), heat, or even chemicals. This versatility allows P2X technologies to be used in a wide range of sectors, including transportation, heating, and chemical industries, by providing an energy source to reduce the carbon footprint in those sectors. It can store excess renewable energy, that can then be converted back to electricity, when necessary, despite the reduction of efficiency at a system level, but promoting the stability of the energy grid.

Research strategy: How to set up an integrated framework proposal

There is significant evidence that hydrogen technology, and the P2X strategies at large, provide a promising technology cluster to address the decarbonization of several different sectors. P2X faces different challenges: competition with available, well known and cost competitive solutions, versatile and carbon emission-free applications, performance (efficiency, effectiveness) according to the advancement of technologies, costs (CAPEX, OPEX), the public perception and acceptance, and the integration with current energy and manufacturing infrastructures that support the national economies are being considered as some of the major challenges for the P2X technologies to be quickly adopted for commercial production of various products.

These challenges are not easy to solve and often slow down the adoption of this sort of technologies, but they can be mitigated - as the global competition process has shown in the human history, and along every value chain – from production to end use applications. In

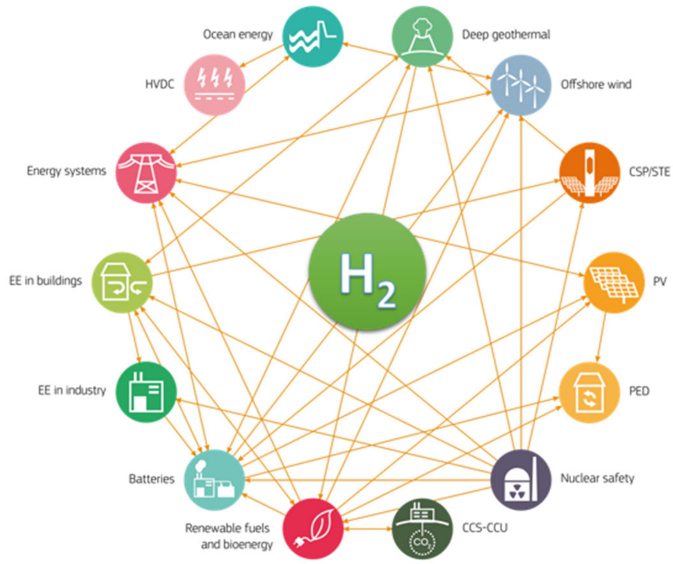
[21] Ullah M et al, 2022; Mertens J et al, 2023

system design and integration, there is a demand for further R&D and innovations that can be brought to market, as well as practical experience in project implementation.

It includes different topical areas (TA_n) which are intended to be used as line of departure for further elaboration of the IWG strategic activities and targets setting on technology development:

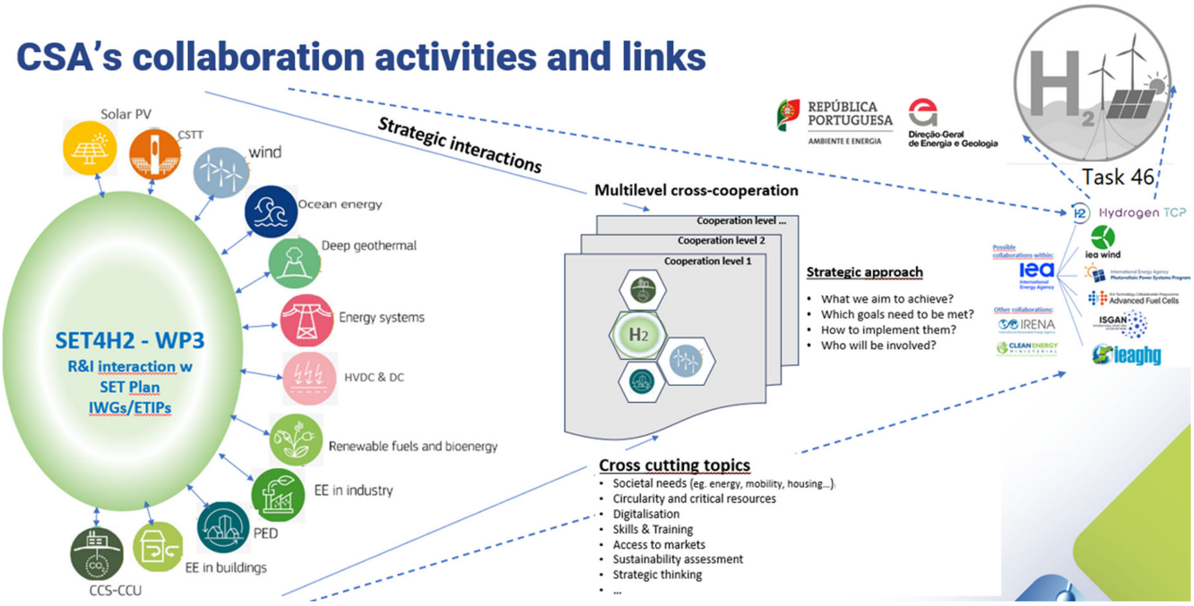
- TA1: 'Clean Energy/Molecules Supply';
- TA2: 'Clean H2 Production, incl. CCUS';
- TA3: 'Biogenic C-based fuels';
- TA4: 'Synthetic fuels';
- TA5: 'Decarbonised Chemicals & Materials';
- TA6: 'Hard-to-Abate & Other uses';
- TA7: 'Cross-cutting areas'.

Fig. 6: Existing collaborations within the SET Plan IWGs enables to anticipate a potential role hydrogen has for cooperation in different areas and contexts.



In the frame of the SET Plan IWGs, there is potential for cooperation between the Hydrogen IWG and other SET-Plan IWGs along the entire hydrogen value chain (Fig. 6). Each topical area requires specific elaboration in the frame of a TWG H2 (Fig. 7), having into consideration the potential role the SET Plan is likely to offer for close cooperation with other IWGs, ETIPs, European Partnerships (e.g. CHP and Processes4planet) and different IEA TCPs and Tasks therein. That is the case of IEA Task 46-H2TCP addressing offshore hydrogen production.

Fig. 7: Insight on the role of SET4H2 project within the SET Plan collaborations

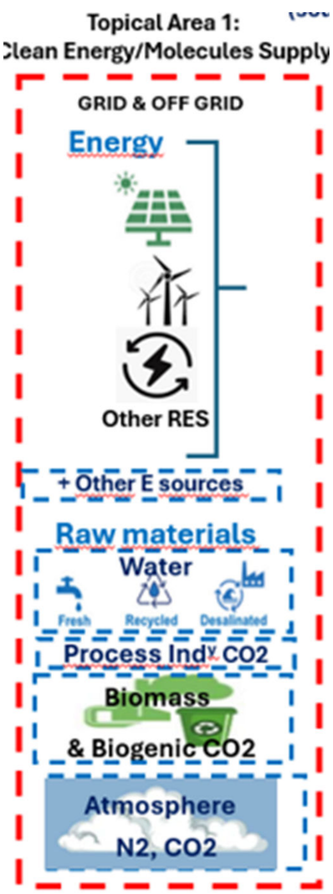


2. Clean energy and molecules supply

The processes of supplying and using renewable and sustainable energy sources to produce hydrogen and its derivatives is a key part of the energy transition towards a more sustainable and resilient future. It involves the production of hydrogen and its derivatives using renewable energy sources, thereby contributing to the decarbonization of various sectors and the reduction of GHG emissions.

2.1 Energy supply

The process of producing hydrogen and its derivatives using renewable energy sources on either on the basis of a grid-connected system or an off-grid system, contributes to the supply of clean energy. This is because it helps reduce our reliance on fossil fuels and lowers greenhouse gas emissions.

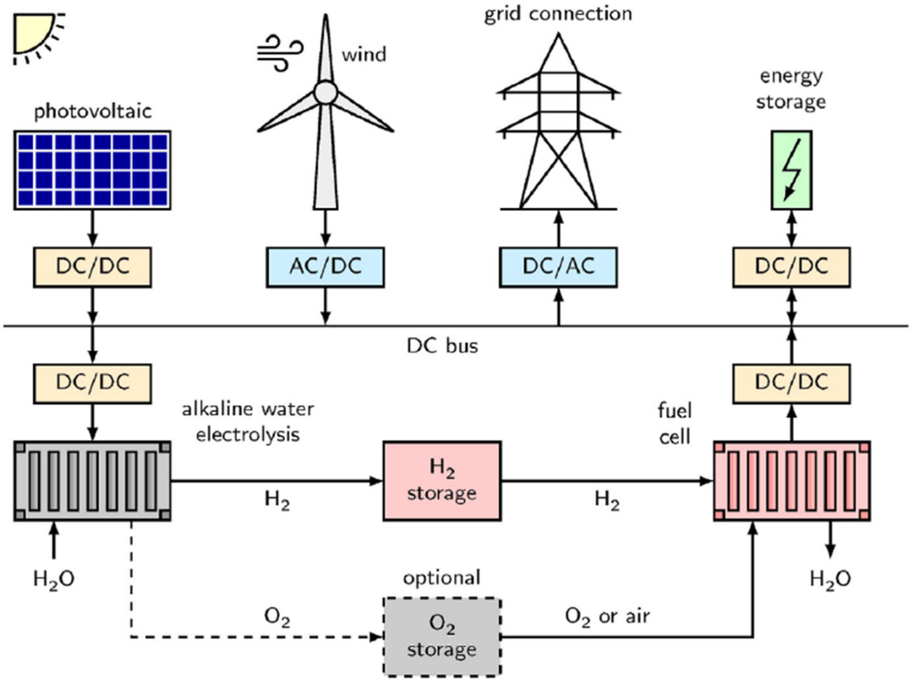


Grid-connected energy system.

Electrolysis involves splitting water molecules into hydrogen and oxygen using an DC electrical current. One of the critical components in the electrolysis process is the DC power supply, which provides the necessary electric current for the electrolysers using rectifier for hydrogen.

Fig. 8 provides a diagram of a grid-connected hydrogen energy system, based on the integration of two renewable energy sources: solar PV and wind. This illustrates the desired stabilisation of the power grid with the introduction of the electrolyser. Photovoltaic panels and wind turbines are interconnected to a direct current (DC) bus through appropriate converters, enabling the provision of electricity to alkaline water electrolysers.[22] The generated hydrogen can be stored for subsequent utilisation in fuel cells. It is possible to utilise the generated oxygen instead of atmospheric air to enhance fuel cell efficiency.

Fig. 8: Schematic diagram of integrating renewable energy sources together with water electrolysis for hydrogen production, in a grid-connected energy system[23]



Consequently, the provision of an extra storage tank necessitates additional expenditures. The fuel cells are additionally linked to the direct current (DC) bus, enabling the power to be harnessed by the energy system through direct current to alternating current (DC/AC) converters.[24][25] Hydrogen can be generated and utilised as an energy source during periods of reduced energy requirements. When an abundance of energy is present, energy storage systems can be charged to their maximum capacity, ensuring that the stored energy is readily accessible when required. Difficulties in maintaining constant power frequency commonly encountered in power grids with a larger share of renewable energies can be addressed by hydrogen energy devices such as alkaline water electrolysers.

The CO_2 emissions that come with hydrogen production can be greatly reduced when synthesised by renewable energy and integrated with the electricity grid to support electricity generation. In addition, the capacity to produce hydrogen in a versatile manner through the process of water electrolysis can contribute to the efficient functioning of the electrical grid by aiding in the preservation of grid stability and the mitigation of operational expenses.

[22] Brauns et Turek (2020)
[23] Brauns et Turek (2020), Processes 8 (2) 248
[24] Ulleberg Ø (2003).
[25] Shen X, Zhang X, Li G, Lie TT, Hong L (2018).

Off-Grid Energy Systems

Off-grid energy systems are innovative approaches designed to operate independently from the main electricity grid. They are particularly useful in remote areas where extending the grid is not feasible. Key components include:

- The renewable energy sources - These systems often rely on solar panels, wind turbines, or small hydroelectric generators to produce electricity.
- The energy storage - Batteries or other storage solutions are used to store excess energy generated during peak production times for use when production is low.
- The energy management system - Advanced control systems manage the generation, storage, and distribution of energy to ensure a reliable supply.

The energy island concept is an innovative approach as well, which strongly combines with the off-grid energy system, to decentralise the generation and distribution of renewable energy. Energy islands are large-scale, artificially created or natural offshore platforms designed to harness renewable energy, primarily from wind farms, and either manage it locally or distribute it to the mainland. Having these features, they can also support the production of green hydrogen and other e-fuels. Key features include:

- **A centralized energy hub** - Energy islands act as central hubs for generating, collecting and distributing renewable energy from multiple offshore sources to nearby regions.
- **Renewable energy generation** - They primarily use offshore wind turbines but can also integrate solar and wave energy. Offshore wind farms are the most common, given the strong and consistent winds at sea.
- **Energy conversion and storage** - These islands can convert electricity into green hydrogen for storage and transport, enhancing energy security and reducing carbon emissions.
- **Benefits by integration** of both off-grid systems and energy islands concepts, contributing to: (a) reduce carbon emissions by relying on renewable energy sources thus contributing to meet climate targets; (b) enhance energy security by providing stable, local sources of renewable energy, reducing dependence on imported fossil fuels; (c) enable scalability, as on the one hand off-grid systems are ideal for small, remote communities, while energy islands can support large-scale energy needs and facilitate the transition to a green energy economy.

Examples of energy islands are being provided by Denmark that is leading the way with plans to establish two large-scale energy islands in the North Sea and the Baltic Sea. These projects aim to significantly increase the country’s offshore wind energy capacity.

2.2 Water supply

To produce the same amount of energy, green hydrogen often consumes less water than fossil fuel-based hydrogen or some types of electricity generation (like nuclear electricity). However, this does not negate the imperative that green hydrogen developers prioritize efficient process design and consider local water availability and treatment in project planning. In areas of water scarcity, consideration of alternative sources such as treated wastewater or desalinated sea water can minimize freshwater reliance.

Per chemistry fundamentals, via electrolysis 9 litres (L) of purified water are required to produce 1 kilogram (kg) of hydrogen (H2). In practice, an additional volume of water of 10-20 L/kgH2 approx. is required for purification and process cooling purposes. Inefficient designs such as evaporative cooling systems may exceed this range, but those systems are uncommon, especially at large scales of production. Green hydrogen's cumulative 20-30 L/kg of water consumption is on par with or even less than the 20 to 40 L/kg of water required for fossil-based hydrogen production pathways.

Water access and requirements for green hydrogen production can be effectively managed if intentional sourcing, project siting, and efficient use is prioritized.

2.3 Carbon dioxide supply

To supply CO_2, the main methods available are the following: Process industry fixed sources; Direct air capture; and Biomass combustion. These methods ensure a steady and renewable supply of CO_2, which is crucial for producing e-fuels in a climate-neutral way.

2.3.1 Process industry source of CO_2

CO_2 can be captured from industrial processes, such as flue gases from fossil fuel combustion or biogas plants. This method is often more efficient because the CO_2 is already concentrated. Includes the CCU systems during the blue H2 production downstream to SMR reactors, and the gaseous process emissions from the energy supplied to drive the CCU system itself.

CCS costs/ ton CO_2 (2023) = US$15-20 (industrial flue gas concentrated flows)

2.3.2 Atmospheric source of CO_2

Direct air capture (DAC) is a technology that captures CO_2 directly from the atmosphere. Although it's more energy-intensive due to the low concentration of CO_2 in the air, it offers a sustainable way to source CO_2. The CCS costs per ton CO_2 amounted in 2023) to US$ 40-120 diluted flows using DAC (Direct Air Capture).

2.3.3 Biogenic sources of CO_2

This method not only provides a renewable source of CO_2 but also helps in managing waste and reducing greenhouse gas emissions.

- Capturing CO_2 using residual biomass as feedstock involves:
- The biomass collection of residual biomasses, such as agricultural waste, forestry residues, or organic municipal waste.
- A combustion or gasification process: The biomass is then subjected to combustion or gasification. In combustion, the biomass is burned in the presence of oxygen, producing CO_2 and heat. In gasification, the biomass is converted into syngas (a mixture of CO and H2) through partial oxidation.
- The CO_2 capture: The CO_2 produced during these processes is captured using technologies like amine scrubbing, where CO_2 is absorbed by a solvent and then released for storage or utilization.

- Utilization or Storage: The captured CO_2 can be used in various applications, such as in the production of e-fuels, or stored underground in geological formations.

2.4 Nitrogen supply

In a given reaction process where nitrogen is required, it is supplied to the reactor primarily through the fractional distillation of air. Main steps:

- Air Liquefaction: Air is cooled to very low temperatures (below -200°C) to liquefy it.
- Fractional Distillation: The liquefied air is then separated into its components. Nitrogen, which has a lower boiling point than oxygen, is distilled off.
- Purification: The nitrogen is further purified to remove any remaining impurities.

This purified nitrogen is then fed into the reactor, where it reacts with hydrogen.

2.5 Critical and strategic raw materials

Different raw materials are key and strategic in the hydrogen value chain. As the same challenge and rational applies to hydrogen derivatives, for the sake of a better focus, the scope of this section is limited to hydrogen and fuel cells.

Materials vital for ensuring the efficiency and sustainability of hydrogen technologies. Particularly for the production and utilization of hydrogen, are included the following:

- Platinum and Iridium: Essential for Proton Exchange Membrane (PEM) electrolysers, which are used to produce hydrogen from water.
- Titanium and Copper: Also used in PEM electrolysers for their durability and conductivity.
- Nickel and Graphite: Important for Alkaline electrolysers, another type of technology used for hydrogen production.
- Aluminium, Zinc, and Copper: Crucial for the infrastructure needed to generate renewable energy, which powers hydrogen production.

In the energy generation process to supply the electrolysers, there are several key materials to ensure the efficient generation and storage of renewable energy, which is then used to power electrolysers for hydrogen production. These include:

- Silicon: Used in solar panels for photovoltaic energy generation.
- Copper: Essential for electrical wiring and components in both solar and wind energy systems.
- Rare Earth Elements (REEs): Such as neodymium and dysprosium, which are crucial for the magnets in wind turbines.
- Lithium, Nickel, and Cobalt: Important for energy storage solutions like batteries, which store the electricity generated from renewable sources.

Fig. 9: Critical and strategic raw materials relevant for electrolysers[26]

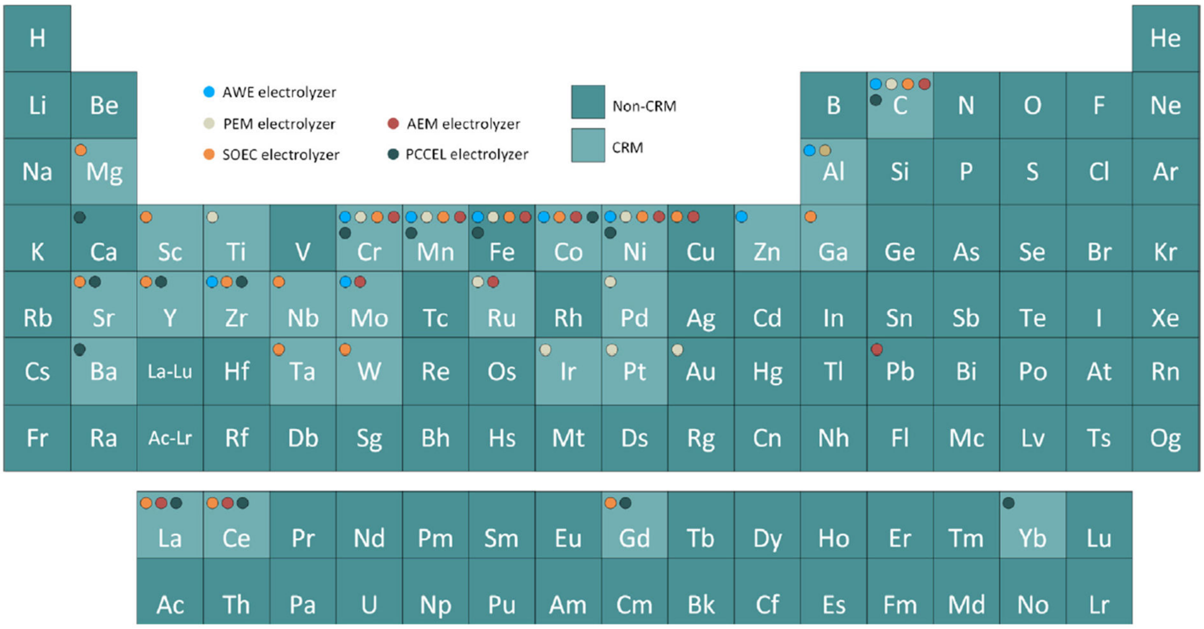


Fig. 9 makes the representation of the material demands from the various existing electrolyser and fuel cell technologies. Here, the critical raw materials (CRM) are colour coded in light teal blue squares, in order to distinguish them from the non-critical raw materials. The materials utilized in different electrolyser technologies, such as AWE, PEM, AEM, SOEC, and PCCEL, are indicated by coloured dots.

Fluoropolymers, more precisely per- and polyfluoroalkyl substances (PFAS), have been a key material for many applications, including in the energy and mobility sectors: Lithium-ion batteries, electrical systems, high-voltage cables, gaskets, seals and many other components. In the hydrogen value chains, PFAS are used in Membrane-Electrode-Assemblies (MEAs), Gas Diffusion Layers (GDLs), diaphragms for chloralkali electrolyzers and other components, in the form of perfluorinated sulfonic acid (PFSA)-based ionomers (Nafion) and Polytetrafluoroethylene (PTFE or Teflon).

On January 2023, the European Chemicals Agency (ECHA) received a proposal to restrict per- and polyfluoroalkyl substances (PFAS) under the REACH Regulation, motivated by the high persistence and possible adverse effects on environment and human health of these “forever chemicals”. The restriction would ban the manufacture, placing on the market and use of PFAS in non-essential applications. PFAS covers an extremely broad range of substances, including some substances used in the manufacture of filter media part of the hydrogen value chain. Fluoropolymers are included in proton exchange membranes, in PEM electrolysers, and fuel cells, as binder materials in the electrodes, as a component of the gas diffusion layers, in gaskets and sealings, and in valves of the transport and distribution system.[27] Discussions on this regulation on PFAS are still ongoing within ECHA's scientific committees[28], in parallel to research and innovation aiming the development of fluorine free hydrogen technologies.

[26] Eikeng et al (2024).
[27] Hydrogen Europe position paper on PFAS, January 2023 (hydrogeneurope.eu)
[28] https://echa.europa.eu/pt/hot-topics/perfluoroalkyl-chemicals-pfas

To gain insight into the electrolysers and fuel cells, to address the critical and strategic raw materials at play, material supply chain and their recycling/ reuse ability must be considered. Their production relies on the availability of those critical and strategic raw materials. In order to reduce the environmental footprint of electrolysers and fuel cells, to make them more sustainable options for energy production and storage, the circularity of electrolysers and fuel cells is being addressed through several key strategies aimed at making these technologies more sustainable and environmentally friendly:

Material Recycling:

Efforts are being made to recycle critical materials used in electrolysers and fuel cells, such as platinum, palladium, and other rare earth elements. This reduces the need for new raw materials and minimizes waste.

Design for Disassembly:

Manufacturers are designing electrolysers and fuel cells in a way that makes them easier to disassemble at the end of their life cycle. This facilitates the recovery and reuse of components and materials.

Extended Product Lifespan:

Improving the durability and efficiency of electrolysers and fuel cells extends their operational life, reducing the frequency of replacements and the associated environmental impact.

Closed-Loop Systems:

Implementing closed-loop systems where the by-products of the electrolysis and fuel cell processes are reused within the system or in other industrial processes helps in minimizing waste.

Sustainable Manufacturing Practices:

Adopting greener manufacturing processes, such as using renewable energy sources and reducing emissions during production, contributes to the overall sustainability of these technologies.

Regulatory and Policy Support:

Governments and regulatory bodies are increasingly supporting circular economy principles through policies and incentives that encourage recycling, reuse, and sustainable design in the production of electrolysers and fuel cells.

3. Hydrogen & H2 derivatives production

On the road to decarbonisation for addressing climate and energy challenges, a sustainable energy policy able to strengthen the sectors' competitiveness is key, while developing and promoting an enhanced balance between the three pillars of sustainability.

Promoting the production and use of energy from renewable or low-carbon sources is not only instrumental to reduce greenhouse gas emissions, but also enables to reduce imports and dependency on fossil fuels, as well as a more diversified national technology portfolio, thus contributing to diversifying the energy mix and the security of supply. As stated in the framework document 'G20 Energy Transitions Working Group Issue Note', there are numerous technological routes to cleaner energy production and there is no one-size-fits-all pathway. It is essential to continue to encourage research, development and innovation, in general as well as focused on local and regional contexts. Sustainable fuels (e.g. liquid biofuels, renewable fuels of non-biological origin, renewable gases, etc.) can play an important role in achieving climate and energy objectives, particularly in end uses where electrification is not an adequate solution or when not economically attractive.

3.1 Renewable Hydrogen versus Clean Hydrogen

Hydrogen is a promising energy source that can be produced using various methods.

3.1.1 Renewable hydrogen

Renewable hydrogen, often referred to as "green", is hydrogen produced from non-fossil feedstock and green energy inputs and therefore included in the renewable fuels category. According to their production paths, three main types of renewable fuels are available: Biogenic C-based Fuels, Synthetic Fuels, and Renewable Hydrogen.

There is evidence however that water electrolysis is the main pathway for producing green hydrogen, due to several factors that make it comparatively a more promising and viable method for producing green hydrogen:

a) Zero Emissions: Electrolysis produces hydrogen by splitting water into hydrogen and oxygen using electricity. When powered by renewable energy sources like wind, solar, or hydro, this process results in zero greenhouse gas emissions;
b) Scalability: Electrolysers can be scaled to match the available renewable energy capacity, from small, distributed systems to large, centralized production facilities;
c) Technological Maturity: Electrolysis technology - particularly the polymer electrolyte membrane (PEM) and the alkaline electrolysers - is well-developed and commercially available. Ongoing advancements are continuously improving efficiency and reducing costs;
d) Versatility: Electrolysis can be integrated with various renewable energy sources, making it a flexible option for different regions and energy systems;
e) Support for decarbonization goals: Electrolysis aligns with global efforts to reduce carbon emissions and transition to a sustainable energy future. It supports the

production of green hydrogen, which can be used in various sectors, including transportation, industry, and power generation.

Production by water electrolysis.

Green hydrogen is produced by water electrolysis in a process using renewable energy sources like wind or/and solar, or hydropower, to split water (H_2O) into hydrogen (H2) and oxygen (O2). This is the more frequent and used path currently, being considered environmentally friendly because it generates very low or no carbon emissions during the production stage of the lifecycle, typically varying in the range: 0 - 2 g CO_2eq /gH2.

Economic viability

Together, the costs of electricity and electrolysers make up the bulk of green hydrogen production costs. Reducing these costs through technological advancements, increased efficiency, and cheaper renewable energy sources is crucial for making green hydrogen economically viable. How significant are the costs of electricity and electrolysers in the production of green hydrogen?

Electricity costs: Electricity is the largest cost driver in green hydrogen production, accounting for about 60-70% of the total production cost. The cost of electricity from renewable sources like wind and solar can vary, but it generally ranges from $20 to $60 per MWh. Lower electricity costs directly reduce the overall cost of hydrogen production. The efficiency of the electrolysers affects how much electricity is needed. Higher efficiency means less electricity is required, which can significantly lower costs.

Electrolyser Costs:

a) Capital Expenditure (CAPEX) The initial investment in electrolysers is another major cost factor, contributing around 20-30% of the total cost;
b) Technological advancements: As technology improves and production scales up, the cost of electrolysers is expected to decrease. Current costs are around $500 to $1,000 per kW of capacity, but this could drop to $200 to $400 per kW by 2030;
c) Operational Expenditure (OPEX): Maintenance and operational costs for electrolysers are relatively low compared to the CAPEX, but they still contribute to the overall cost.

Other green H2 production pathways

Hydrogen can be produced as well via biomass gasification (thermal, biological, air driven), pyrolysis (thermal, catalytic, hydrothermal) or by other renewable processes, which use electricity, heat and/or (bio)chemical reactions to release hydrogen from organic feedstocks.

Hydrogen can be used for directly for combustion (either alone or blended with other gases such as methane) or in fuel cells to produce electricity and heat. The indirect uses are also important, such as an input for producing conventional fuels in oil refineries, for assembling biological fuels (e.g. HVO), or as a feedstock for assembling non-energy products (e.g. plastics, fertilisers) or synthetic fuels.

3.1.2 Clean hydrogen – A non-nuclear approach

All renewable hydrogen is clean, but not all clean hydrogen is renewable, because there are differences how renewable/ "green" hydrogen compared to other forms of hydrogen is produced. Therefore, clean hydrogen is a broader term that can include "renewable" and "low-carbon (low-C)" hydrogen where the latter encompasses hydrogen produced through other methods and feedstock plus add-on technology to include end-of-pipe approaches (e.g. CCUS), which aim to reducing carbon emissions without entailing other greenwashing effects.

It should be underlined that low-C hydrogen, often referred as blue hydrogen, as a strategy only works to the extent it is possible to use or store carbon dioxide long term indefinitely into the future without leakage back to the atmosphere. That said, renewable hydrogen is a standard for sustainability, while clean hydrogen represents a range of methods with varying environmental impacts along the whole lifecycle, which leads to an extra requirement of identification and accountability.

For example, low-C hydrogen is produced from the SMR of natural gas (NG) assisted by carbon capture, use and/or storage (CCUS) to reduce CO_2 emissions from steam reforming at a certain efficiency level – according to the CO_2 emission reduction technology used. However, such process must address different emission sources, as detailed described by Howarth et Jacobson (2021).[29] Therefore, not all clean hydrogen is as environmentally friendly as renewable hydrogen, as low-C hydrogen still involves some carbon emissions, although significantly less than grey hydrogen, which is produced from NG without CCUS.

Adding to those CO_2 emissions, the methane emissions should be added. Thus, beyond those clean conditions, i.e. if the clean condition is not met anymore by producing "grey" and "brown" hydrogen, respectively from NG (the SMR process) or from coal, because of their high carbon intensity.

According to Bauer et al[30] in order to be competitive with renewable hydrogen in terms of climate impacts over the long-term, low-C hydrogen should exhibit a life cycle GHG footprint of not more than 2–3.5 g CO_2- eq./g H2. This is only possible with high CO_2 removal rates and methane emission rates below about 1% (GWP100) or 0.3% (GWP20).

For more insight on clean hydrogen, please refer to the carbon capture of CO_2 emissions in grey H2 production, in the frame of the carbon capture, use and/or storage section of this report.

3.1.2 H2 as a system facilitator

The hydrogen molecule can be converted into other useful compounds, known as hydrogen derivatives – the so called P2X products. Those hydrogen derivatives, such as ammonia, methanol, jet fuel and other synthetic fuels, play a significant role in the economy, particularly in the context of the energy transition and decarbonization efforts. Overall, hydrogen derivatives are poised to play a transformative role in achieving a sustainable energy landscape and driving economic growth in the emerging clean hydrogen economy.

Their relevance will be highlighted in Sections 3.3 and 3.4, by providing the following features packed into different solutions for integrated approaches compatible with the clean energy

[29] Howarth et Jacobson (2021).
[30] Bauer et al (2022), (2021:70).

transition complexity, having H2 (electron/molecule) in a central role, and taking from there a wide range of applications (end use product; intermediate product; or industrial commodity) as well as the support and assistance from product quality infrastructure ecosystem[31], which provide instruments and services to reduce safety, financial and reputational risks in the P2X sector[32]. P2X strategies, where 'X'= H2, and other products, includes gaseous fuels (hydrogen, methane), liquid and synthetic fuels (gasoline, kerosene or diesel, e-SAF), and chemicals, e.g. ammonia and methanol.

3.2 Carbon Capture, Use and/or Storage (CCUS)

Carbon capture, use and storage (CCUS) is an abatement dual path strategy aimed at reducing carbon dioxide (CO_2) emissions by capturing those fixed source emissions from industrial processes and power generation, followed either by a CO_2 utilization or by a permanent storage step.

Emissions from steel, cement and chemicals can be cut using carbon capture technology, which can work well at scale. Adding to that, an emerging market for carbon capture technology is to decarbonize the hydrogen production by steam methane reforming (SMR). However, the carbon intensity of the CO_2 capture from those flue gas emissions from CCUS can itself vary widely - typically in the range: 56-90%, depending on the specific technology and application. Where adequately applied (above 90%)[33], overall CCUS is considered a key technology for reducing gaseous emissions in sectors where other methods are less effective or more expensive. Let's take the SMR case followed by CCU, aiming at just producing blue hydrogen (fig. 10).

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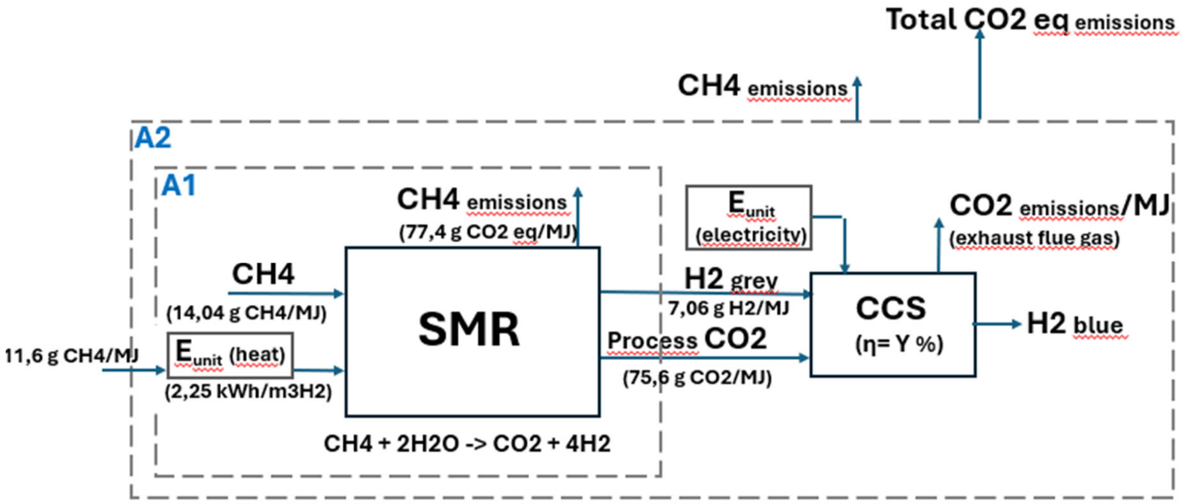
[31] Quality infrastructure ecosystem incl. standardisation, metrology, conformity assessment, accreditation as well as technical regulations.
[32] IRENA, 2024
[33] Being renewable H2 the reference (ie. a carbon intensity lower than approx. 3 g CO_2eq /gH2).

Fig. 10: The role of CCU in blue hydrogen production



Considering an established average footprint[34] of 11,5 gCO$_2$eq per gH2 for grey hydrogen[35] when SMR is not assisted by any CCU approach, if it is the case however that only the CO_2 from the SMR process itself is captured (i.e. methane not included), it is also well reported[36] that total emissions of CO_2 are 51.7 g CO_2 per MJ (i.e. 6,2 g CO_2 /gH2, at an LHV of 120 MJ/kg approx.)[37]. When efforts are also taken, in the frame of the CO_2 approach, to capture the CO_2 from the flue exhaust from the energy driving the SMR process, the total CO_2 emissions are 39.7 g CO_2 per MJ (i.e. 4,8 g CO_2 /gH2). By treating the exhaust flue gases for CCS reduces total lifecycle CO_2 emissions by 23%, less than might have been expected. This is due both to a relatively low efficiency for the carbon capture of flue gases – which has been extensively reported, and to the increased combustion of NG needed to provide the electricity for the carbon capture.

The methane (CH4) emissions from blue hydrogen are the same as for grey hydrogen, except for those associated with the increased use of energy from NG to drive the CCS process. The emissions for grey hydrogen are 77.4 g CO$_2$eq per MJ. The additional CH4 emissions from the NG used to drive CCS are: 9.5 g CO$_2$eq per MJ when only SMR is treated just by CCS and 18 g CO$_2$eq per MJ when the exhaust flue gases are also captured. Therefore, the total upstream CH4 emissions for the blue hydrogen production are 86.9 g CO$_2$eq per MJ, when just emissions from the SMR process are captured. If flue gases are also treated, the total upstream CH4 emissions are 95.4 g CO$_2$eq per MJ.

Overall, by considering all those CO_2 and CH4 emissions streams for the blue H2 case, when the SMR process is analysed to include not just downstream but also upstream emissions, then total emissions are 139 g CO$_2$eq per MJ (i.e. 51.7 g CO_2/ MJ + 86.9 g CO$_2$eq/ MJ).

[34] Bauer et al (2022).

[35] The grey H2 footprint is identified by Wood Mackenzie in the range: 9,8 – 13 g CO$_2$eq per gH2.

[36] Howarth et Jacobson (2021).

[37] To convert emissions from g CO_2/MJ to g CO_2/g H2, consider: the energy content of H2 = 120 MJ/kg approx., or 0.12 MJ /gH2. Then, CO_2 emissions per H2 mass are the following: g CO_2/MJ x 0.12 MJ/g H2

Those total emissions of 139 g CO_2eq per MJ for blue H2 can be lowered down to 135 g CO_2eq per MJ (i.e. 39.7 g CO_2/ MJ + 95.4 g CO_2eq/ MJ) with a more elaborated layout, where a CO_2 treatment is added to the CCU own exhaust flue gas.

To conclude:

a) When compared to the green H2 case, and despite a serious ongoing effort to provide a competitive playing field for blue H2, the fact is that it is not enough just producing grey H2 followed by an end-off pipe CCUS treatment - and very often introducing it as a proxy of green H2 - as the zero or very low GHG emissions cannot be met during the 'blue H2 value chain'. As shown before, for that to happen, blue H2 needs to exhibit a life cycle GHG footprint of not more than 2–3.5 g CO_2-eq /g H2. Adding to that, CH4 emissions must be accounted throughout the NG value chain – considering the scientifically-based fact that it has a more powerful GHG potential than CO_2 and causing 86 times the warming as CO_2 over a 20 year period.

b) As a strategy, blue H2 only works to the extent it is possible to store CO_2 long-term indefinitely into the future and without leakages back to the atmosphere, otherwise the net-zero condition will never be met.

c) In the short term, there is a non-negligible risk that policymaking and industry investments in different World regions, including Europe, are on a misleading track to subsidise and trade hydrogen molecules which drastically exceed their thresholds for carbon intensity, undermining any attempt to reduce GHG emissions. This is increasingly becoming a fact unfortunately, even though project developers for blue hydrogen claim and promise a cheaper and easier option than renewable H2 — the capture and storage of up to 98% of CO_2 emissions - which is in practice not achievable due to the non-competitive extra costs that exponentially escalate beyond the 90% of CO_2 capture efficiency. The next biggest risk is that governments accept to set their carbon intensity thresholds for "clean" or "low-carbon" H2 on a well-to-gate basis, i.e. only including emissions from production, which very seldom enables to achieve a CO_2 capture efficiency beyond the 56-90% range.

3.2.1 CO_2 capture efficiency

CCU or CCS projects ideally aim for around 90% capture efficiency, meaning they capture, and use or store 90% of the CO_2 emissions from industrial sources and power plants. The efficiency of CO_2 removal in CCUS processes can vary significantly based on the technology and specific application.

Higher Efficiency: Achieving efficiencies above 90% is possible but becomes increasingly challenging and expensive. As the efficiency approaches 100%, the process requires more energy and larger equipment, leading to diminishing returns.

Technological Variations: Different CCUS technologies, such as chemical absorption, physical adsorption, and membrane separation, have varying efficiencies and energy requirements. The choice of technology can impact the overall efficiency of CO_2 capture.

What is the compared CO_2 efficiency removal for chemical absorption and membrane separation? The efficiency of CO_2 removal can vary between chemical absorption and membrane separation technologies. Here's a comparison:

Chemical Absorption

Efficiency: Typically achieves around 90% CO_2 capture efficiency.

Process: Involves using solvents like monoethanolamine (MEA) to chemically absorb CO_2 from flue gases. The CO_2 is then released from the solvent and compressed for storage.

Energy Requirements: Generally higher due to the need for solvent regeneration, which involves heating the solvent to release the captured CO_2.

Summing up, the chemical absorption enables on the one hand a higher CO_2 capture efficiency, but higher energy requirements on the other.

Membrane Separation

Efficiency: Can vary widely but generally achieves lower efficiencies compared to chemical absorption, often around 60-85% depending on the membrane material and design.

Process: Uses selective membranes to separate CO_2 from other gases based on differences in permeability. This process is typically less energy-intensive than chemical absorption.

Energy Requirements: Lower than chemical absorption, as it doesn't require solvent regeneration. However, the efficiency can be affected by factors like membrane fouling and pressure drop.

Summing up, membrane separation enables on the one hand a lower CO_2 capture efficiency, but lower energy requirements as well as a simpler operation on the other.

To conclude, those technologies must be chosen based on specific application needs and economic considerations.

3.2.2 Energy Requirements

The process of capturing and storing CO_2 requires significant energy besides the consequent flue gas emissions, which can affect the overall carbon intensity of the system. However, advancements in technology are continuously improving the efficiency and reducing the energy demands of CCUS. Consequently, there is a related energy penalty, as the process of capturing and compressing CO_2 consumes energy, which can reduce the net efficiency of the power plant or industrial process.

3.2.3 CCUS costs and H2 competitiveness

Currently green H2 costs are higher than those of blue H2, and, despite a huge cost reduction potential, it is uncertain when cost parity will be achieved, as it is heavily dependent on the increasing electrolyser sizes, efficiency improvements, and the significant lowering of renewable energy costs. In addition, the competitiveness of hydrogen is increasingly determined by the carbon tax across fuels and resulting costs from their life-cycle emissions.

To be competitive, it has been shown[38] that:

[38] Ueckerdt et al (2024).

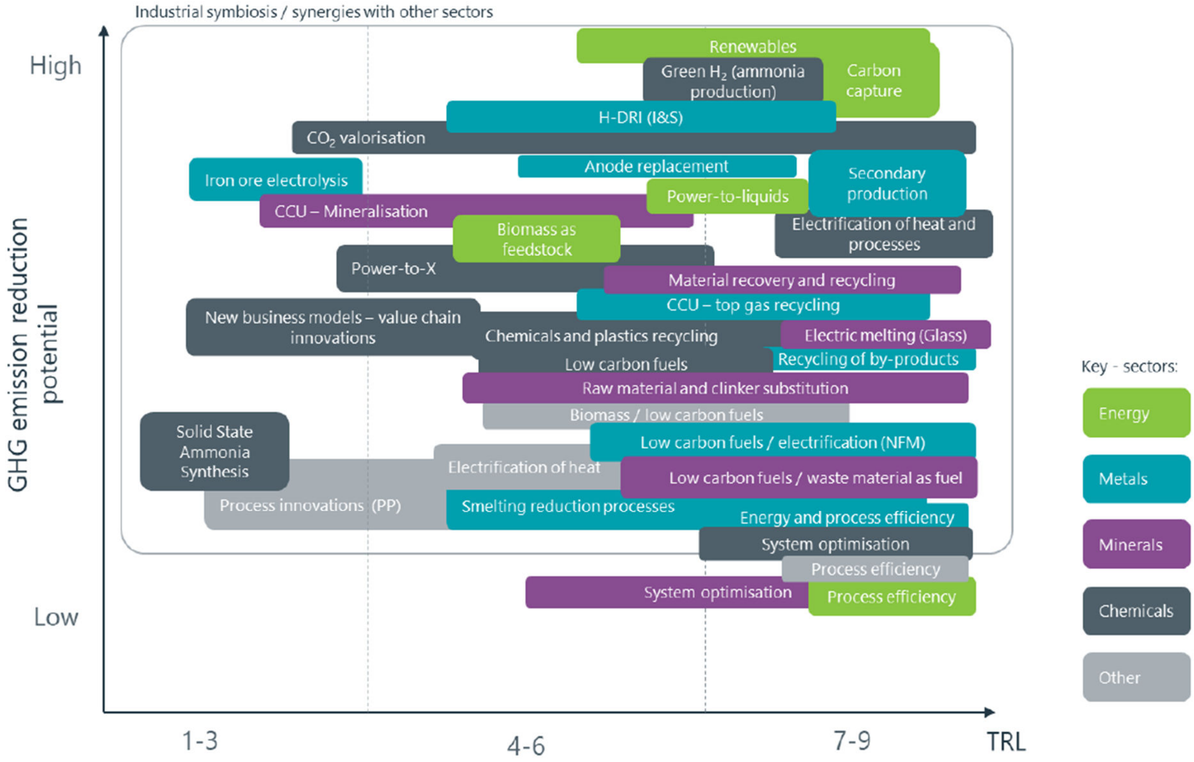
a) Green H2 requires >90% renewable electricity input to compete with NG[39] and low-emission blue H2.
b) Blue H2 requires >90% net CO_2 capture rates and close-to-zero methane leakage, to compete with green H2 produced with >90% renewable electricity.

Low-emission blue H2 may play a valuable role in bridging the scarcity of green H2. Yet, depending on regional circumstances, it may have a limited window of competitiveness.

3.3 The production of H2 derivatives

Clean H2 is a key component in the production of biofuels and e-Fuels, which are relevant examples of H2 derivatives, contributing to the transition of the energy system towards more sustainable stages, namely via the reduction of GHG emissions. The fig.11 exemplifies the main identified options in key industry sectors[40] for decarbonisation, from fuel switching and CCU to electrification, new business models and renewable hydrogen, their TRL and GHG emission reduction potential.

Fig. 11: Main identified options for decarbonization in industry, their TRL and GHG reduction potential[41]



[39] With reference to the SMR path, production costs for grey H2 gas generally range from 1 to 3€ / kg H2 approx. depending on the region and the NG price (BloombergNEF, 2023). In Europe they are currently of 3 € / kg H2 approx. incl. 0,5 €/kgH2 for the carbon tax, due to the NG cost 47€/MWh, and to the carbon tax of 75€/Ton.
[40] Industry sectors included: Energy sector, Refineries, Iron and Steel, Non-ferrous metals, Chemicals, Food and Drink, Cement, Lime and Magnesium Oxide, Surface Treatment with Solvents, Pulp and Paper, Rendering, Ceramics, Glass and Textiles.
[41] In: Wood, Deloitte et IEEP, 2021

Hydrogen derivatives do align well with H2 related key drivers and enablers as described in the Annex. Being integral to the hydrogen economy, Overall, they are not just complementary to the hydrogen economy - they are pivotal in driving its growth and achieving its goals. The following are illustrations how they match up:

- **Decarbonization Goals:** Hydrogen derivatives are essential for achieving global decarbonization targets. They provide low-carbon alternatives for sectors that are hard to electrify, such as heavy industry, shipping, and aviation.
- **Energy Storage and Transport:** These derivatives facilitate the storage and transportation of hydrogen. Ammonia, for example, can be more easily stored and transported than pure hydrogen, making it a practical carrier for hydrogen energy.
- **Economic Viability:** The production and trade of hydrogen derivatives can lower overall system costs. By connecting regions with abundant renewable resources to high-demand areas, global trade routes for hydrogen derivatives can reduce energy costs and investment needs.
- **Infrastructure Development:** Investments in infrastructure for hydrogen derivatives, such as pipelines and shipping routes, are crucial. These investments enable the efficient transport of hydrogen over long distances, supporting the global hydrogen economy.
- **Market Growth and Job Creation:** The hydrogen economy, driven by the production and use of hydrogen derivatives, has the potential to create millions of jobs and stimulate economic growth. This is particularly true in regions investing heavily in renewable energy and hydrogen production.
- **Regulatory Support and Certification:** The development of regulatory frameworks and certification schemes for hydrogen derivatives ensures their sustainability and market acceptance. This regulatory support is a key enabler for the growth of the hydrogen economy.

Power-to-X (P2X) technologies are key in the production and final use of hydrogen derivatives like ammonia, methanol, and synthetic fuels. Overall, P2X technologies are a key enabler for the hydrogen economy, providing a pathway to produce and use hydrogen derivatives on sustainable and efficient ways. That may be found in the following applications:

Conversion of Renewable Energy: P2X technologies convert renewable electricity into hydrogen through electrolysis. This hydrogen can then be used to produce various derivatives. For example, combining hydrogen with nitrogen produces ammonia, while combining it with carbon dioxide produces methanol.

Carbon Capture and Utilization: P2X processes often involve capturing carbon dioxide (CO_2) from industrial emissions or directly from the air. This CO_2 is then used as a feedstock to produce synthetic fuels and chemicals, effectively recycling carbon and reducing overall emissions.

Synthetic Fuels Production: P2X technologies enable the production of synthetic fuels (e-fuels) like synthetic kerosene and diesel. These fuels can be used in existing internal combustion engines and aviation, providing a sustainable alternative to fossil fuels.

Energy Storage and Grid Balancing: By converting surplus renewable energy into hydrogen and its derivatives, P2X technologies help balance the grid and store energy for later use. This is particularly important for integrating variable renewable energy sources like wind and solar.

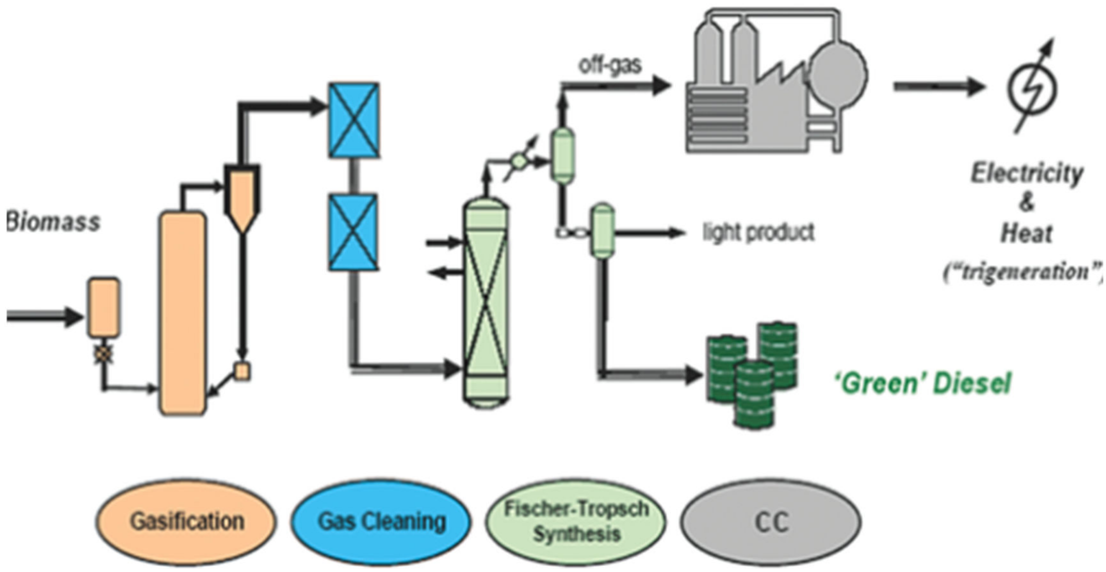
Industrial Applications: The hydrogen and derivatives produced through P2X can be used in various industrial processes, such as in the chemical industry for producing plastics, fertilizers, and other essential materia3s.

3.3.1 Biogenic C-based Fuels

Biofuels include fuels derived from biomass feedstocks, which are organic-based materials directly available from plants or from agricultural, domestic, or industrial biowaste. Besides biomethane, examples of biofuels are the following:

a) Bioethanol (C2H5OH), which can be produced by fermentation from 2nd and 3rd generation feedstocks and biowastes.
b) Green methanol (CH3OH), which can be produced from virgin or waste biomass, non-biogenic waste streams, or even CO_2 from flue gases; these feedstocks are converted by a multistep process - typically through biomass gasification - into syngas (i.e. a mixture of carbon monoxide, hydrogen, and other molecules), followed by a catalytic process.
c) Renewable biodiesel (HVO) - Conventional biodiesel (FAME- Fatty Acid Methyl Esters) is produced from vegetable oils, by transesterification mechanisms, while green diesel (HVO- Hydrotreated/ hydrogenated vegetable oil) is produced by hydrogenation and hydrocracking of vegetable oils and animal fats using hydrogen and catalysts at high temperatures and pressures. Switching from grey hydrogen to green hydrogen shrinks the carbon footprint of biodiesel further, meaning the fuel fetches higher prices.
d) Bio-jet fuels (included in the category of SAF – Sustainable Aviation Fuels) have different path productions, from: (i) plant or animal sources (e.g. Jatropha, algae, tallows, waste oils, and palm oil); (ii) solid biomass using pyrolysis and a Fischer–Tropsch process (fig. 12); (iii) alcohol-to-jet process from waste fermentation; or (iv) via a synthetic biology approach within a solar reactor.

Fig.12: Fischer–Tropsch conversion of biomass-derived synthesis gas to liquid fuels[42]



3.3.2 E-fuels

E-fuels are synthetic fuels, or electro fuels, produced from water and CO_2 following a synthesis reaction path by using renewable energy sources. Producing e-Fuels is energy intensive. Roughly 60 % of the cost of producing synthetic fuels is spent on the renewable electricity needed to extract the hydrogen via electrolysis. For this reason, e-Fuels are produced in parts of the world where conditions are particularly favourable for generating electricity from renewable sources of energy.

E-fuels together with renewable hydrogen, they are also called renewable fuels of non-biological origin. I.e. they are a subset of RFNBO, which are those synthetic fuels primarily derived from electricity that can help meet the EU's demand for renewable fuels in the coming years. The Additionality Delegated Act is a key piece of EU legislation that ensures RFNBOs are produced from "additional" renewable electricity generated at the same time and in the same area as their own production[43]. This is crucial for the EU's goals of reducing GHG

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[42] In: Lillebø et al, 2013

[43] The Additionality Delegated Act is a part of the EU's Renewable Energy Directive, and it outlines the conditions under which hydrogen, hydrogen-based fuels, or other energy carriers can be considered as RFNBOs. The principle of "additionality" aims to ensure that the supplies of renewable hydrogen, which are due to come on board by 2030, are connected to new, rather than existing, renewable energy production. This incentivizes an increase in the volume of renewable energy available in the EU. The Act also sets criteria to ensure that renewable hydrogen is only produced when and where it is needed and outlines how producers can demonstrate compliance with the rules. It provides a framework for calculating the life-cycle greenhouse gas emissions for RFNBOs. The methodology takes into consideration emissions associated with taking electricity from the grid, from processing, and those associated with transporting these fuels to the end-consumer. These Acts are part of a broad EU regulatory framework for hydrogen that includes energy infrastructure investments and state aid rules, as well as legislative targets for renewable hydrogen for the industry and transport sectors. They will provide regulatory certainty to investors as the EU aims to reach 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imported renewable hydrogen by 2030 in line with the REPowerEU Plan.

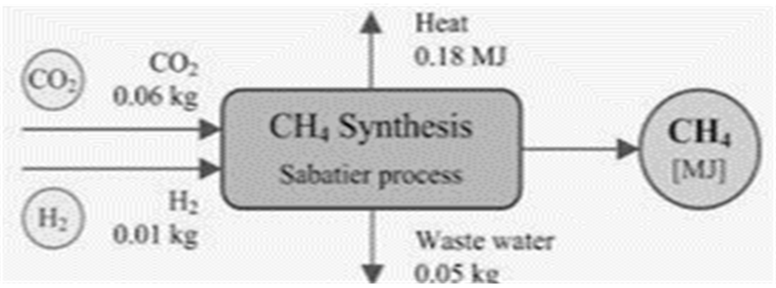
emissions and transitioning to a more sustainable energy system. These fuels are part of a broader strategy to reduce carbon emissions and reliance on fossil fuels. However, their production is currently limited by upstream hydrogen supply and carbon capture solutions.

They represent a promising pathway towards a more sustainable and integrated energy system, playing a crucial role in the systematic structuring of end-use technology, namely in the context of achieving climate neutrality and decarbonising transport by replacing fossil fuels and in most applications currently involving internal combustion engines. In fact, when e-Fuels are burned, the only carbon emission stems from carbon that was captured from the industrial process flue gases or directly from the atmosphere to produce them. Therefore, it results in a neutral carbon balance.

The role of e-Fuels in decarbonising transport is significant. Fuels obtained from electrolytic hydrogen, or e-Fuels, could be a viable pathway and scale up quickly by 2030, underpinned by a massive expansion of cheaper renewable electricity and anticipated cost reductions of electrolysers.

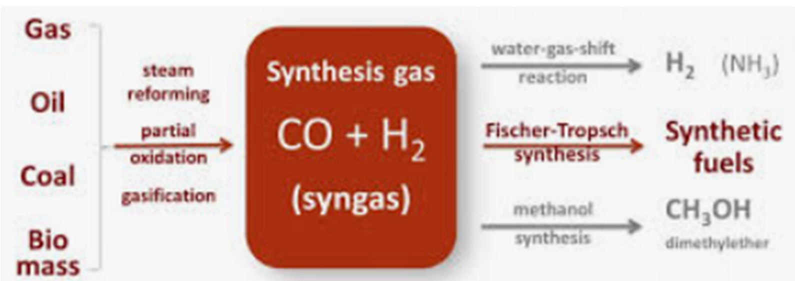
The carbon dioxide used in synthetic fuels can be captured from flue gases (mostly from boilers), from process emissions (e.g. in the cement and lime industry), from biogas, or even from Direct Air Capture. Chemical pathways for some of these e-fuels are:

Fig. 13: The Sabatier process



a) The Sabatier process provides an alternative to natural gas (NG), by a catalysed reaction to produce synthetic methane (e-CH4): CO_2 + 4H2 CH4 + $2H_2O$. By steam reforming, that synthetic methane reacts with steam to produce a synthesis gas (a mixture of hydrogen and carbon monoxide): CH4+H_2O→CO+3H2. Having the goal to perform the e-methanol synthesis step, captured CO_2 and hydrogen are combined in a catalytic reactor (catalyst: typically, copper, zinc oxide, and alumina) to produce methanol: CO_2+3H2→CH3OH+H_2O.

Fig 14: The Fischer-Tropsch process



b) The Fischer-Tropsch process sequence of catalysed chemical reactions that again convert syngas (i.e. a synthesis gas mixture of carbon monoxide and hydrogen) produced through biomass gasification or pyrolysis, into synthetic hydrocarbons such synthetic paraffinic kerosene (e-SAF).

c) The Haber-Bosch process, to produce ammonia (NH3), by a catalysed reaction of atmospheric sourced nitrogen (N2) with green hydrogen (H2). Ammonia is gaining traction as a e-fuel for maritime transports, competing with e-methanol due to its zero-carbon emissions and ease of storage. Ammonia is already widely used in industrial chemical applications (see next section), while its role as a e-fuel could expand with advancements in technology and infrastructure.

In 2020, the EU Strategy for Energy System Integration[44] emphasizes the need for an integrated energy system for a climate-neutral Europe. This involves the deep decarbonisation of all sectors of the economy, and higher greenhouse gas emission reductions for 2030. New fuels like hydrogen or synthetic fuels, which use significant amounts of energy to be produced, will likely be required in certain end-uses.

In 2023, the European Union was recognizing the importance of e-Fuels in achieving a climate-neutral economy. The Article 25 of the Renewable Energy Directive III[45] focuses on the use of renewable fuels in the transport sector. This directive aims to promote the use of renewable energy sources to reduce greenhouse gas emissions and enhance energy efficiency within the EU. By doing so, it sets ambitious targets for the share of renewable energy in the transport sector, contributing to the overall goal of climate neutrality by 2050, and encourages the use of renewable electricity to produce synthetic fuels, particularly for hard-to-decarbonize sectors like aviation and maritime transport.

In the case of aviation, the 'ReFuelEU Aviation' Regulation[46], Art. 4 with a focus on Annex I addresses the minimum shares of SAF and eSAF to be made available to aircraft operators in EU airports (fig.15).

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[44] Delivered in the COM(2020) 299 final (8 Jul)
[45] (Directive 2023/2413, 18 Oct)
[46] (EU) 2023/2405 (18 Oct)

Fig 15: Minimum shares of SAF and eSAF to implement in aviation transports.

From:	SAF (%)	e-SAF (%) (RFNBOs)
1 Jan 2025	2	-
1 Jan 2030	5	0,7
1 Jan 2035	20	5
1 Jan 2040	32	8
1 Jan 2045	38	11
1 Jan 2050	63	28

In: COM(2021) 561 final, Annex I (14.7.2021)

As e-Fuels are synthetic fuels produced using renewable electricity, they consist of a subset of RFNBOs – a broader category that includes all renewable fuels from non-biological sources, including e-fuels and other synthetic fuels like ammonia and methanol when produced from renewable hydrogen. As such, all e-fuels are RFNBOs, but not all RFNBOs are e-fuels. The e-fuels production process typically involves using electrolysis to produce hydrogen from water, which is then combined with carbon dioxide to create various hydrocarbons like e-methanol, e-diesel, and e-kerosene.

3.3.3 Chemicals & Materials

Hydrogen has also the potential as a chemical feedstock to help decarbonize industrial processes that currently rely on fossil fuels.

Chemicals

Ammonia production: Producing green ammonia involves using renewable energy sources to create ammonia without emitting carbon dioxide. This method significantly reduces the carbon footprint compared to traditional ammonia production, which relies on natural gas. A simplified overview of the green ammonia production process consists of three main steps:

- **Hydrogen Production:** The first step is to produce green hydrogen. This is done by splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electrolysis, powered by renewable energy sources like wind or solar.
- **Nitrogen Extraction:** Nitrogen (N_2) is extracted from the air using an air separation unit. The air is composed of about 78% nitrogen, so this step involves isolating nitrogen from other gases.
- **Haber-Bosch Process:** The green hydrogen and nitrogen are then combined in the Haber-Bosch process to produce ammonia (NH_3). This process typically requires high temperatures and pressures, which are also powered by renewable energy.
- **Storage and Use:** The green ammonia can be stored and used as a fertilizer, a fuel, or a hydrogen carrier for various applications.

Materials

Steel production. Green steel production follows a process that replaces the use of fossil fuels with renewable energy sources. Here are the key steps involved in the production of green steel:

- **Hydrogen Production:** Green hydrogen is produced through a process called electrolysis, where water molecules are split into hydrogen and oxygen using renewable electricity.
- **Direct Reduced Iron (DRI) Production:** The green hydrogen is then used in a DRI plant to reduce iron ore into sponge iron. This process is done at high temperatures but below the melting point of iron (800 – 1200 °C), which saves energy costs.
- **Raw Steel Production:** The sponge iron is then heated and liquified together with steel scrap in an Electric Arc Furnace (EAF) to produce raw steel.
- **HYBRIT - Hydrogen breakthrough ironmaking technology:** This is another method where hydrogen replaces fossil fuels in both the manufacture of iron pellets and the carbon purification process.

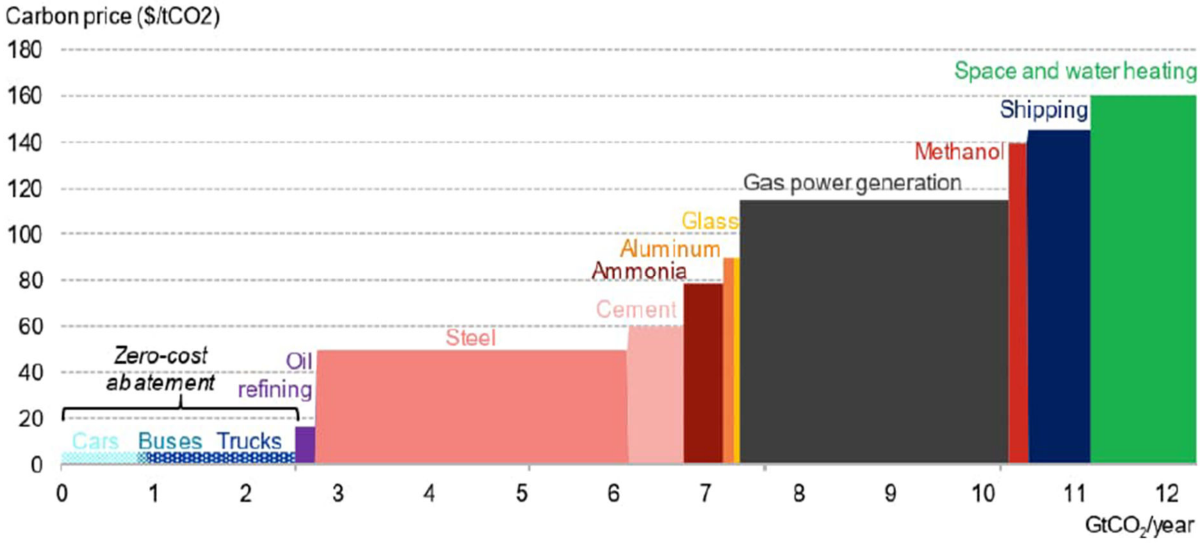
These methods are part of a broader strategy to reduce carbon emissions and reliance on fossil fuels. However, the production of green steel is currently limited by the availability of renewable energy and the cost of producing green hydrogen.

3.4 End-use sectors and cross-cutting applications

By following the path on P2X strategies, complexity is addressed in the end-use sectors taking system integration approaches at a higher level, e.g. through value chains, sector coupling, flexibility, and modularity among others.

To have a significant impact to the clean energy transition, H2 and its derivatives need to be adopted in sectors where H2 or its derivatives are likely to offer a competitive advantage. Renewable technologies such as solar and wind (combined with storage) could largely decarbonize the energy sector by replacing fossil fuels with clean electricity. As demonstrated by Bloomberg NEF (2020), the strongest cases for hydrogen are those with direct use in heavy duty transportation and manufacturing processes (fig.16), which as they require fuel that is high in energy density or heat at high temperatures.

Fig.16: Marginal abatement cost curve from using \$1/kg hydrogen for emission reductions, by sector in 2050[47]



That is the case of hard to electrify sectors - such as the heavy and energy intensive industry (e.g. iron & steel, cement, glass, and ceramics), chemicals and materials, and heavy-duty transportation. That is also the case of energy storage when addressing RES variability and intermittency - and its transportation helping to balance supply and demand on the power grid by storing excess renewable energy and releasing it when needed. And it is the case as well in production of energy vectors and industrial commodities for mainstream and niche markets, which will be offering sustainable or low-C certified H2-based solutions for market growth, thus by building consumer and regulatory confidence.

Hydrogen derivatives are crucial for reducing emissions in sectors that are difficult to electrify, such as heavy industry, chemicals, and long-distance transportation. For example, ammonia can be used as a carbon-free fuel for shipping or as a carbon-free industrial feedstock in the Haber-Bosch process. Also, methanol can be used in various industrial processes, such as a chemical feedstock, as direct fuel or converted to dimethyl ether (DME) as a diesel substitute, on energy storage to feed fuel cells, on wastewater treatment to denitrify water, and as an antifreeze in car windshield water fluids.

3.4.1 Hard-to-electrify heavy and energy intensive industries

Due to the technical and economic adjustments, several heavy industries required in reducing their carbon emissions, are challenging to electrify due to their reliance on high-temperature processes and fossil fuels. The most notable ones include:

As 1 Mton of steel produces 1,5-3 ton of CO_2, efforts to reduce CO_2 emissions in iron and steelmaking focus on alternative reducing agents and carbon capture technologies. Common approaches include replacing coal with hydrogen, which has a lower carbon footprint and reduces CO_2 emissions. Adding to that, steel can be produced via primary or secondary routes.

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[47] In: Bloomberg NEF, 2020

Primary steel production involves two steps: ironmaking, where iron ore is reduced to pig iron in a blast furnace using coal or gas as heat source – making it difficult to replace with electricity, or sponge iron is produced via direct reduction, and steelmaking, where the iron is processed in a basic oxygen furnace or an electric arc furnace (EAF), depending on the type of iron input. In secondary steel production, steel scrap is reclaimed and re-melted in an EAF, without the need for a new iron ore reduction process. Finally, as referred in the previous section 3.3.3 "Chemicals & Materials", renewable steel production follows a process that replaces the use of fossil fuels with renewable energy sources – starting by producing an electrolytic grade hydrogen to finally achieve green steel as final product by a breakthrough ironmaking technology.

Cement Manufacturing:

Cement production involves heating limestone to very high temperatures, which releases CO_2 as part of the chemical process (1 Mton of cement produces 0,8 ton of CO_2). Its massive production contributes significantly to present-day global anthropogenic CO_2 emissions, yet its hydrated products gradually reabsorb substantial amounts of atmospheric CO_2 (carbonation) in the future. The role of this sponge effect along the cement cycle (including production, use, and demolition) in carbon emissions mitigation, however, remains hitherto unexplored. Z. Cao et al (2020), by using a multilayer dynamic material flow analysis model, quantified the effects of demand- and supply-side mitigation measures considering this material-energy-emissions-uptake nexus, and concluded that climate goals would be imperilled if the growth of cement stocks continues. Furthermore, future reabsorption of CO_2 will be significant (~30% of cumulative CO_2 emissions from 2015 to 2100), but climate goal compliant net CO_2 emissions reduction along the global cement cycle will require both radical technology advancements (e.g. CCS) and widespread deployment of material efficiency measures, which go beyond those envisaged in current technology roadmaps.

Chemical and petrochemical industry:

Many chemical processes such as the production of ammonia, methanol, and high value chemicals also known as primary chemicals (olefins incl. ethylene, propylene and butadiene; and aromatics incl. benzene, toluene and xylenes), have been increasing over the last few decades, and their production still relying almost entirely on fossil fuels as feedstocks. Emissions from this sector derive from energy used in production processes as well as energy carriers used as feedstock for chemicals. Both sources need to be eliminated, if the sector's emissions are to be reduced to zero. To achieve this, a combination of decarbonisation pathways is necessary. These routes include reducing demand by increasing re-use and recycling of products; reducing energy consumption by improving the energy efficiency of processes; adopting renewables-based alternatives to fossil fuel feedstocks; and switching to renewable-based electricity and the use of CCUS technologies, including bioenergy with carbon capture and storage.

3.4.2 Mobility and Transports sector

Heavy-duty transportation sectors that are particularly challenging to electrify, because of the significant technical and economic challenges involved in transitioning to electric power, include:

Long-Distance Trucking:

Heavy-duty trucks rely today almost exclusively on diesel, petrol and natural gas. Biofuels account for less than 5% of total consumption in the sector.[48] The sector has made some progress towards decarbonisation in more recent years, however electrifying long-haul trucks is exhibiting evidence that is difficult due to the need for large batteries, which add significant weight and reduce cargo capacity. Additionally, the infrastructure for rapid charging on long routes is still underdeveloped. While the scope of application of batteries and of its infrastructure is expanding to a broader set of road vehicle segments and types of services, and even if there is a rapid adoption of electric trucks, a large fleet of internal combustion engine vehicles will unavoidably be in operation for the next two to three decades. For these, emission reductions can also be achieved in the short- to medium-term by using sustainably sourced biomass-based diesel substitutes. As far as the longer run is considered, the use of sustainably sourced biomass needs to be prioritised in those sectors where there is a limited scope for electrification and other low-carbon alternatives. There are also ongoing efforts to explore the use of hydrogen trucks. However, the economics and technical characteristics of these vehicles lag far behind those of electric trucks. Moreover, the use of renewable hydrogen should be prioritised in sectors where it adds the most value to decarbonisation efforts (i.e. where direct electrification with renewable power is not an option). Such applications include the production of key industrial commodities such as ammonia and the production of synthetic fuels for long haul aviation and shipping. In these, renewable hydrogen can be a complementary solution to sustainable biofuels.

Shipping:

Maritime transport is not only a consumer of energy, but also a means for its transport. Being amongst the least carbon-intensive transport modes, in terms of emissions per passenger kilometre (pkm) and per tonne kilometre (tkm)[49], the sector is still a major polluter given the sheer magnitude of its activity - maritime trade activity has roughly doubled in the last 20 years. Ships require a tremendous amount of energy for long voyages, making current battery technology impractical due to weight and space constraints. Being heavily dependent on inexpensive, low-grade fossil fuels such as heavy fuel oil (HFO) and marine diesel oil, the International Maritime Organization introduced in 2020 a global regulation - towards adopting very low sulphur fuel oil - aimed at significantly curbing sulphur oxide emissions. This showcased the ability of the sector to rapidly adapt and implement policy-driven changes, therefore several net-zero compatible alternatives for conventional marine fuels emerged, such as sustainably produced e-ammonia and low-carbon biofuels, e.g. biodiesel, renewable diesel, bio-LNG and bio-methanol, can be effective short- to medium-term options for shipping. Biofuels boast high technological readiness, allowing them to be immediately harnessed as blends or drop-in fuels, requiring little to no changes in terms of operation and infrastructure. However, it is crucial to acknowledge that the rapid scale-up of sustainable biomass sourcing requires careful consideration of its potential negative impacts, including land-use change and lifecycle GHG emissions.

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[48] IEA, 2023
[49] EEA, 2023

Aviation:

Airplanes need high energy density fuels to remain airborne for long distances. Batteries are too heavy and do not provide the necessary energy density for commercial flights. As one of the most carbon-intensive transport modes, aviation is a significant contributor to global GHG emissions and climate change. It is worth noting that the sector is also responsible for non-carbon emissions, i.e. other gases and aerosol particles which affect the atmospheric composition and affect cloudiness, adding to the impact of the sector's CO_2 emissions. The most technologically straightforward pathway to decarbonise the sector is the use of advanced biofuels, namely biojet, given the maturity of the technology. Biojet can be used as a drop-in fuel on existing and future aircraft, making it a practical and immediately implementable option. Another option is the adoption of synthetic fuels produced from renewable hydrogen – that produced from electrolysed water using renewable electricity. This can then be combined with a renewable source of carbon to produce a hydrocarbon fuel. The two options being currently considered are renewable hydrogen and e-kerosene. Yet, while hydrogen could eliminate exhaust emissions from aviation, hydrogen aircraft technology for large passenger or cargo transport does not exist yet. This technology is also not expected to reach commercial maturity within a timeframe compatible with making a material impact on carbon neutrality by mid-century. A fundamental issue revolves around the low volumetric energy density of hydrogen, which would require a fundamental redesign of airframes as well as operational procedures and safety standards. Furthermore, there is no hydrogen refuelling infrastructure in place. E-kerosene, on the other hand, is chemically identical to its fossil counterpart and could be used in existing aircraft. The use of e-kerosene opens the door for deep emissions reductions. However, the fact that the e-kerosene molecule contains carbon adds a layer of complexity. For e-kerosene to be an effective decarbonisation solution, it would have to be low-carbon and this carbon would need to come from a sustainable source, i.e. from biogenic sources such as bioenergy with carbon capture.

3.4.3 Energy storage and transportation

Hydrogen derivatives enable the storage and transportation of renewable energy. This is important because hydrogen itself has a low volumetric energy density, making it challenging to transport over long distances. Converting hydrogen into derivatives like ammonia or methanol makes it easier to handle and ship. The production and trade of hydrogen derivatives can create new economic opportunities. Countries with abundant renewable resources can produce green hydrogen and its derivatives at a lower cost, and complementarily having low-carbon H2 production capacity, positioning themselves as key players in the global clean hydrogen market.

3.4.4 Integration by sector coupling with hydrogen

Sector coupling in line with hydrogen-driven decarbonization processes involves integrating different energy sectors—such as electricity, heating, and transportation—using hydrogen as a key energy carrier. It helps create a more resilient and sustainable energy system, leveraging the strengths of different energy carriers and technologies to achieve deep decarbonization goals. This approach aims to enhance the flexibility and efficiency of the overall energy system, facilitating the use of renewable energy sources and reducing carbon emissions. Sector coupling depends on system elements like:

Hydrogen production and storage:

Hydrogen is produced using renewable energy sources like wind and solar through a process called electrolysis, which splits water into hydrogen and oxygen. This hydrogen can be stored and used later, providing a way to balance supply and demand in the energy system.

Integration with Electricity Grid:

Hydrogen can be used to store excess electricity generated from renewable sources. When there is a surplus of renewable energy, it can be converted into hydrogen (power-to-gas). This hydrogen can then be converted back into electricity when needed (gas-to-power), although this step is less efficient and often avoided if direct use of hydrogen is possible.

Decarbonizing Hard-to-Electrify Sectors:

Hydrogen can be used directly in sectors that are difficult to electrify, such as heavy industry, transportation (e.g., fuel cell vehicles), and heating. This reduces reliance on fossil fuels and helps to decarbonize these sectors.

Flexibility and Cost Savings:

By coupling sectors, the energy system can become more flexible. For example, hydrogen production can be ramped up or down based on the availability of renewable energy, helping to stabilize the grid. This integrated approach can also lead to cost savings by optimizing the use of infrastructure and resources across sectors.

4. Industrial and infrastructural scaleup of P2X technologies

4.1 The scaling-up of P2X value chains

The Net Zero Industry Act (NZIA) sets several ambitious targets to enhance the EU's manufacturing capacity for clean technologies and support the transition to a net-zero economy. These targets aim to boost the EU's industrial competitiveness, create quality jobs, and support the transition to a sustainable and energy-independent future. Here are the key targets:

- Manufacturing Capacity: Achieve at least 40% of the EU's annual deployment needs for strategic net-zero technologies by 2030.
- CO_2 Storage: Establish an annual CO_2 storage capacity of at least 50 million tonnes by 2030.
- Market Access and Investment: Improve market access and attract investments for clean technologies, ensuring the EU remains competitive in the global market.
- Regulatory Framework: Simplify and streamline the regulatory framework to accelerate the deployment of net-zero technologies.
- Skills Development: Establish Net-Zero Industry Academies to develop the necessary skills and workforce for the clean tech sector.

4.2 How will NZIA target renewable hydrogen and RFNBO technologies?

The Net Zero Industry Act (NZIA) aims to bolster the manufacturing and deployment of clean technologies within the EU, including hydrogen and Renewable Fuels of Non-Biological Origin (RFNBO) technologies. Overall, the NZIA provides a comprehensive framework to accelerate the deployment of hydrogen and RFNBO technologies, supporting the EU's goals for decarbonization and energy independence. Here's how these technologies are addressed:

- **Strategic Importance:** Hydrogen technologies, including electrolysers and fuel cells, as well as RFNBO technologies, are classified as strategic under the NZIA. This means they are prioritized for development and support.
- **Permitting and Manufacturing:** The NZIA sets ambitious targets for manufacturing capacity, aiming for 40% of the EU's annual deployment needs by 2030. It also streamlines permitting processes, with a maximum of 18 months for large projects and 12 months for smaller ones.
- **Market Access and Investment:** The Act facilitates market access through public procurement and auctions, encouraging the adoption of these technologies. It also aims to attract investments by creating favourable conditions for clean tech manufacturing.
- **Support for Innovation:** Member states can establish regulatory sandboxes to test innovative net-zero technologies, including hydrogen and RFNBOs, in a controlled environment.

- **Skills Development:** The NZIA emphasizes the development of skills necessary for the clean tech sector, ensuring a qualified workforce to support the growth of hydrogen and RFNBO technologies.

4.3 The infrastructural scaleup of P2X technologies

The infrastructural scale-up of Power-to-X (P2X) technologies involves expanding and enhancing the infrastructure needed to convert surplus renewable electricity into other forms of energy or products. This process is a complex but crucial for achieving large-scale decarbonization and supporting the transition to a sustainable energy system. It requires coordinated efforts across multiple sectors and significant investment in new and existing infrastructure. Some key aspects are the following:

- **Expansion of Renewable Energy Capacity:** To support P2X technologies, we need to significantly increase the capacity of renewable energy sources like wind, solar, and hydro. This involves not only building more generation facilities but also upgrading transmission networks to handle the increased load.
- **Development of Low-Carbon Fuel Supply Chains:** This includes creating supply chains for clean fuels such as green hydrogen and its derivatives. These fuels can be used in various sectors, including transportation, industry, and heating.
- **Retrofitting and Building New Infrastructure:** Existing infrastructure needs to be adapted, or new infrastructure built to use P2X fuels. This includes everything from industrial plants to transportation systems.
- **Government and Policy Support:** Governments play a crucial role in establishing policies and regulations that incentivize the development and deployment of P2X technologies. This includes financial incentives, research funding, and setting regulatory frameworks.
- **Integration with Existing Systems:** P2X technologies need to be integrated into existing energy systems in a way that ensures reliability and efficiency. This requires advanced planning and coordination among various stakeholders.

5. How to contribute to the H2 IWG?

5.1 The SET Plan's H2 IWG role

Having into consideration:

a) The SET Plan is instrumental in driving Europe's clean energy transition, fostering innovation, and ensuring a sustainable and resilient energy future, it plays a key role at different dimensions in advancing decarbonization efforts across Europe. Besides a legal and policy support, it is also supporting R&I, as well as the coordination within the NZIA Regulation, and cooperation among EU countries, companies, and research institutions, aiming to bring down the costs of new technologies through coordinated research efforts, making clean energy solutions more accessible and economically viable.

b) The SET Plan's IWG on Hydrogen will play a vital role in strategic guidance and coordination by:
b.1) Advancing hydrogen strategies and technologies in Europe, by having a focus on setting strategic targets and coordinating efforts across EU member states and stakeholders to build a hydrogen economy by 2050.
b.2) Fostering cross-thematic cooperation and collaboration across various thematic areas, integrating hydrogen initiatives with other energy sectors.
b.3) Ensuring that hydrogen technologies are developed efficiently and effectively, leveraging synergies between strategic planning and practical implementation.

c) The key features and key conditions on 'Decarbonization Goals' (see Annex);

The deliverable D3.4 SET4H2 aims to provide insight on an innovative hydrogen approach at a system level, by adopting a modular-based holistic framework. That enables to design an innovate IWG strategy addressing the hydrogen either as a final/intermediate product, or an industrial clean commodity/energy source to integrate the SET Plan framework.

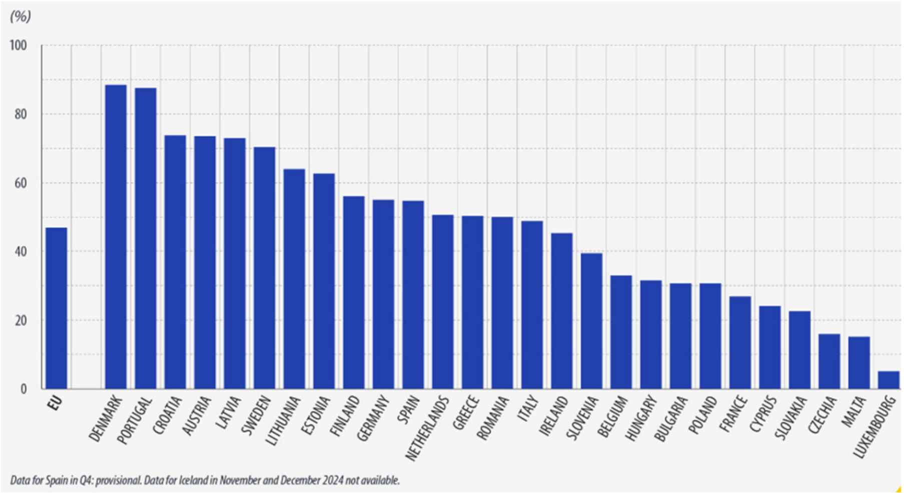
5.2 Achieving the 2030 decarbonization targets - Key requirements

Complementary steps are key in MSs to meet the EU goals set for 2030. When adopting the hydrogen economy, a mix of requirements at a national level is key:

a) Accelerated transition to a renewable energy system: Increasing the share of renewable energy sources like wind, solar, and hydro in the energy mix is crucial. As of 2024, the performance level of each Member State regarding the share of renewable energy sources in their net electricity generation vary significantly, as shown in Fig. 17.

In 2024, 46.9% of net electricity generated in the EU came from renewable energy sources, which compares with previous years: 45.3% (2023), 41.2% (2022), 39.9% (2021), and 38.2% (2020). (In: Eurostat, 2024)

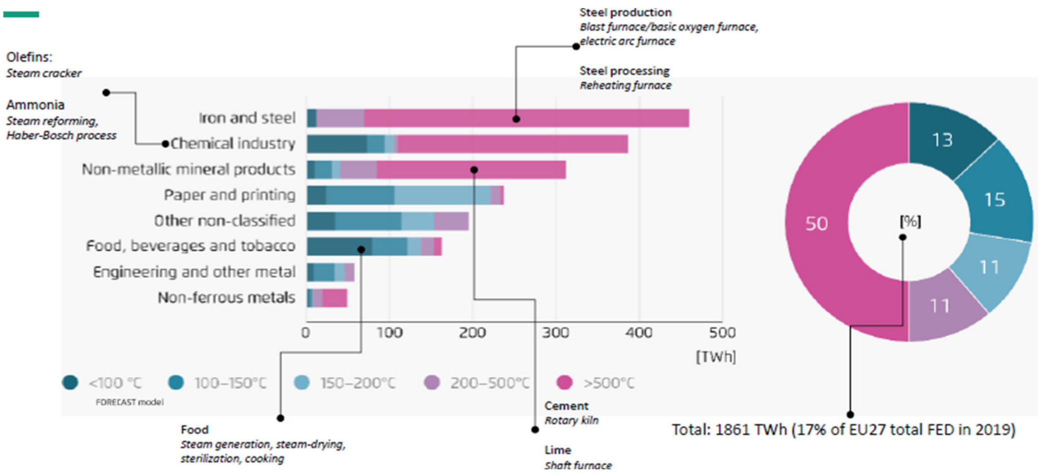
Fig. 17 – Share of renewables in net electricity generation, in 2024[50]



The EU overall reached a 24.5% share of its gross final energy consumption from renewable sources in 2023. The EU aims to achieve at least 42.5% of its energy consumption from renewable sources by 2030, and there is an aspiration to reach 45% by then. When produced using renewable energy sources, hydrogen can achieve high overall system efficiencies, especially when integrated with processes that require both electricity and heat.

b) Enhanced energy efficiency: Implementing measures to improve energy efficiency across materials, industries, buildings, and transportation can significantly reduce emissions. The Energy Efficiency Directive (EU/2023/1791) aims to reduce final energy consumption by at least 11.7% by 2030, compared to projections based on the 2020 reference scenario. This translates to a primary energy consumption target of 992.5 million tonnes of oil equivalent (Mtoe) and a final energy consumption target of 763 Mtoe by 2030. EU countries are required to achieve an average annual energy savings rate of 1.49% from 2024 to 2030, up from the previous requirement of 0.8% for 2021-2023. This will drive energy savings in critical sectors like buildings, industry, and transport. Transitioning to hydrogen isn't straightforward.

Fig. 18 – Estimated total final energy demand for process heating by temperature, in 2019[51]



[50] Eurostat (2024)
[51] Fraunhofer ISI (2024)

Besides growing competition from direct electrification in industry process heating (Fig. 18), existing equipment designed for fossil fuels may need modifications due to hydrogen's unique properties, such as its fast flame speed and high flame temperature. In industries like steel and cement, hydrogen can replace carbon-intensive fuels, leading to more efficient and cleaner processes. Hydrogen can store excess renewable energy, which can then be used during periods of high demand. This helps in balancing the grid and improving overall energy efficiency.
Regarding the electrification of transportation, it is key to promoting electric vehicles (battery; fuel cell) and developing the necessary infrastructure to support them. Electric car penetration in the EU has been increasing. In 2024, the market share of new electric cars accounted for 13.6% in the EU. This is a slight decrease from 14.6% in 2023. Approximately 1.99 million battery electric vehicles (BEVs) were reported as total sales in Europe (including EU, EFTA, and UK) during 2024. Hydrogen fuel cells can convert hydrogen into electricity with efficiencies exceeding 60%, which is a higher conversion rate than the traditional combustion-based power generation methods.

c) Stimulating supply and demand

Lack of suppliers and mass demand for hydrogen end-uses: The hydrogen economy is currently gaining momentum through the funding of large-scale projects. But this transition is at its early stages meaning that there is a lack of hydrogen demand in mass scales. For instance, hydrogen vehicles are currently a minuscule percentage of the total vehicle fleet. Especially large-scale hydrogen projects that are focused on mobility end-uses suffer from current lack of mass manufacturers and suppliers of hydrogen vehicles. To this end, supply and demand technologies have to grow and funded alongside hydrogen production. The "chicken-egg" problem is envisaged to be solved through public funding initiatives and additional incentives for the establishment and creation of hydrogen infrastructures as well as hydrogen end-uses/demands.

d) Circularity by carbon capture, use and storage (CCUS)

In line with the adoption of the EU Industrial Carbon Management Strategy in February 2024, investing in technologies that effectively capture and store carbon emissions from industrial processes and power generation is getting traction. The Clean Energy Technology Observatory's 2025 report[52] highlights significant advancements in CCUS technologies, trends, and market positions. In Europe, CCS projects at different stages of development, support industries like hydrogen, ammonia and fertiliser production (20 facilities), power generation and heat (19 facilities), cement (17 facilities), and biomass to power/heat (15 facilities). The EU is well positioned in key CCS component manufacturing sectors for capture technologies, such as amine solvents used for absorption (the most mature technology). However, it does not operate at scale nor have specialised value chains yet[53]. While CCU and CCS offer circular carbon economy benefits, there are concerns about leakages, safety, and public acceptance. Addressing these issues is crucial for the successful implementation of these technologies. By capturing CO_2 from industrial processes and utilizing it in fuel production, CCU helps reduce overall GHG emissions. This is particularly important for achieving net-zero emissions targets. As a source of CO2 taken as an industrial commodity, CCU will play a crucial role in the production of synthetic fuels, contributing to cleaner energy solutions.

[52] EC-CPR (2025)
[53] CETO, 2024

e) Policy and regulatory support

Political support at a municipal, regional, national and international level could help identifying obstacles related to regulation, financing, permitting and citizen involvement. The would be the case, for instance, regarding the systems' interconnections to the electricity grids or the existing regulation and licensing procedures for national and international projects. Due to the lack of hydrogen-specific legislation, existing framework must be used that present however several gaps regarding hydrogen integration. The inclusion of those policy makers and regulatory bodies, and regular communication could provide key factors for the successful operation of the hydrogen initiatives at a regional and municipal level, such as hydrogen valleys.

Strong government policies and regulations to incentivize and accelerate a transition process towards a net-zero condition, and ensure compliance with climate neutral targets are being adopted:

e.1) Carbon pricing: Many countries have adopted carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, to encourage industries to reduce their greenhouse gas emissions. The EU Emissions Trading System (ETS) is one of the largest and most established cap-and-trade systems.

e.2) Subsidies and tax credits: Governments provide subsidies and tax credits for renewable energy projects, energy efficiency improvements, and carbon capture and storage (CCS) technologies. For instance, the US offers tax credits under the IRA-Inflation Reduction Act to support clean energy initiatives.

e.3) Regulatory mandates: Some governments impose regulatory mandates requiring industries to meet specific emission reduction targets. These mandates often include penalties for non-compliance and incentives for early adoption of clean technologies.

e.4) Public procurement policies for net-zero emissions: Governments use public procurement policies to drive demand for renewable or low-carbon products and services. By prioritizing the purchase of sustainable goods, governments can stimulate market growth for green technologies.

e.5) Auctions: providing a structured and competitive mechanism to support and incentivize hydrogen production and consumption, they are a powerful tool for driving the clean hydrogen market forward by balancing supply and demand, reducing costs, and ensuring the timely delivery of projects. They can be designed to achieve broader policy objectives, such as promoting green industrialization, energy independence, and job creation.

e.6) R&D funding: Significant investments in research and development (R&D) are made to advance decarbonization technologies. The EU, for example, funds numerous R&D projects aimed at developing innovative solutions for reducing emissions.

e.7) Infrastructure development: Governments support the development of infrastructure necessary for decarbonization, such as electric vehicle charging stations, renewable energy grids, and CCS facilities.

e.8) Regulatory sandboxes: are essential for fostering innovation, reducing regulatory uncertainty, and accelerating the transition to a sustainable hydrogen economy.

f) Technological innovation

Developing and deploying new technologies that can reduce CO2 emissions and improve sustainability and value added along the different roles hydrogen is a key issue, each impacting specific markets: end use products, intermediate products, industrial commodities, and industrial process heat in hard-to-abate sectors. That is the case already when the H2 technology is applied to decarbonise final and intermediate products, the renewable H2 production by water electrolysis, the H2 molecule conversion into electricity with high efficiency and zero emissions in fuel cells, the blending of hydrogen with natural gas for use in existing gas infrastructure enabling to reduce CO_2 emissions from heating and power generation, and the production of hydrogen-based synthetic fuels by the Fischer-Tropsch synthesis, and the Haber-Bosch process for the industrial synthesis of ammonia, are gaining traction in sectors like aviation and shipping.

g) Social awareness, capacity building and stakeholder engagement

Persuading the public about the significance of hydrogen and renewable energy projects could present a challenge, particularly in proximity to urban areas. Citizens are particularly worried about the safety, environmental benefits and costs of such actions. Collaborating with citizen communities and municipal/regional/national policy makers could raise awareness and clarify any misconceptions that could eventually create serious burdens to a project. The added value of a project can be showcased by the creation of job opportunities in the area, the safe and reliable operation of zero-emission vehicles and public transportation systems, as well as the associated environmental and health benefits.

Due to the recent momentum of hydrogen technologies, there is a lack of trained and specialized technical and scientific personnel that has extensive practical and theoretical experience in large-scale hydrogen systems. This includes technicians, engineers, project managers as well as legal and financial advisors. This is particularly prevalent for former fossil fuel-based economies and regions transitioning to other energy sources, which have based their economies and regional development on fossil resources. To this end, innovation and hydrogen valleys are useful concepts that can evolve to deliver local education and training hubs where practical training and education can be provided to students and technical personnel.

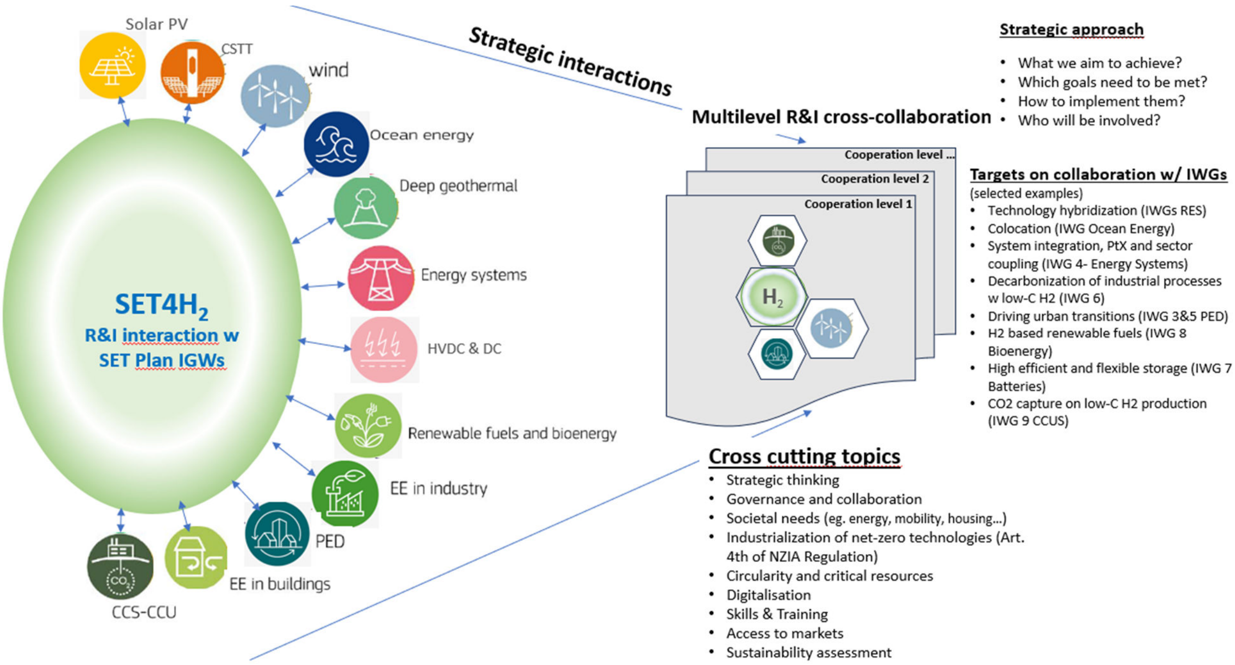
Engaging with customers, suppliers, employees, investors, and communities to drive demand for sustainable practices and products. To fulfil such requirement, aiming at achieving the decarbonization targets, the following paths provide effective strategies: Early and transparent communication, ensure inclusive participation, conduct education and awareness campaigns, community benefit agreements, establishing regular feedback mechanisms, implement demonstration projects, and form collaborative partnerships to leverage expertise and resources.

5.3 Concluding remarks

By adopting a modular-based holistic framework - as introduced in Fig.4 - an innovative hydrogen approach at a system level is proposed, where H2 takes multiple forms either as a final/intermediate product, or an industrial clean commodity/energy source. Based on PtX strategies (X= H2, Synthetic fuels, etc) a set of system enablers is provided to apply having variable purposes (e.g. flexibility, sector coupling) in a national economy according to the respective mix of enabling conditions and drivers.

At that level, designing an innovate and coherent IWG strategy is possible - as represented in Fig. 19 by using selected examples - from which a set of collaborative R&I directions may be derived to integrate an implementation plan in the frame of the IWG H2, particularly when interacting with a wide range of other IWGs of the SET Plan framework, such as: IWG1 RES: solar, wind ocean, and geothermal, IWG3 PED, IWG4 Energy Systems, IWG5 Buildings, IWG6 EE-Industry, IWG7 Batteries, IWG8 Renewable fuels and bioenergy, and IWG9 CCUS.

Fig. 19 – Strategic interactions between IWG H2 with other IWGs of the SET Plan framework



6. Conclusion

This report:

i. Acknowledges the role of hydrogen as a system facilitator in both the molecule and electron forms, depending on system efficiency in each case, from the access to clean energy sources at competitive costs to the circular economy of each value chain, and including along the chain reliable suppliers, carbon leaks avoidance, qualified job creation, risk management and strategic investments.
ii. Provides a structured and systematic non-nuclear approach to hydrogen and its derivatives by building on the value chain concept for hydrogen, as the hydrogen molecule can be converted into other useful compounds with variable roles in the product design: end use products, intermediate products, industrial commodities or industrial process heat.
iii. Believes on the feasibility of a transition process to a climate-neutral energy system by a combination of both new and existing elements on the wider system – which are enablers of disruption effects that lead to developing and industrializing net-zero technologies in a fast and cost-effective way.
iv. Provides insight on a modular hydrogen approach at a system level, which enables to design an innovate IWG addressing hydrogen and derivatives assisted by PtX technologies, to integrate the SET Plan framework. Overall, P2X strategies are key for achieving a sustainable and carbon-neutral future. They offer a viable path to reduce emissions, enhance energy security, and support economic growth.

Key conclusions:

- **Decarbonization of hard-to-electrify sectors**: P2X technologies provide carbon-neutral alternatives for sectors that are difficult to electrify, such as heavy industry, aviation, and maritime transport. By converting renewable electricity into fuels like hydrogen, ammonia, and synthetic hydrocarbons, these sectors can significantly reduce their carbon footprints.
- **Energy storage and grid stability:** P2X plays a crucial role in addressing the intermittency of renewable energy sources. By converting surplus renewable electricity into storable forms, P2X helps balance supply and demand, ensuring a more stable and reliable energy grid.
- **Sector coupling and integration:** P2X facilitates the integration of various energy sectors (electricity, heating, transportation) by providing versatile energy carriers that can be used across different applications. This sector coupling enhances overall energy system efficiency and resilience.
- **Economic opportunities:** The development and deployment of P2X technologies can drive economic growth by creating new industries and job opportunities. It also positions countries as leaders in the emerging green hydrogen and synthetic fuel markets.
- **Policy and regulatory support:** The successful scale-up of P2X technologies requires strong policy and regulatory frameworks. Governments need to provide incentives,

funding, and clear regulations to support the development and adoption of these technologies.

- **Proposed framework a SET Plan IWG level**: At a system level, designing an innovate and coherent IWG H2 strategy is possible and selected examples provided - from which a set of collaborative R&I directions may be derived to integrate an implementation plan in the frame of the IWG H2, particularly when interacting with a wide range of other IWGs of the SET Plan framework, such as: Renewable Energy Sources: solar, wind ocean, and geothermal; Cities, Urbain districts, Buildings and Communities; Energy Systems; Energy Efficiency in Industry; Batteries and other storage strategies; Renewable fuels of non-biologic origin and biofuels, and Carbon Capture Use and Storage.

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8. Annex - Methodological note

Note on the use of key drivers and enablers being considered in a clean hydrogen (H2) economy.

Introductory note

In the context of energy transition towards a net-zero economy, the relationship between drivers and enablers is quite interdependent, playing crucial roles over different time periods to achieve a sustainable energy transition[54]. Whether one comes first or the other, depends very much on the context. In the case of the current energy transition, there is a general acceptance that:

a) **Drivers** are the forces that push the need for action whatever the scale is, e.g. a system transformation and transition to another performance stage on value creation along time. Drivers can include:
(i) **Environmental concerns** (e.g. decarbonization and the urgent need to reduce/prevent GHG emissions and/or mitigate climate change);
(ii) **Economic factors** (e.g. the rising costs of fossil fuels, energy security, market demand, economic opportunities and benefits of RES);
(iii) **Policies and Regulation** (e.g. government policies and international agreements like the Paris Agreement adopted in 2015, and the Montreal Protocol signed in 1987)

b) **Enablers** are those technologies, policies, and practices that provide the means to achieve the change or action, making that transition possible. Enablers may include:
(i) **Technological innovations** (e.g. advances in renewable energy technologies, energy storage, and smart grids);
(ii) **Financial mechanisms** (e.g. funding, investments and financial and non-financial incentives that support the development and adoption of clean energies);
(iii) **Infrastructure development** (e.g .building the necessary infrastructure for renewable energy generation, storage and distribution).

In practice, drivers come first when addressing sustainability transition issues as they create the urgency and demand for change. For example, the growing awareness of climate change (a driver) has led to increased investment in renewable energy technologies (an enabler). However, without enablers, the transition cannot be effectively realized. That is, while drivers initiate the process, enablers are essential for achieving the goals set by the drivers. They work ‘hand-in-hand’ to ensure a successful energy transition.

[54] From short to long term: (i) Short term (2020-2030): The focus is on rapid deployment of existing technologies, massive adoption of tested effective solutions, policy implementation, and initial investments. (ii) Medium term (2030-2040): The focus is on scaling up renewable energy capacity, enhance energy efficiency measures, and integrate new technologies. (iii) Long term (2040-2050): The focus is on achieving net-zero emissions, complete the transition to a sustainable energy system, and ensure global energy security.

Method

The aim of this bottom-up approach is to get insight on key elements to design new strategic activities in desired directions when deploying a clean hydrogen (H2) economy.

Based on the drivers and enablers being considered, 5 key drivers ('D') are involved, each dependent on different key features ('F'), and different key conditions ('C') for being well succeeded. The 5 drivers selected show that the current energy transition depends not only on technological advances, but also on societal integration as a whole – namely, the implementation of sustainable consumption practices, towards widespread decarbonisation by 2050.

Key Drivers

Drivers collectively support the transition to a clean hydrogen economy, promoting sustainability and economic growth. Deploying a hydrogen (H2) economy involves 5 key **drivers ('D'),** where each depends on different **key features ('F')** and different key conditions ('C') to be successful

Driver 1 (D1) Decarbonization Goals:

Many countries are committed to reducing greenhouse gas emissions toward a net-zero economy and mitigating the climate change. Clean hydrogen, especially green hydrogen produced from renewable electricity, is considered as a crucial element in achieving these targets. The key features and key conditions on 'Decarbonization Goals' are identified in Table 1.

Table 1: Main features and conditions for D1

Key features	Key conditions
Contributing to a comprehensive and effective strategy for decarbonizing the economy, ensuring a sustainable and resilient future	**Creating a supportive environment for achieving a low-carbon economy, ensuring sustainability and resilience**
D1F1 **Transition to a renewable energy system**: Shifting the energy mix from fossil fuels to energy from renewable sources like wind, solar, and hydropower is fundamental.	D1C1 **Strong Policy Framework**: Implementing sound and effective policies, including carbon reduction targets and carbon pricing, emissions standards, and funding, financing and incentives for clean technologies, is crucial.
D1F2 **Energy Efficiency**: Improving energy efficiency across all sectors, including buildings, transportation, and industry, helps reduce overall energy demand.	D1C2 **Technological Innovation**: Continuous advancements in clean technologies, such as renewable energies and clean hydrogen, energy storage, and carbon capture, utilization, and storage (CCUS), are essential
D1F3 **Electrification and decarbonisation of hard to abate sectors:** Electrifying sectors that traditionally rely on fossil fuels, such as transportation and heating, using clean electricity. Prioritize hydrogen and its derivatives in sectors	D1C3 **Funding and financing**: Funding and financing of research, development and deployment in the construction and modernisation of infrastructure to support renewable energies, electric vehicles and the production and distribution of clean hydrogen, as well as

where direct electrification with renewable energy is not an option.	its use in hard to abate sectors, such as the production of ammonia, steel and synthetic fuels for long-haul aviation and shipping. .
D1F4 **Low-Carbon Hydrogen (CCUS):** Natural gas reforming with carbon capture and storage/utilisation ('CCUS') is often cited as the most cost-effective pathway in the near term. However, its economic viability depends heavily on CO2 transport and storage infrastructure, which has not been developed on a large scale yet.	D1C4 **Financial Investment**: Significant investment from both public and private sectors to fund research, development, and deployment of low-carbon technologies
D1F5 **Circular Economy**: Promoting a circular economy to reduce waste and increase the reuse and recycling of materials.	D1C5 **Criteria for low-carbon hydrogen**: Laying out precise criteria for low-carbon hydrogen. This will establish the standards, counting rules and thresholds required to categorise hydrogen production methods as low carbon, facilitating clearer guidance for industry practices and regulatory compliance.
D1F6 **Policy and Regulation**: Enacting supportive policies and regulations, including carbon reduction targets and pricing, emissions standards, and financial and non-financial incentives for clean technologies.	D1C6 **Recycling critical raw materials**: By using circular economy strategies in the development of hydrogen technologies, critical raw materials can be recycled to the greatest possible extent and a more stable supply of raw materials can be achieved through closed value-added cycles.[i]
D1F7 **Innovation and Technology**: Investing in research and development to drive technological advancements in clean energy and low-carbon solutions.	D1C7 **Shaping the clean hydrogen economy:** Policies will shape the hydrogen economy and impact hydrogen-related investment decisions. First, RED III,ReFuelEU Aviation Regulation and FuelEU Maritime Regulation set binding targets for RFNBO uptake in industry and transport. This will benefit renewable hydrogen and limit the accessible markets for low-carbon hydrogen. [ii]
D1F8 **Public and Private Investment:** Mobilizing significant investment from both public and private sectors to fund the clean energy transition.	D1C8 **Technological and Economic Diversification**: Transitioning economies away from fossil fuel dependence towards more sustainable industries. Drive the adoption of innovative technologies such as clean hydrogen technologies to avoid lock-in.
D1F9 **International Cooperation**: Collaborating globally to share best practices, technologies, and resources to achieve decarbonization goals.	D1C9 **Public Awareness and Engagement**: Raising awareness and engaging the public in the importance of decarbonization efforts. The existing market and regulatory conditions are not sufficient to trigger the necessary investments in clean hydrogen. To improve competitiveness, Europe needs to increase public investment, including public procurement, and focus on demand-side support.

	D1C10 By setting ambitious targets for renewable hydrogen supply in 2030 and beyond in the REPower EU plan, the European Commission has facilitated large-scale imports of clean hydrogen, recognising that renewable resources will face intense sectoral competition and deployment barriers.

D2 Economic Opportunities:

The hydrogen economy presents significant economic opportunities, including job creation in new industries and the potential for countries to become leaders in hydrogen technology and exports. Key features and key conditions on 'Economic Opportunities' are identified on Table 2.

Table 2 – Main features and conditions for D2

Key features	Key conditions
Highlighting the diverse and substantial economic benefits of transitioning to a clean hydrogen economy	**Creating a supportive environment for the clean hydrogen economy, driving economic growth and sustainability**
D2F1 **Job Creation:** The development of clean hydrogen technologies and infrastructure can create numerous jobs in manufacturing, construction, and maintenance.	D2C1 **Industry needs and training programmes offered**: To effectively educate, upskill and reskill individuals and address the needs of the hydrogen sector, a set of six strategic axes are proposed for consideration: Development of modular trainings; Definition of training standards for hydrogen; Improvement of access to continuing professional development; Establishment of an online hydrogen community; Encouraging the uptake of mobility for education in hydrogen; Promoting the attractiveness and raising awareness of the hydrogen sector.[iii]
D2F2 **Investment Opportunities**: There are significant opportunities for investment in clean hydrogen production, storage, and distribution technologies. These include private equity and venture capital financing in fuel cell technologies and infrastructure developments such as storage hubs and refuelling stations.	D2C2 **Investment in R&D**: Continuous investment in research and development is crucial for advancing hydrogen technologies and reducing costs. The Member States still have to clarify the legal framework that can drive investments by hydrogen off takers, producers, and infrastructure operators.
D2F3 **Export Potential**: Countries with abundant renewable energy resources can produce green hydrogen for export, potentially transforming their economies, provided their national decarbonisation plans are met. For example, countries in South and South-East Europe, as well as Chile, Morocco, and	D2C3 **Infrastructure Development and Building**: Building the necessary pan-European interconnecting infrastructure for hydrogen production, storage, and distribution is essential. This includes pipelines, refuelling stations, and storage facilities.

Namibia are poised to become green hydrogen exporters.	
D2F4 **Industrial Applications**: Clean Hydrogen can be used to decarbonize various industrial processes, such as steel production and chemical manufacturing, creating new markets and business opportunities.	D2C4 **Market Demand**: Developing a robust market for clean hydrogen by promoting its use in various sectors such as transportation, industry, and power generation. Provide visibility at Member State level on how the industry and transport targets will be transposed.
D2F5 **Energy Security**: By producing clean hydrogen domestically, countries can reduce their dependence on imported fossil fuels, enhancing energy security and economic stability.	D2C5 **National transposition of RED3 and Hydrogen and Decarbonised Gas Markets package** Rapidly implement the Hydrogen and Decarbonised Gas Markets package at national level, designating a hydrogen network operator, clarifying the framework for third party access to infrastructure, and design a funding framework for infrastructure roll out**.**
D2F6 **Technological Innovation**: The clean hydrogen economy drives innovation in related technologies, such as electrolysers, fuel cells, and hydrogen storage solutions, fostering a dynamic and competitive tech sector.	D2C6 **Public and Private Investment**: Significant investment from both public and private sectors is needed to fund the development and deployment of hydrogen technologies. The EU Hydrogen Bank should evolve to further support off taker risks and to include imports. Rules on accumulation need to be addressed to facilitate the funding of projects. Member States should develop mechanisms to address the cost gap between clean and conventional hydrogen.
	D2C7 **Technological Advancements**: Innovations in hydrogen production, storage, and utilization technologies are essential for making hydrogen more viable and cost-effective.
	D2C8 **Public Awareness and Acceptance**: Raising awareness about the benefits of hydrogen and gaining public acceptance is crucial for the widespread adoption of hydrogen technologies.

D3 Energy Security:

Clean Hydrogen can be produced domestically from various r sources, reducing dependence on imported fossil fuels and enhancing energy security. Key features and key conditions on 'Energy Security' are identified on Table 3.

Table 3 – Main features and conditions for D3

Key features	**Key conditions**
Developing a comprehensive approach to energy security to ensure reliable, affordable and sustainable access to renewable and clean	**Creating a secure and resilient energy system capable of supporting economic stability and growth**

energy, and contribute to a secure and resilient energy system capable of promoting economic stability and growth.	
D3F1 **Availability**: Ensuring a consistent and sufficient supply of renewable and clean energy to meet current and future demands.	D3C1 **Diverse Energy Sources**: Utilizing a mix of energy sources, including renewables, nuclear, and fossil fuels with carbon capture, to reduce dependency on any single source and enhance stability.
D3F2 **Accessibility**: Access to renewable and clean energy resources for all regions and populations, including remote and underserved areas.	D3C2 **Robust Infrastructure**: Developing and maintaining resilient energy infrastructure that can withstand natural disasters, cyber-attacks, and other disruptions.
D3F3 **Affordability**: Keeping energy prices stable and affordable for consumers and industries.	D3C3 **Energy Storage**: Investing in energy storage solutions, such as batteries, pumped hydro and hydrogen storage, to balance the energy system, supply and demand and ensure reliability.
D3F4 **Reliability:** Maintaining a stable and uninterrupted energy supply and a secure and reliable energy system, minimizing the risk of outages and disruptions.	D3C4 **Smart Grids**: Implementing smart grid technologies to better match the supply and demand of electricity in real time while minimizing costs and maintaining the stability and reliability of the grid.
D3F5 **Infrastructure security and system resilience**: Protecting critical energy infrastructure from physical and cyber threats Enhancing the energy system's ability to withstand and recover from disruptions, such as natural disasters, cyber-attacks, and geopolitical conflicts.	D3C5 **Cybersecurity Measures**: Protecting critical energy infrastructure from cyber threats through robust cybersecurity protocols and incident response plans.
D3F6 **Diversity and sustainability**: Diversifying energy sources and suppliers to reduce dependence on any single source or supplier, thereby mitigating risks. Integrating renewable and low-carbon energy sources to reduce environmental impact and ensure long-term sustainability.	D3C6 **Policy and Regulation**: Establishing supportive policies and regulatory frameworks that promote energy security and resilience.
	D3C7 **International Cooperation**: Collaborating with other countries to share best practices, technologies, and resources to enhance global energy security.
.	D3C8 **Public Awareness and Engagement**: Educating the public about energy security and resilience to foster support for necessary measures and investments.

D4 Industrial Demand:

Industries such as steel, chemicals, and heavy transport are looking to clean hydrogen to decarbonize processes that are difficult to electrify. Key features and key conditions on 'Industrial Demand' are identified on Table 4.

Table 4 – Main features and conditions for D4

Key features	Key conditions
Highlighting the significant role hydrogen plays on industrial demand	**To create a supportive environment for the growth of industrial demand within the hydrogen economy, driving economic growth and sustainability**
D4F1 **Decarbonization of hard to abate industries**: Hydrogen is crucial for reducing emissions in sectors like steel, cement, and chemicals, where electrification is challenging as well as the production of synthetic fuels for long haul aviation and shipping. Hydrogen is used as a feedstock in the production of ammonia for fertilizers and in refining processes	D4C1 **Cost Competitiveness**: Hydrogen must become cost-competitive with fossil-fuel-based hydrogen, traditional fuels and feedstocks. This requires advancements in production technologies, such as electrolysis, low-cost renewable electricity and economies of scale.
D4F2 **Feedstock for Chemical Production**:.	D4C2 **Infrastructure Development**: Adequate infrastructure for hydrogen production, storage, and distribution is essential. This includes pipelines, refuelling stations, and storage facilities.
D4F3 **Energy Storage and Grid Balancing**: Hydrogen can store excess renewable energy and help balance the grid, providing a stable energy supply for industrial operations.	D4C3 **Policy Support**: Government policies and incentives, such as subsidies, tax exemptions, and carbon pricing, can drive the adoption of hydrogen in industrial applications.
D4F4 **High-Temperature Processes**: Hydrogen can generate the high temperatures needed for industrial processes, which are difficult to achieve with electricity alone.	D4C4 **Technological Innovation**: Continuous innovation in hydrogen technologies, including fuel cells and hydrogen storage solutions, is crucial for enhancing efficiency and reducing costs.
D4F5 **Emerging Applications**: New uses for hydrogen are emerging in industries such as synthetic fuels production and heavy transport, further driving demand.	D4C5 **Market Demand**: Developing a robust market for hydrogen by promoting its use in various industrial sectors, such as steel production, chemical manufacturing, and heavy transport.
	D4C6 **International Collaboration**: Global cooperation can help standardize hydrogen production and usage, facilitating international trade and investment.
	D4C7 **Public and Private Investment**: Significant investment from both public and private sectors is needed to fund the development and deployment of hydrogen technologies.

D5 Policies and Incentives:

Supportive policies, funding, and regulatory frameworks are crucial in driving investment and development in the clean hydrogen sector. Key features and key conditions on ‘Government Policies and Incentives’ are identified on Table 5.

Table 5 – Main features and conditions for D5

Key features	Key conditions
Government policies and incentives that create a conducive environment and play a crucial role in fostering the clean hydrogen economy.	**Provided by Government policies and incentives to create a conducive environment for fostering an effective hydrogen economy.**
D5F1 **Tax Credits and Subsidies**: Governments often provide tax credits and subsidies to reduce the cost of hydrogen production and fuel cell technologies. For example, the U.S. Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act includes tax credits for hydrogen production and fuel cell vehicles.	D5C1 **Clear Regulatory Frameworks**: Establishing clear and supportive regulations for clean hydrogen production, storage, and distribution is essential. This includes safety standards, certification schemes, and environmental regulations, funding, tax exemptions, renewable electricity price reduction etc..
D5F2 **Research and Development Funding**: Significant funding is allocated to research and development (R&D) to advance hydrogen technologies. Programs like the EC Horizon Europe - Cluster 5 ‘Climate, energy and mobility’, or the U.S. DOE’s ‘H2@Scale’ initiative focus on innovation and commercialization.	**D5C2 Research and Development Support:** Investing in R&D to drive innovation in hydrogen production, storage, and utilization technologies. This can include funding for pilot projects and public-private partnerships.
D5F3 **Public-Private Partnerships**: Collaboration between government agencies, industry, and academia is promoted to accelerate the development and deployment of clean hydrogen technologies.	D5C3 **Public authorities support:** Public authorities can play an important role in scaling up the hydrogen ecosystem by ensuring sufficient demand for hydrogen applications and taking over some of the investment costs and associated risks
D5F4 **Regulatory Frameworks**: Establishing clear and supportive regulatory frameworks is essential for standardizing hydrogen production, storage, and distribution. The European Union, for instance, has developed comprehensive policies under the European Hydrogen Strategy.	D5C4 **Transposing regulations at national level** : Under the Fit for 55 package, the European Union has designed a regulatory framework which could help the emerging clean hydrogen market. Most of this pioneering regulation still has to be transposed at national level to drive investments by hydrogen off takers, producers, and infrastructure operators.
D5F5 **Infrastructure Development**: Governments invest in building the necessary infrastructure, such as	D5C5 **Market Creation**: Implementing policies that create demand for clean hydrogen, such as mandates for its use in certain sectors (e.g., transportation,

hydrogen refuelling stations and pipelines, to support the hydrogen economy.	industry) and public procurement of hydrogen technologies.
D5F6 **International Collaboration**: Countries often collaborate internationally to share knowledge, technologies, and best practices. Japan, for example, works with Australia to develop a stable hydrogen supply chain.	D5C6 **International Collaboration**: Engaging in international cooperation to standardize hydrogen production and usage, facilitating global trade and investment.
D5F7 **Market Creation**: Policies aimed at creating a robust market for hydrogen, such as mandates for hydrogen use in certain sectors, help drive demand and investment.	D5C7 **Public Awareness and Education**: Raising awareness about the benefits of clean hydrogen and educating the public and businesses on its potential uses and advantages.

D6 Technological Advancements:

Innovations in clean hydrogen production, storage, and utilization technologies are making hydrogen more viable and cost-effective. Key features and key conditions on 'Technological Advancements' are identified on Table 6.

Table 6 – Main features and conditions for D6

Key features	**Key conditions**
Driving rapid technological change and its profound impact on society and the economy	**Creating an environment conducive to technological innovation and advancement, enabling the development of cutting-edge solutions that drive progress and improve quality of life**
D6F1 **Increased Computing Power**: Advances in computing power, such as quantum computing and more powerful processors, enable complex calculations and data processing at unprecedented speeds.	D6C1 **Strong Research and Development (R&D)**: Continuous investment in R&D is crucial for driving innovation and discovering new technologies.
D6F2 **Connectivity and Speed**: Technologies like 5G and fibre optics significantly enhance connectivity and data transfer speeds, facilitating real-time communication and data sharing.	D6C2 **Skilled Workforce**: A well-educated and skilled workforce is essential for developing, implementing, and maintaining new technologies.
D6F3 **Artificial Intelligence and Machine Learning**: AI and ML are driving automation, predictive analytics, and personalized experiences across various sectors.	D6C3 **Supportive Policy and Regulation**: Government policies and regulations that encourage innovation, protect intellectual property, and provide funding and incentives for technological development.
D6F4 **Data Analytics**: The ability to collect, store, and analyse vast amounts of data is transforming	D6C4 **Infrastructure**: Robust infrastructure, including high-speed internet, advanced manufacturing facilities,

decision-making processes and enabling new insights.	and reliable energy sources, supports the development and deployment of new technologies.
D6F5 **Internet of Things (IoT)**: IoT connects everyday devices to the internet, allowing for smarter homes, cities, and industries through real-time monitoring and control.	D6C5 **Collaboration and Partnerships**: Collaboration between academia, industry, and government can accelerate technological advancements by pooling resources and expertise.
D6F6 **Sustainability**: Technological advancements are increasingly focused on sustainability, with innovations in renewable energy, energy efficiency, and waste reduction.	D6C6 **Market Demand**: A strong market demand for new technologies drives investment and innovation. Understanding and anticipating market needs is crucial.
D6F7 **User Experience**: Enhancements in user interfaces and user experience design make technology more accessible and intuitive for users.	D6C7 **Access to Capital**: Availability of funding from venture capital, government grants, and other sources is essential for startups and established companies to invest in new technologies.
D6F8 **Security**: As technology evolves, so do the measures to protect data and systems from cyber threats, ensuring privacy and security.	D6C8 **Cultural Acceptance**: Societal acceptance and adoption of new technologies are necessary for their widespread implementation and success.

D7 International Collaboration:

Global cooperation and standardization efforts are essential for addressing global challenges, creating a robust clean hydrogen market and facilitating international trade. Key features and key conditions on 'International Collaboration' are identified on Table 7.

Table 7 – Main features and conditions for D7

Key features	**Key conditions**
Advancing scientific and technological progress, enabling partners to achieve more together than they could individually and contributing to the success of international collaborations	**Creating a supportive environment for effective and successful international collaborations**
D7F1 Shared Goals and Objectives: Successful collaborations are built on common goals and mutual interests, ensuring all parties are aligned and motivated.	**D7C1 Clear Objectives and Goals:** Establishing well-defined objectives and goals ensures all parties are aligned and working towards a common purpose.
D7F2 Diverse Expertise: Bringing together diverse expertise and perspectives enhances creativity and innovation, leading to more comprehensive solutions.	**D7C2 Strong Communication:** Maintaining open, transparent, and frequent communication helps coordinate efforts, share knowledge, and resolve conflicts.
D7F3 Effective Communication: Clear and consistent communication is crucial for coordinating efforts, sharing knowledge, and resolving conflicts.	D7C3 **Mutual Trust and Respect**: Building trust and respect among collaborators fosters a positive working relationship and enhances cooperation.

D7F4 Cultural Understanding: Awareness and respect for cultural differences help build trust and foster a collaborative environment.	D7C4 **Cultural Sensitivity**: Understanding and respecting cultural differences helps prevent misunderstandings and promotes a harmonious collaboration.
D7F5 Resource Sharing: Collaborations often involve sharing resources, such as funding, facilities, and data, to maximize efficiency and impact.	D7C5 **Leadership and Coordination**: Strong leadership and effective coordination are essential for guiding the collaboration, making decisions, and ensuring that objectives are met.
D7F6 Strong Leadership: Effective leadership is necessary to guide the collaboration, make decisions, and ensure that objectives are met.	D7C6 **Flexibility and Adaptability**: Being open to change and adaptable to new circumstances helps collaborations navigate challenges and seize opportunities.
D7F7 Flexibility and Adaptability: Being open to change and adaptable to new circumstances helps collaborations navigate challenges and seize opportunities.	
D7F8 Long-term Commitment: Sustained commitment from all parties is essential for achieving long-term goals and maintaining the collaboration.	

Enablers

Enabling a clean and renewable hydrogen (H2) economy involves several enablers that collectively contribute to the development and scaling of a clean hydrogen economy.

Key factors (enablers) are:

Enabler 1 (E1) Sustainable energy sources:

a) Renewable energy sources: The renewable hydrogen is produced using renewable energy sources like wind, solar, and hydropower. Ensuring a steady and scalable supply of these renewables is crucial. These sources are virtually inexhaustible over human timescales, but environmental impacts - though generally low, are likely in some renewable sources (e.g. large-scale hydropower) to exhibit significant environmental impacts.

b) clean energy sources: All renewable energy is clean, but not all clean energy is renewable. Clean sources generate energy having little to no GHG or pollutants during generation. The key feature of these sources is on minimizing environmental harm, particularly air pollution and carbon emissions.

E2 Infrastructure development: Building the necessary infrastructure for hydrogen production, storage, and transportation is essential. This includes pipelines, refuelling stations, and storage facilities.

E3 Technological advancements: Innovations in hydrogen production technologies, such as electrolysis, and improvements in fuel cell efficiency are vital for reducing costs and increasing efficiency. As production scales up, the cost of hydrogen technologies tends to decrease. This is due to factors like improved manufacturing processes, economies of scale, and technological successful innovation.

E4 Policy and Regulation: Supportive government policies and regulations can incentivize investment in hydrogen technologies. This includes subsidies, tax incentives, and clear regulatory frameworks.

E5 Public and Private Investment: Significant investment from both public and private sectors is needed to fund research, development, and deployment of hydrogen technologies.

E6 Market development & Expansion: Creating a robust market for hydrogen by promoting its use in various sectors such as transportation, industry, and power generation. As costs decrease, hydrogen becomes more competitive with traditional energy sources, leading to wider adoption in various sectors such as transportation, industry, and power generation.

E7 Applications & Learning curves: Learning curves in hydrogen application markets refer to the relationship between the cumulative production of hydrogen technologies, the efficiency improvements and overall costs reduction over time. Understanding these learning curves and enhancement factors is essential for predicting future cost trends and making informed decisions about competitiveness and investments in hydrogen strategies.

E8 Knowledge sharing: Collaboration and cooperation can help standardize hydrogen production and usage, facilitating international trade and investment. International cooperation and knowledge sharing can enhance the learning curve by spreading best practices and innovations across borders.

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[i] https://www.vde.com/en/press/press-releases/impulse-paper-hydrogen-circular-economy-din-dke-vdi
[ii] European Hydrogen Skills Strategy
[iii] Assessing the impact of low-carbon hydrogen regulation in the EU, 2024 Deloitte

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