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Renewable Gases – Hydrogen in the Grid

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Synthesis Report

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Abbreviations and Acronyms

ACER	European Union Agency for the Cooperation of Energy Regulators
AT	Austria
AU	Australia
BCM	billion cubic meters
BE	Belgium
BEV	battery electric vehicle
CA	Canada
CAPEX	capital expenditure
CCC	Committee on Climate Change
CCS	carbon capture and storage
CCUS	carbon capture, use and storage
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CENELEC	Comité Européen de Normalisation Électrotechnique (European Committee for Electrotechnical Strandardization)
CH_4	methane
CL	Chile
CO	Colombia
CO_2	carbon dioxide
CMS	CMS Legal Services EEIG
CN	China
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CZ	Czech Republic
DAC	Direct Air Capture
DE	Germany
DK	Denmark
EBA	European Biogas Association
EC	European Commission
EE	Estonia
EEB	European Environmental Bureau
ERIG	European Research Institute for Gas and Energy Innovation
ES	Spain
ETC	Energy Transitions Commission
EU	European Union
FCV	fuel-cell vehicle
FE	Frontier Economics
FI	Finland
FH	France Hydrogène
FR	France
FSR	Florence School of Regulation
GO	Guarantee of Origin
GR	Greece
H_2	(molecular) hydrogen
HE	Hydrogen Europe
HIGG	hydrogen injection into the gas grid
HU	Hungary

ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IEA Bio	International Energy Agency Bioenergy Technology Collaboration Programme
IEA H2	International Energy Agency Hydrogen Technology Collaboration Programme
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
ISO	International Standardization Organization
IT	Italy
JP	Japan
JRC	European Commission Joint Research Centre
KR	Republic of Korea
LHV	lower heating value
LU	Luxembourg
MENA	Middle East and North Africa
Mt	million tonnes
NECP	National Energy and Climate Plan
NL	The Netherlands
NO	Norway
NRCan	National Resources Canada
NZE	net zero emission
OIES	Oxford Institute for Energy Studies
PL	Poland
PSA	pressure swing adsorption
PT	Portugal
PtG	power-to-gas
RG	renewable gas(es)
RU	Russian Federation
SEA	Swedish Energy Agency
SK	Slovakia
SM	renewable synthetic methane
SMR	steam methane reforming
SNG	Synthetic Natural Gas
TRL	Technology Readiness Level
vol%	per cent by volume
UAE	United Arab Emirates
UN-ECE	United Nations Economic Commission for Europe
UK	United Kingdom
US	United States of America
US DOE	United States Department of Energy
WI	Wobbe Index

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Objectives of the IEA Bioenergy Task 41 Special Project "Renewable Gases – Hydrogen in the grid"

The project's objective is to carry out a thorough study on **renewable gases (RG)** and the effect of hydrogen (H_2) addition in the gas grid as well as applications at increased concentrations up to 100%.

The project collected existing data, performance indicators, information on RG studies, projects and analyzed national strategies.

It also identified and discussed the numerous **challenges and hurdles** for the **gradual replacement** of natural gas by **renewable gases**, with emphasis **on H_2 addition** to the natural gas grid, and dedicated H_2 grids.

Summary of key findings

This synthesis report summarizes the key findings from the *Renewable Gases - H_2 in the grid* project[1] with a particular focus on the specific role of **hydrogen** (H_2) **in gas grids**, as H_2 is the one renewable[2] gas that

- has very high long-term potential due to fact that its production is limited only in terms of available renewable electricity, but
- implies compatibility issues with the current gas infrastructure.

Renewable gases, including H_2, will be a key component of the global energy system aiming at **net zero** greenhouse gas (GHG) emissions by 2050, compatible with the 1.5 °C goal of the 2015 Paris Agreement on mitigating climate change. IEA's recent Net Zero Emissions scenario for 2050 shows that under a strict GHG mitigation logic, fossil gas supply will be peaking in the mid-2020s and shrinking up to 2050. In parallel, **renewable gases (biomethane, H_2, H_2-based synthetic methane) will have to strongly increase**.

The role of renewable gases in national policies for GHG emission reductions by 2030-2050 and respective estimates for the amounts needed by 2030-2050 was analyzed with a focus on **H_2 strategies and roadmaps**[3]. **All** of those (except Russia) indicate the need for H_2 to decarbonize their economies in the 2030-2050 time horizons, with significant contributions of H_2 to achieve country commitments under the Paris Agreement. Most country strategies and roadmaps see H_2 as a means to overcome the **limits of electrification** and to **help stabilize** electricity grids against a growing share of variable renewable generation, especially solar and wind. Some H_2 strategies address the potential role of longer-term energy storage needs to bridge seasonal variations in renewable electricity generation.

Several countries indicate their **ambition to export** H_2 in the 2030 timeframe and after, while others assume **H_2 imports**. Besides trade, most strategies focus on domestic H_2 application in **hard-to-abate** sectors, i.e., those where GHG emission reduction by renewable electrification is hindered, e.g., the chemical industry, steel-making, and transport (aviation, long-haul road, shipping).

Nearly all country strategies and roadmaps address the role of **existing** gas infra-structure for future H_2 transmission and distribution, and see H_2 **clusters** as an important step towards H_2 use, both in industry, and in regional H_2 networks.

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1 An extensive presentation of renewable gases, including biogas and biomethane, and respective policies and perspectives is given in IEA Bio (2018 + 2021). Further information on renewable and "green" gases is given in e.g., Decorte et al. (2020); ERIG (2021); Wouters et al. (2020).

2 In this report it is assumed **that H_2 is "green", i.e. produced from renewable sources** such as sustainable biomass, and renewable electricity. There are many other options for H_2 supply of various "colors" (blue, gray, etc.), see e.g., Conti (2020), and Section 5.1 of this report.

3 In general, H_2 country strategies do not only concern H_2 as such but include products such as ammonia or synthetic methane (SNG) or renewable methane (RM), and some recognize other renewable gases such as biogas, and biomethane.

Several country strategies address the "**color**" of H_2, i.e., its origin, and some focus on green H_2 while others include a broader range, especially "blue" H_2.

19 country strategies and roadmaps give ambitious **quantitative H_2 production targets** for the year 2030. For 2050, just four countries out of the 21 countries included in the analysis provide targets, with one of them only addressing exports. **All** quantitative targets are **subject to significant advances in cost-reduction** for low-carbon[4] and green H_2 production: Target levels for 2030 are in the \$2 – \$5/kg H_2 range[5], with prospects of a \$1 – \$2/kg H_2 for 2050. The strategies and roadmaps commonly assume market introduction and support schemes for H_2 as well as increased R&D over the next decade to deliver on the expected H_2 production cost reduction. In that regard it is encouraging that many countries already committed significant financial resources to H_2 development.

With regard to options and hurdles for H_2 **injection in gas grids**, biomethane and synthetic methane (SM) can already be added to the existing gas infrastructure without problems. **Co-processing** biogas and H_2 to SM could boost near-term grid-compatible production. Next to that, direct H_2 injection in gas grids (HIGG) could provide a steppingstone for developing a H_2 infrastructure with adding **up to 20 vol% of H_2 to the gas grid**, i.e. about 7 % by energy content.

For higher H_2 shares in the gas grid without compromising downstream distribution and end-uses, the gas transmission system could be used **for H_2 transport only** and H_2 could be **separated** from transported natural gas **before** it is distributed to end-users. H_2 separation would add \$2 - \$4 per kg of H_2 in the longer-term.

A potential alternative to HIGG (and later separation) is to convert H_2 into **renewable synthetic methane** (SM) to make H_2 **fully compatible** with existing natural gas infrastructure and end-use technologies. Methanation of H_2 costs about 50% less than the longer-term additional cost of H_2 separation and could help balancing the electricity system and longer-term storage of renewable electricity.

Converting existing natural gas **transmission** pipelines to H_2 ("repurposing") is possible in many cases. Cost of doing so would add approx. 0.05 \$/kg H_2, while cost for new dedicated H_2 pipelines are twice as high. Costs to convert the gas **distribution** to be fully H_2-compatible are about 20 % of repurposing transmission pipelines, and approx. 1/3 of new dedicated H_2 pipelines, but strongly depend on the geographical distribution of end-users, and the topography of the area served.

There is a clear **transition logic** from natural to renewable gas which also helps integration with the (decarbonized) electricity system.

4 The term "low-carbon" refers to H_2 produced from fossil fuels with CCS, or from grid electricity that has a low GHG footprint. The benchmark for "low" is typically the GHG intensity of natural gas.

5 Note that the costs indicated here refer to the production cost alone. For H_2 delivery, further cost for transmission and distribution as well as respective margins for system operators would need to be added.

Yet, there are many hurdles and obstacles in the **regulatory system**: As H_2 in the grid is a rather new issue, the transformation of the gas system and "coupling" with other energy sectors is quite complex, and the international dimension of trade, especially when including climate policies, is challenging.

Fundamental legal and administrative barriers which **hinder** H_2 injection into gas grids concern legal complexity or absence of permitting rules, divergent regulation on H_2 concentration levels in gas grids, contracts and billing arrangements based on calorific value or Wobbe Index, safety requirements for connection/injection of H_2, and for all types of end-user equipment.

Among the regulatory issues, the color and origin of H_2 and respective GHG emission thresholds, the *additionality* requirements for green H_2, access for H_2 producers to the gas grid and respective grid development planning are, together with H_2 *safety issues*, the most relevant topics which need to be addressed.

Open questions on "H_2 in the grid" remain for which further research should be carried out:

- Is H_2 more favorable that direct electricity use in the (non-industrial) heat and road transport sectors?
- What is the longer-term perspective of H_2 vs. renewable synthetic methane, considering economic benefits for electricity system services and the economic value of existing gas infrastructure?

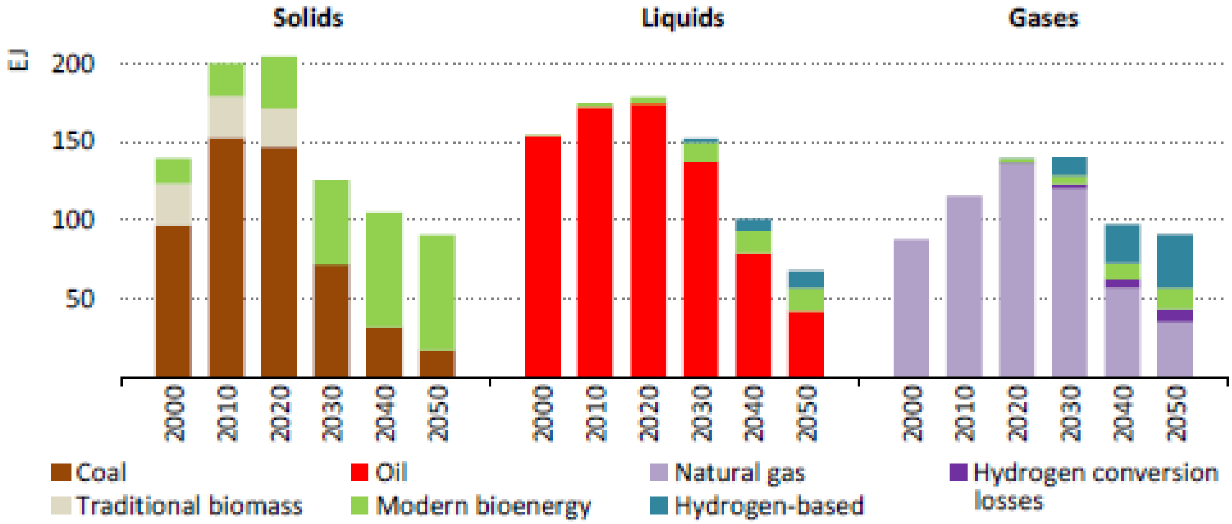
1. The role of H_2 in global decarbonization until 2050

Renewable gases, including hydrogen (H_2), will be a key component of the global energy system aiming at **net zero** greenhouse gas (GHG) emissions by 2050, compatible with the 1.5 °C goal of the 2015 Paris Agreement which is seen as urgent to implement for mitigating climate change (IPCC 2021).

Already in 2018, the IPCC underlined the role of **H_2 in decarbonizing industry** (IPCC 2018), and IEA followed-up on that in its *Net Zero by 2050* scenario (IEA 2021a)[6] and the 2021 World Energy Outlook (IEA 2021c).

The growing shares of renewables and H_2 in IEA's NZE scenario until 2050 and the respective fossil shares are shown in Figure 1 for solids, liquids, and gaseous fuels.

Figure 1 Fossil fuels, renewables, and H_2 in the IEA NZE Scenario



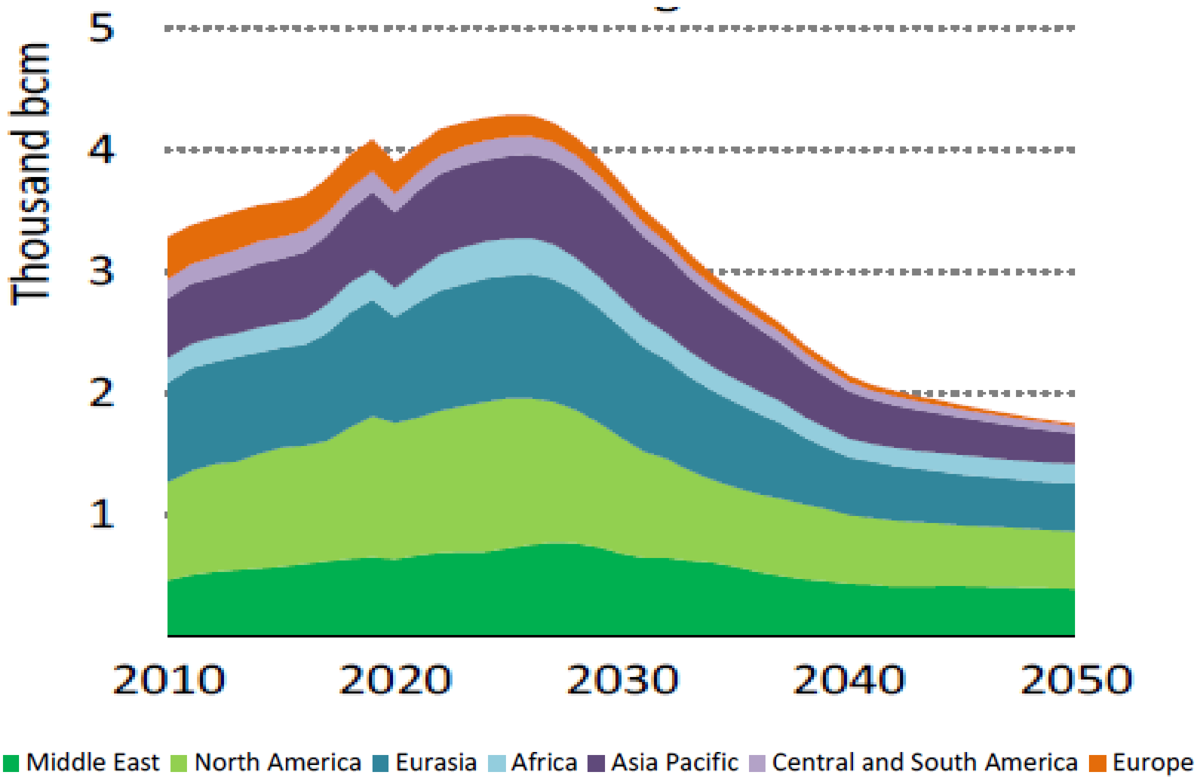
Source: IEA (2021a)

There will be a prominent role for modern solid and liquid bioenergy (light green bars in Figure 1), but also comparatively high shares of H_2-based energy carriers (blue bars in Figure 1), both for liquids, and gaseous fuels.

With fossil gas supply peaking in the mid-2020s and shrinking up to 2050 (Figure 2), **renewable gas supply will have to strongly increase**.

[6] For a presentation and discussion of other recent "net zero" scenarios and comparison with the IEA's NZE scenario see Fulwood (2021).

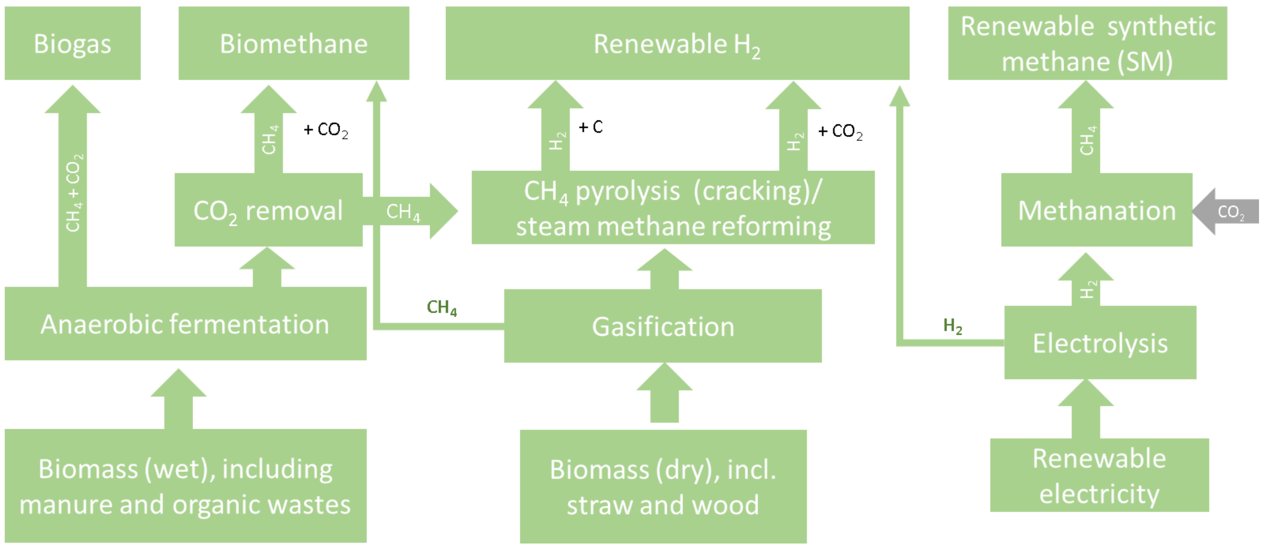
Figure 2 Global natural gas production in the IEA NZE Scenario



Source: IEA (2021a); bcm = billion cubic meters (approx. 40 PJ)

Several pathways exist to provide renewable gases, as depicted in Figure 3.

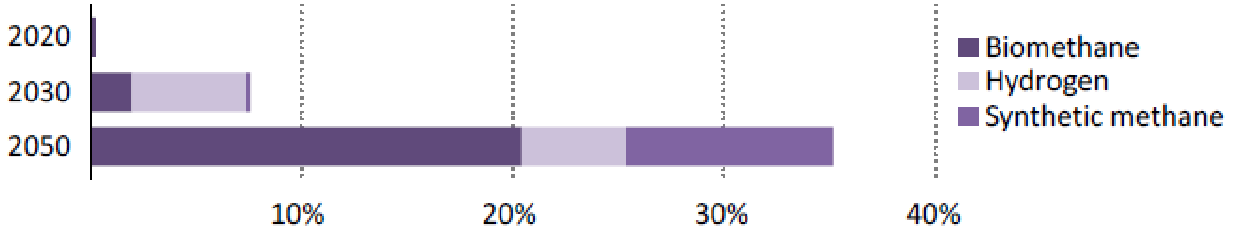
Figure 3 Simplified overview of renewable gases production pathways



Source: adapted from ERIG (2021); note that several further biomass options (e.g., algae, dark fermentation, bioethanol and biooil reforming, and emerging new pathways such as photolytic H_2 are not included

The IEA NZE scenario assumes a major role for renewable gases, especially for biomethane, but also for H_2, and H_2-based synthetic methane (Figure 4).

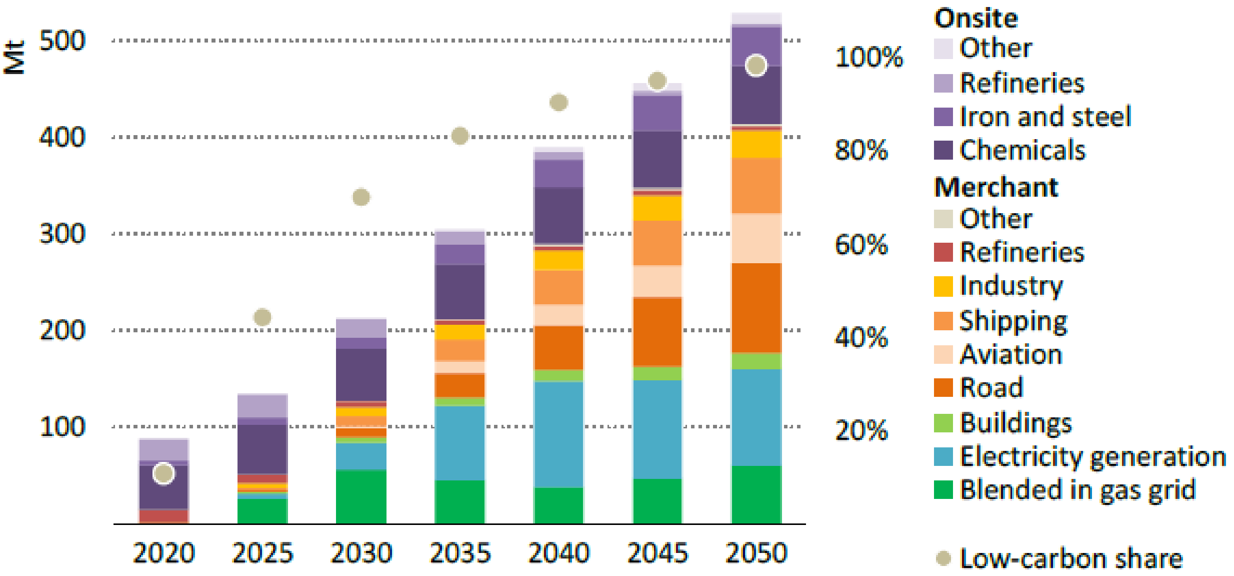
Figure 4 Gas grid shares of renewable gases in the IEA NZE Scenario



Source: IEA (2021a)

Beyond grid injection, H_2 plays a key role in the decarbonization of the future energy system by 2050, with more than a five-fold production increase on 2020 levels, as indicated in Figure 5.

Figure 5 Role of H_2 in the IEA NZE Scenario



Source: IEA (2021a); Mt = million tonnes (1 Mt H_2 is equivalent to approx. 33 TWh or 120 PJ, based on LHV)

H_2 use today is mainly in oil refining and the chemicals industry (for ammonia and methanol production) in the order of 90 Mt in 2020, mainly produced from fossil fuels (natural gas).

The IEA NZE scenario starts with converting existing fossil-based H_2 uses to low-carbon and renewable H_2.

Up to 2050, H_2 and H_2-based fuels are projected to expand across all end-uses.

2. H_2 needs for decarbonization targets until 2050, and respective strategies and policies for greening the gas grids

The IEA NZE scenario depicts **a radical change** in the global energy system up to 2050, with renewable gases – including H_2 – being massively increased to replace fossil fuels, especially natural gas.

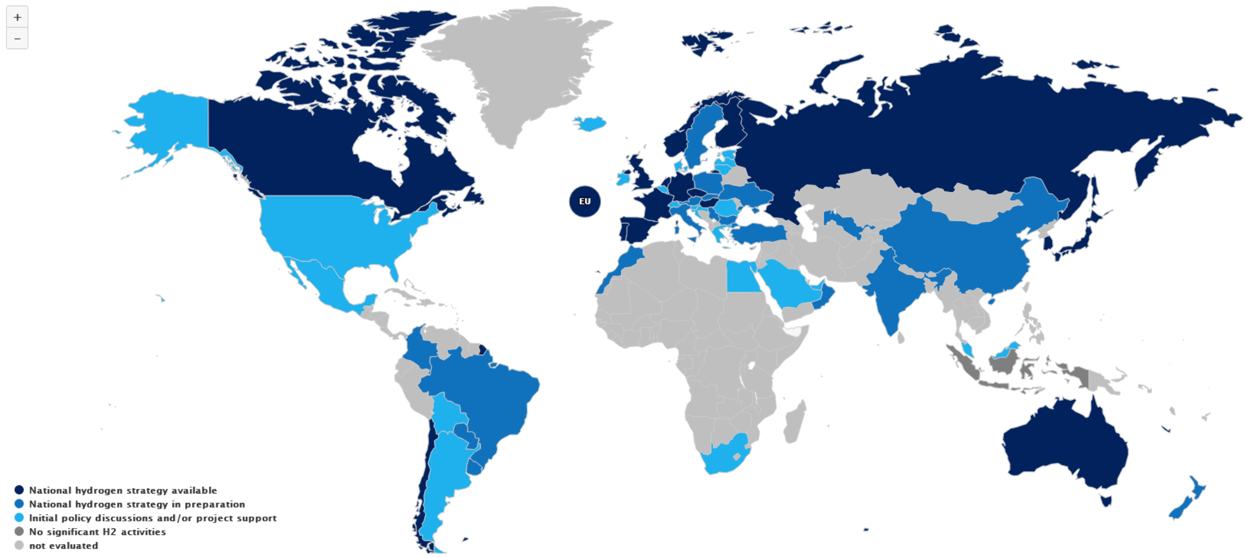
How do current country strategies for renewable gas and introduction of H_2 in the grid match this global scenario?

2.1 Global overview

Since about 2017, national governments of a variety of countries began to consider the potential role of H_2 in their economies and developed respective *H_2 strategies and roadmaps*. Several countries have already published such documents, other countries have related activities – and the process is ongoing (IEA 2021b).

A snapshot of the status is given in Figure 6, reflecting the mid-2020 situation.

Figure 6 Status of H_2 activities of countries, territories and economies



Source: Albrecht et al. (2020)[7]

On the international level, the Clean Energy Ministerial's Hydrogen Initiative was launched in 2019 to *"[…] drive international collaboration on policies, programs and projects to accelerate the commercial deployment of hydrogen and fuel cell technologies across all sectors of the economy"*[8].

[7] For updated information see https://www.weltenergierat.de/publikationen/studien/international-hydrogen-strategies

[8] https://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/hydrogen-initiative

In 2020, a UN Economic Commission for Europe recognized the relevance of H_2 for carbon neutrality (UN-ECE 2020), and recently, Mission Innovation started the Clean Hydrogen Mission (MI 2021).

Table 1 lists countries that developed national strategies and roadmaps for H_2 and included quantitative targets[9] for 2030, and some for 2050. As can be seen, the majority of such targets is set by IEA member countries, but Chile, China, and Colombia as well as Russia are noteworthy exceptions[10].

Table 1 H_2 supply targets in various countries for 2030 and 2050

Country Code	Country name/region	TWh of H_2 by		Source
		2030	**2050**	
AT	Austria	4 – 8		Streitner (2021)
CA	Canada	133	667	NRCan (2020)
CL	Chile*	125		CL (2020)
CO	Colombia	5		CO (2021a+b)
CN	China	297		Albrecht et al. (2020)
CZ	Czech Republic	3		CZ (2021)
DE	Germany	14		BMWi (2020)
ES	Spain	20		ES (2020)
EU	European Union	200		EC (2020)
FI	Finland	3-5		Laurikko et al. (2020)
FR	France	33		FR (2021)
HU	Hungary	2		HU (2021)
IT	Italy	25		IT (2020)
JP	Japan	10-100	667	JP (2017); METI (2021)
KR	Korea	88		KR (2019)
NL	The Netherlands	15 – 20		NL (2020a+b)
PT	Portugal	10 – 13	25	PT (2020)
RU	Russia*	67		RU (2020 + 2021)
SE	Sweden**	25	75	SEA (2021)
UK	United Kingdom	25		UK (2021)
US	United States of America***	567	2100	FCHEA (2020)

Source: own compilation; data given in TWh_{H2} based on lower heating value, derived either from mass-based targets (in Mt H_2), or targeted electrolyser capacities (in GW H_2 production). For the latter, a general figure of 5,000 operating hours per year was assumed unless states otherwise in the source.
** = includes exports; **= proposal, 50 TWh target is for 2045; ***= no official governmental target*

Some H_2 country strategies and roadmaps do not provide quantitative targets, as shown in Table 2: 21 out of 30 IEA member countries already developed national

9 Note that the quantitative targets given in Table 1 refer to domestic low-carbon or "green" H_2 production. Some of the national strategies and oradmaps indicate also overall domestic H_2 demand (e.g., for Germany, 90 – 110 TWh by 2030). Note also that target sectors for H_2 use (industry, heat, transport etc.) are discussed for selected countries in IEA (2021b).

10 For a list of all hydrogen strategies/roadmaps of IEA member countries see Table 2.

H_2 strategies and/or roadmaps, and four more countries have such documents under preparation.

Table 2 H_2 strategies and roadmaps of IEA member countries

		H_2 strategy/ roadmap/vision	**H_2 targets***		**H_2 trade**	
Code	**Name**		**2030**	**2050**	**export**	**import**
AT	Austria	(x)	x			x
AU	Australia	x			x	
BE	Belgium (Flanders)	x				
CA	Canada	x	x	x	x	
CH	Switzerland	(x)				
CZ	Czech Republic	x	x			
DE	Germany	x	x			x
DK	Denmark					
EE	Estonia	x				
ES	Spain	x	x		x	
FI	Finland	x	x	x		x
FR	France	x	x			x
GR	Greece					
HU	Hungary	x	x	x		
IE	Ireland					
IT	Italy	x	x			x
JP	Japan	x	x	x		x
KR	Korea	x	x			x
LU	Luxembourg					
MX	Mexico					
NL	The Netherlands	x	x			x
NO	Norway	x			x	
NZ	New Zealand	x			x	
PL	Poland	x	x			
PT	Portugal	x	x	x	x	
SE	Sweden	x	x	x**	x	
SK	Slovakia	x				
TR	Turkey	(x)				
UK	United Kingdom	x	x			x
US	United States of America	(x)				

*Source: own compilation; * = see Table 1 for details; **= Swedish target is for 2045; (x) = under preparation*

Besides IEA member countries' roadmaps and strategies, there are similar activities for H_2 in sub-Saharan Africa (e.g., Nigeria, Namibia, South Africa), Latin America (e.g., Argentina, Bolivia, Brazil), the MENA region (e.g., Egypt, Morocco, Saudi Arabia, Tunisia, UAE), and Asia (e.g., India[11], Malaysia, Singapore).

Before discussing some of the key national H_2 strategies and roadmaps of selected countries[12] it should be noted that since 2020, a rapid growth of bi- and trilateral **H_2 partnerships** between countries can be seen. These arrangements emerge to prepare for future international H_2 trade between potential export and import countries (see last columns in Table 2), as shown in the following figure.

Figure 7 Bi- and trilateral H_2 partnerships between countries

Source: *https://www.weltenergierat.de/publikationen/studien/international-hydrogen-strategies/* *(accessed Sep 24, 2021)*

IEA's recent *Global Hydrogen Review 2021* listed selected bilateral agreements between governments to co-operate on hydrogen development (IEA 2021b).

[11] India has announced mandatory quota for using renewable hydrogen in refining (up to 25% by 2030) and fertilizer production (20% by 2030), with potential extension to the steel industry in the near future (IEA 2021b).

[12] Note that more information on IEA country perspectives on renewable gases in general, i.e., biogas, biomethane, and H_2-based gases, is available in IEA Bio (2021) which also includes results from surveys.

2.2 Australia

In December 2018, the Council of Australian Governments (COAG) Energy Council agreed to establish a Hydrogen Working Group which prepared Australia's *National Hydrogen Strategy* (COAG 2019) which provided a broad discussion of issues around H_2, underlined Australia's ambition to become a global leader in clean H_2 by 2030 and presented three possible scenarios up to 2050.

A first *National Hydrogen Roadmap* for Australia was published in 2018 (CSIRO 2018). Further work concerned analyses of future H_2 demands (Deloitte 2020).

Meanwhile, the *Advancing Hydrogen Fund* announced in the National Hydrogen Strategy was created and offers **\$300 million for H_2** investments[13].

On the sub-national level, the New South Wales and Western Australian governments set aspirational targets of **blending up to 10 % H_2** in the gas network by 2030 (Norman & Grubnic 2021).

2.3 Canada

The *Hydrogen Strategy for Canada* (NRCan 2020) indicates targets of 2 - 4 Mt H_2 until 2030, rising up to 20 Mt H_2 by 2050 (see Table 1). The strategy highlights the important role of H_2 to meet Canada's climate targets for 2030 and 2050:

H_2 could contribute 21% of the GHG reductions required by 2030, and nearly 30% by of those required by 2050 (NRCan 2020).

For the implementation, the strategy assumes the development of regional industrial clusters.

2.4 European countries and the EU

Before discussing in the following sub-sections country-specific H_2 strategies for Finland, France, Germany, Netherlands, Sweden and the EU, it should be noted that **several other European countries are active** as well[14]:

- **Austria** currently develops a national H_2 strategy, supported by a national study (FE 2021). It is expected that the strategy will have a focus on the role of H_2 in the chemical and steel industry, and a target of 1 – 2 GW electrolyser capacity for "green" H_2 (Streitner 2021). With its recent Renewable Energy Extension Law aiming at 100% renewable electricity in Austria by 2030, it will also provide up to € 500 million for H_2 projects (BMK 2021).
- In **Belgium**, the Flemish government published the *Flanders Hydrogen Vision* (BE 2021) while in Wallonia, and industry-led *Hydrogen Roadmap*[15] was approved by the regional

[13] See for details https://www.cefc.com.au/where-we-invest/special-investment-programs/advancing-hydrogen-fund/

[14] H_2 targets of EU countries – if available – are summarized in Table 1. For more information on current H_2 activities of EU countries see HE (2021a), IEA & CIEP (2021), and CMS (2021).

[15] See for details: https://clusters.wallonie.be/tweed/fr/news/communique-de-presse-lindustrie-le-cluster-tweed-publie-sa-vision-strategique-du-developpement

government already in 2018. Both documents state that hydrogen can contribute to decarbonizing industry and recognize the longer-term potential for low-cost H_2 imports. Belgium and its regions Brussels, Flanders, and Wallonia now are actively seeking H_2-related investments with support from EU funds (IEA & CIEP 2021).

- The **Czech Republic**'s national H_2 strategy approved in July 2021 aims to establish the necessary infrastructure for producing and using low-carbon H_2 to contribute to reach its GHG reduction targets. The strategy primarily focuses on gradually increasing H_2 use in transport and heavy industry (CZ 2021).
- **Denmark** has no dedicated H_2 strategy, but is actively exploring options for greening the gas grid (IEA Bio 2019), and is ambitious in expanding the renewable share in its electricity system. The Danish government announced to produce H_2, methanol and ammonia with commercial partners (DK 2020). To fulfill its 2050 climate neutrality goal, Denmark is pioneering in developing "energy islands", i.e. large-scale offshore wind projects with up to 12 GW, and cooperates in this with Belgium, Germany, Luxembourg, and the Netherlands (DK 2021)[16]. A joined Power-to-X and CCU/CCS strategy from the Danish government is expected at the end of 2021 (GfC 2021).
- **Estonia** is yet preparing its H_2 roadmap, and Estonian companies are trying to participate in the respective EU financing schemes[17].
- **Hungary** prepared in national H_2 strategy in May 2021, including production targets for "blue" and "green" H_2 by 2030, and 2050, as indicated in Table 1 (HU 2021).
- **Italy** presented *guidelines* for a national hydrogen strategy (IT 2020) with a H_2 production target of 5 GW by 2030, and various supporting measures to introduce H_2 into the Italian energy sector, including H_2 addition to its already comparatively large fleet of buses, cars and trucks using natural gas. In its recent *National Recovery and Resilience plan* which will significantly draw from the EU Recovery and Resilience Facility funds, Italy earmarked more than € 3 billion for H_2 development (IT 2021)[18].
- **Norway** published its government's hydrogen strategy in June 2020 (NO 2020) and recently added a respective H_2 Roadmap (NO 2021). An important component is the future role of natural gas SMR combined with CCS to deliver "blue" H_2, with sequestering CO_2 in depleted offshore gas fields. Furthermore, five H_2 "hubs" are to be established in the area of maritime transportation by 2025.
- **Poland** released its draft Hydrogen Strategy for 2030 (with perspectives for 2040) which sets a target of 2 GW H_2 electrolyser capacity and 2,000 H_2 fuel-cell busses by 2030 (PL 2021a+b).
- **Portugal** published its H_2 strategy in 2020, including a target of 2 GW H_2 electrolyser capacity by 2030 (PT 2020), and a law on the organization and functioning of the national

[16] As a first step, Denmark with develop "wind islands" with a capacity of 4 GW by 2030: In the North Sea, Denmark has an artificial island is under construction with a minimum of 2 GW offshore wind (connected in 2030 to Denmark and the Netherlands), with a long term capacity reaching 10 GW offshore wind. In the Baltic Sea, the island of Bornholm will be made an energy island to establish and connect up to 2 GW of offshore wind by 2030 with connections to Poland. These activities are contributing to the EU offshore wind target of 300 GW by 2050.

[17] See https://www.riigikogu.ee/en/sitting-reviews/the-riigikogu-discussed-achieving-climate-neutrality/

[18] It should be noted that the Italian guidelines have been criticized to ignore that the renewable electricity used for national H_2 production would imply a reduced decarbonization of the power sector unless a massive expansion of renewable expansion would be reached by 2030 (Armaroli & Barbieri 2021).

gas system to include renewable gases (Cabrita 2021). The strategy also highlighted the role biomethane, and calls for establishing a *Hydrogen Valley* with deep-sea port access for H_2 exports.

- **Slovakia** adopted its National Hydrogen Strategy in June 2021, stating that H_2 should be used in all industries and areas of public life in which it is impossible or not cost-effective to be directly electrified[19].
- **Spain** endorsed its H_2 strategy in July 2020 with a target of 4 GW H_2 electrolyser capacity by 2030 (ES 2020). A respective roadmap for implementation of the strategy is under development.
- In **Switzerland**, the government published a position paper on H_2 and mobility already in the year 2016 (BFE 2016), and in June 2021, the National Council adopted initiatives of the Swiss parliament to prepare a Green hydrogen strategy for Switzerland, and an assessment and options for action (CH 2021a+b).

More information on activities of EU Member States is provided on the HyEnet platform hosted by the EC[20].

Further information on the regulatory situation and key actors gives CMS (2021).

2.4.1 Finland

Finland's national hydrogen roadmap states that "*Hydrogen plays a key role […]in combating climate change and reaching Finland's national goal of carbon neutrality by 2035*" (Laurikko et al. 2020). It also discusses the **colors** of hydrogen, i.e., from which source it is produced and if CO_2 is captured during production from e.g., natural gas (blue H_2), and concludes that "*supply chain emissions should also be taken into account when calculating emissions of blue hydrogen*" (op. cit.).

It pointed out the relevance of H_2 for steel-making in Finland and the options for synthetic chemicals, and transport fuels (power-to-X), and mentioned the suitability of tube trailer trucks for distribution of H_2 in sparsely populated areas.

2.4.2 France

France released its H_2 deployment plan in 2018, covering the period of 2019-2028, with targets for decarbonizing industrial H_2 use, and H_2 vehicle deployment (FR 2018). Building on this, the *Strategy for the development of renewable and low-carbon hydrogen* was released in 2020 with a H_2 production target of 6.5 GW by 2030 (FR 2020).

[19] See https://www.tasr.sk/tasr-clanok/TASR:2021062300000291

[20] This is an informal platform to sharing information on good practice, experience and the latest developments, as well as joint work on specific issues between EU Member State representatives from the energy ministries in. It aims to help national energy authorities build on the opportunities offered by hydrogen as an energy carrier. For agendas, presentations and meeting notes see https://ec.europa.eu/energy/topics/energy-system-integration/hydrogen/hydrogen-energy-network-meetings_en

France also has a target for all gas suppliers to provide a natural gas/hydrogen mix (10% H_2) by 2030, to enable network operators to adapt their equipment, facilities and operating models and systems to achieve this target (FH 2021).

In 2021, The French government introduced the *Hydrogen Ordinance* to legally define H_2 as well as traceability and support mechanisms (Floréa 2021).

Recently, France Hydrogène, the French H_2 industry association, proposed further steps (FH 2021). Given the rather unique characteristics of the French electricity system, there are excellent opportunities to produce low-carbon H_2 (RTE 2020).

2.4.3 Germany

In the German NECP of 2020, renewable gases are projected to reach about 21 TWh by 2030, including approx. 6 TWh of “green” H_2 (Prognos et al. 2020). Given that the German government raised its climate ambition in 2021 to become climate-neutral already by 2045, it is expected that the next German NECP will have a higher figure for H_2 in 2030.

The German *National Hydrogen Strategy* released in mid-2020 identifies a key role for H_2 in the further development and completion of the energy transition to reduce GHG emissions especially in industry and the transport sector (BMWi 2020). In the future, priority will be given to the use of green hydrogen for this purpose (BMWi 2021a). The strategy establishes a “green” H_2 target of 14 TWh by 2030, corresponding to 5 GW of electrolyser capacity[21].

For implementing the strategy, Germany allocated €7 billion for national projects, including a funding programme for production and use of sustainable electricity-based fuels for aviation and sea transport with a total volume of close to €600 million (BMWi 2021a). Germany also exempted electricity used directly for H_2 production from the Renewable Energy Sources Act (EEG) surcharge.

Meanwhile, Germany started to select *Important Projects of Common European Interest* (IPCEI), providing €8 billion for H_2 with a focus on industry (especially steel), and transport (BMWi 2021b). There are many activities to engage with European and international partners in H_2 research and development, and to prepare for future H_2 trade[22].

The German gas grid is well-developed and could be used for H_2 transport up to 20 vol% blending without major modification. There are plans by the gas transport system operators to do so gradually, starting in clusters and branching out from these (DVGW 2020). Furthermore, German and Dutch gas operators are exploring a future integrated gas infrastructure and the prospective role of H_2 (Gasunie &

[21] The strategy estimates that a total of 90 - 110 TWh H_2 will be needed by 2030, i.e. there will be significant imports required to meet this demand. In that regard, the strategy acknowledges that “blue” H_2 may be temporarily used.

[22] Australia, Canada, Chile, Iceland, Morocco, Norway, Russia, Saudi-Arabia, Tunesia and Turkey are named as potential suppliers of H_2 using renewable energy sources (BMWi 2021a+b).

TenneT 2019; DBI-GUT et al. 2021), and Germany is a partner in the European H_2 "backbone" initiative (see Section 2.4.6).

2.4.4 The Netherlands

Currently, natural gas is the major energy source for the Netherlands – but since the 2011 to 2018 earthquakes around the Groningen gas field, the Dutch government decided to phase out its production by 2030 at the latest (Beckman & van den Beukel 2019), resulting in the need to change the gas system. For this, the Dutch gas industry developed a strategy based "sustainable gases" such as biogas, biomethane, and H_2.

In parallel, the Dutch government took up the challenge to mitigate climate change through the *Klimaatakkoord*, a 2019 agreement between government, industry, and civil society to reduce Dutch GHG emissions below 50% by 2030, and identifying H_2 to play a major role, especially after 2030.

The Netherlands already uses H_2 as a feedstock in its chemical industry, and is - after Germany - the largest producer of "grey" H_2 in Europe: About 10% of Dutch natural gas is currently used for the production H_2.

The *Dutch Hydrogen Strategy* (NL 2020) sees, alongside green gases from biomass, H_2 as a means to decarbonize hard-to-abate sectors. Its initial focus is on scaling-up H_2 deployment in industrial clusters (Amsterdam, Rotterdam) by 2026, connecting those through repurposed gas pipelines, and later a development of international connections to neighbouring countries[23].

A Dutch H_2 backbone of more than 1,000 km will be built (85% repurposed, 15% new dedicated H_2 pipelines) to connect the Dutch industrial H_2 clusters, with first segments ready by 2024-2025, and completed by 2027 (GfC 2021).

In order to realize the production of "green" H_2 in the future, an expansion of the wind capacity at sea and a corresponding expansion of electrolyser capacity of up to 3 - 4 GW is foreseen for 2030, with a production of 15 - 20 TWh H_2 (see Table 1). As mentioned above, this H_2 will be used in the hard-to-electrify sectors industry and heavy transport. Cars running on biofuels or electric are seen as more efficient than H_2, due to conversion losses when producing hydrogen from electricity. A certification system to guarantee the green origin of H_2 is still required and urgently needed to allow for trading and import of green H_2.

2.4.5 Sweden

The Swedish Energy Agency recently prepared a draft national H_2 strategy (SEA 2021) which considers that Sweden aims to have zero net GHG emissions by 2045

[23] As mentioned, Dutch and German gas operators started to explore a future integrated gas infrastructure and the prospective role of H_2 (Gasunie & TenneT 2019; DBI-GUT et al. 2021).

(Hallonsten 2021). The draft proposes a 5 GW_{el} electrolyser capacity for 2030, and 15 GW_{el} electrolyser capacity for 2045. A non-governmental H_2 strategy was published recently as a contribution to the Swedish discussion (FFS 2021). The Swedish H_2 Strategy focuses on the industry sector, especially steel-making, as Sweden has limited gas infrastructure (grid, storage) so that H_2 supply most probably will be on decentral production close to industrial users.

In Sweden's recent recovery and resilience plan includes finance measures that contribute to reducing greenhouse gas emissions, and H_2 is included in the eligible funding (SE 2021).

2.4.6 European Union

Given the EU's ambition to become climate-neutral by 2050 (EC 2021a), its decarbonization must address not only electricity, but also natural gas use, among others. Furthermore, the EU – as other countries and regions – is home to industrial sectors that are hard-to-abate, especially the cement and chemical industry, refineries, and steel making (Wachsmut et al. 2021). Accordingly, renewable and low-carbon gases are already developed in Europe (Decorte et al. 2020; Wouters et al. 2020).

In that context the EU prepared *A hydrogen strategy for a climate-neutral Europe* (EC 2020) which is part of the overall European Green Deal announced in 2020 by the European Commission. The EU H_2 strategy identified ambitious H_2 targets for 2030 (see Table 1), and stated that

"[…] *the priority for the EU is to develop renewable hydrogen, produced using mainly wind and solar energy [since] renewable hydrogen is the most compatible option with the EU's climate neutrality and zero pollution goal in the long term and the most coherent with an integrated energy system*" (EC 2020).

In follow-up, the EC secured significant funding not only for further H_2 research and demonstration (as part of the Horizon Europe research programme) but also for implementation of the strategy, with a focus on H_2 infrastructure, through its post-pandemic recovery programme.

In parallel and related to the extensive stakeholder discussions around the EU's H_2 strategy, the European gas industry engaged in the *Gas for climate* initiative and prepared several influential studies and reports (e.g., Peters et al. 2020; Wang et al. 2021) which lay the foundation of the concept of a *European Hydrogen Backbone* (Wang et al. 2020) and its extensions (Jens et al. 2021).

There is overall agreement that to allow for deep decarbonization and for achieving the energy transition envisioned in the European Green Deal and the H_2 strategy, the existing natural gas infrastructure needs – at least in the longer-term – conversion or extension to dedicated H_2 transnational pipelines (FE & IAEW 2019; PwC 2021). EU Member States such as Denmark, France, Germany, Italy, Poland, Spain and the Netherlands are very active in respective joint activites to enable the gas grid for H_2 (see Section 3.3).

Interestingly, the EC recently re-branded its collaboration with industry on H_2 (operated as a public-private partnership): The formerly "Fuel Cell and Hydrogen Joint Undertaking" has been renamed "Clean Hydrogen Partnership", and now

"Focus is placed on producing, distributing and storing clean hydrogen and, supplying hard to decarbonise sectors such as heavy industries and heavy-duty transport applications" (EC 2021c).

This new Joint Undertaking will receive funding of €1 billion from the EU's Horizon research program and another €1 billion from industry partners.

While there is agreement within the EU on the overall importance of H_2, there are **different views** on the role and pathways of H_2 towards 2050 (Lambert & Schulte 2021):

- One area of discussion is the potential role of "blue" H_2 from natural gas (with CCS) versus "green" H_2 from renewable energy, and the relevance of potential "turquoise" H_2 from natural gas imports, especially from Russia. This is linked to the questions on how to **characterize the sustainability of H_2** – by "colors", GHG intensity, or more refined criteria (see Section 5.1).
- Controversial is prospective H_2 use in the residential **heating** sector: As in the UK (see Section 2.8), EU Member States as well as the EC are not clear if energy efficiency, biomass, district heating, and electric heat pumps are more cost-effective decarbonization options than the direct use of H_2 in boilers for low-temperature heat[24]. A brief discussion of this issue is given in Section 6.1.
- The third controversial issue is the extent to which **new** dedicated H_2 transmission pipelines ("backbones") are needed to connect larger H_2 demand clusters or regional H_2 "islands" with centralized national or international H_2 production, especially for the 2030 time horizon. Sections 3.6 and 4.3 give more detail.

Disregarding these open issues, H_2 is recognized in the EU as a key **element of longer-term decarbonization** (CAN & EEB 2020; JRC 2020; H4EU 2021).

With the recent EC proposals for a regulation on internal markets for renewable and natural gases and for hydrogen (EC 2021d) and a Directive on common rules for the internal markets in renewable and natural gases and in hydrogen (EC 2021e), the long-awaited update of the overall gas system governance and the certification of H_2 (see Section 5) is now on the table and will be negotiated between the EC, the European Parliament, and the European Council.

[24] See e.g. AVERE et al. (2021); Baldino et al. (2021); Bothe et al. (2021); Gatzen & Lenz (2021); IRENA (2021b)

2.5 Japan

Japan has more than 40 years of hydrogen history, from the mid-1970s with its Sunshine and Moonlight projects to 2010 (technological development program on new energy including H_2) and is actively supporting IEA's work on hydrogen since then (IEA 2019 + 2020). Japan was the first in the world to formulate the *Basic Hydrogen Strategy* in 2017, aiming at 0.3 Mt of H_2 supply by 2030, and adding 800,000 fuel cell vehicles to road transport (JP 2017)[25].

In 2019, Japan released its *3rd Strategic Roadmap for Hydrogen and Fuel Cells*, with updates on the targets for H_2-based electricity, mobility, and other H_2-related areas and sets goals for basic technology specifications and cost breakdowns[26].

Meanwhile, Japan's METI formulated the *Green Growth Strategy Through Achieving Carbon Neutrality in 2050*, aiming at 3 Mt H_2 by 2030, and up to 20 Mt by 2050 (METI 2020+2021)[27].

Japan's H_2 strategy implied that the country will import H_2 in the future, and respective partnerships are under development with Australia, Brunei, Norway and Saudi Arabia, considering also "blue" H_2 (Nagashima 2018 + 2020)[28].

Japan is also very active in converting H_2 into *green ammonia* for chemicals, fertilizers, and power production[29], and supports the international harmonization of technical standards for H_2 and ammonia (METI 2021).

2.6 Korea

In January 2019, Korea's government published its *Hydrogen Economy Roadmap* with targets of nearly 2 Mt H_2 supply by 2030, and to more than 5 Mt H_2 by 2040, in parallel to significant cost reductions of electrolysers (KR 2019)[30]. A focus concerns the rapid expansion of fuel cell car use, and respective infrastructure.

In addition, the Korean National Assembly enacted the *Hydrogen Economy Promotion and Safety Management Act* which came into force in 2021, making provisions for H_2 equipment safety requirements, certification processes and the roles and responsibilities of various government agencies (intralink 2021).

Besides Japan, Korea is the main Asian countries expecting to **import** significant amounts of H_2 from abroad, and is active in shaping respective trade arrangements.

[25] The strategy also includes a "post-2050" target of 5 – 10 Mt of H_2 at costs below US$ 2/kg.

[26] See https://www.meti.go.jp/english/press/2019/pdf/0312_002a.pdf

[27] It should be noted that there are contrasting views on the role of H_2 in reaching Japan's climate neutrality goal by 2050: Bogdanov et al. (2021) argue that a fully renewable pathway mostly relying on direct electrification and only little H_2 is more favorable.

[28] Japan also collaborates with Australia on low-carbon H_2 from brown coal gasification and transport of liquefied H_2 to Japan, see http://www.hystra.or.jp/en/

[29] See https://www.ammoniaenergy.org/organization/green-ammonia-consortium/

[30] It should be noted that Korea's roadmap has been criticized as not "in balance" with the renewable electricity supply targets, i.e. the electricity demand for the H_2 production target in 2040 is higher than the renewable electricity production target for 2040 (Kwon 2021).

2.7 Russia

For many years, H_2 has not been an issue for the Russian government (Mitrova et al. 2019), but in 2020, it joined the international discussion with its *energy strategy* declaring a *H_2 export target* of 2 Mt by 2030 (Zabanova & Westphal 2021), and a respective roadmap (RU 2020).

Following-up on that in August 2021, the Russian government adopted a *Concept for the development of hydrogen energy* (RU 2021) which identifies "blue" H_2 from natural gas (and coal gasification) with CCS as major options for Russia[31].

Exports will mainly focus on Europe (especially Germany), and Asia, and respective industrial clusters for exports are to be developed.

In contrast to most other countries, the Russian H_2 strategy aims not at decarbonization but to maintain the economic value of its gas infrastructure, and revenue from energy exports (Gayda & Mitrova 2021).

Gazprom suggested repurposing the Nord Stream II pipeline for H_2 as a step to better "align" Russia with EU – and German – security of supply expectations, but this would require that Russia adopts more ambitious decarbonization policies at home (Zabanova & Westphal 2021).

2.8 United Kingdom

The UK's national policy on H_2 was first outlined by the Committee on Climate Change which underlined the country's need for H_2 in a low-carbon economy, and recommended that the UK should be "*[…]using hydrogen where the alternative is continuing to burn unabated fossil fuels or where there are limits to feasible electrification*" (CCC 2018).

The UK government developed its H_2 strategy not only with regard to its carbon neutrality goal for 2050: "*Our ambition for hydrogen goes beyond decarbonisation. It also means a focus on supporting industry to develop sustainable, home-grown supply chains, create high quality jobs, and capitalise on British innovation and expertise"* (UK 2021a).

The UK strategy sets a target of 5 GW of low-carbon H_2 by 2030, aims to decarbonize existing H_2 supply through CCUS and/or "green" H_2 and adopts a whole-systems approach for all sectors. The UK strategy includes also to develop indicators and metrics to monitor progress against the targets.

Further, the UK H_2 strategy points to regional H_2 activities in e.g., Scotland and Wales, and states that a decision on the role of H_2 in heat sector will have to be

[31] The Russian natural gas exporter Gazprom is also actively developing "turquoise" H_2 from natural gas pyrolysis which could offer low-carbon H_2 without CCS, and the major Russian nuclear industry player Rosatom aims at nuclear-based H_2 production (Zabanova & Westphal 2021).

taken in the mid-2020s based on the outcome of “heat village” trials. The strategy also commits to finalize design of a UK standard for low-carbon H_2 by early 2022.

The UK H_2 strategy highlights the need for **strategic decisions on blending H_2 into the gas grid** (see Section 3.3) and that other countries are considering the need for dedicated H_2 networks (alongside conversion of existing gas infrastructure) which may enable the UK to trade H_2 through existing or new gas interconnectors with Belgium, the Netherlands, and Ireland.

Recently, the UK government published the *North Sea Transition Deal* which inclu-des up to £10 billion for H_2 production as joint government and oil and gas sector investments (UK 2021b).

2.9 USA

In 2004, the governor of California promised a *hydrogen highway*, and President George W. Bush fueled a mini-van with H_2 in Washington, DC in 2005. Since then, little happened in the US in terms of H_2 – the H_2 gas station in Washington, DC is closed, but many US cities are developing low-carbon transport systems, including H_2-fueled vehicles.

The rise of the electric car in US markets (and beyond) so far outpaced H_2 as a means of to decaronize light duty vehicles, but renewable gas in California is quite successful in heavy duty transport (IEA Bio 2021b).

The return of the US to the Paris Agreement early 2021 could be a game changer:

Already in 2020, the US Department of Energy prepared its hydrogen strategy under the sub-title *Enabling A Low-Carbon Economy* (US DOE 2020). The strategy does not give goals or targets in terms of H_2 production volumes over time but outlines a R&D strategy which builds on earlier achievements, and considers inter-national collaboration and cooperation.

Recently, the US government launched the ambitious *Hydrogen Earthshot* program which aims at green H_2 production with cost of $1/kg by 2030 (US DOE 2021). The US joined the *Clean Hydrogen Mission* (MI 2021), and it can be expected that the current US administration will include low-carbon H_2 in its future commitments under the Paris Agreement.

From the US industry side, a *Road Map to a US Hydrogen Economy* was prepared (FCHEA 2020) which suggests H_2 production targets for 2030 and 2050, and the State of California has an impressive list of legislation to foster H_2-driven fuel cell vehicles (buses, cars, trucks)[32], and California’s Low-Carbon Fuel Standards is a regulation that also includes H_2.

[32] See https://afdc.energy.gov/fuels/laws/HY?state=CA

2.10 Summary of country H_2 strategies and roadmaps

With the noteworthy exception of Russia, **all** country strategies and roadmaps analyzed in the previous sub-sections indicate the **need for H_2 to decarbonize** their economies and point out the significant contribution of H_2 to achieve country commitments under the Paris Agreement.

In that context, most country strategies and roadmaps see H_2 as a means to overcome the limits of electrification and to **help stabilizing** their electricity grids against a growing share of variable renewable generation, especially solar and wind. Some H_2 strategies also address the potential role of longer-term energy **storage** needs to bridge seasonal variations in renewable electricity generation.

Several countries indicate their **ambition to export** H_2 in the 2030 timeframe and after, while others assume **H_2 imports** (see Table 2 for IEA countries).

Besides trade, the majority of country strategies focus on domestic H_2 application in hard-to-abate sectors where GHG emission reduction through renewable electrification and/or CCUS is hindered, e.g., the chemical industry, steel-making, and transport (aviation, long-haul road, shipping).

Table 3 summarizes for which sectors country strategies agree on the future role of “green” H_2, and for which there are controversies.

Table 3 Agreement on sectors in which H_2 is needed for decarbonization

Sector	Uncontroversial	Controversial
Industry	- Reaction agents (steel) - Feedstock (ammonia, chemicals)	High temperature heat
Transport	- Long haul aviation (H_2-based synthetic fuels) - Maritime shipping (ammonia, H_2-based synthetic fuels)	- Road - Short haul aviation and shipping
Power	- Long term storage for variable renewable energy back up - (Some) system flexibility	Size of need, given other flexibility and storage options
Buildings	District heat (residual heat load)	Heat for individual buildings/apartments

Source: *own compilation based on Deutsch (2021); note that most country strategies assume that H_2 in district heating is mainly used for cogeneration, i.e., contributes to power generation.*

In **nearly all** country strategies or roadmaps, the role of existing gas infrastructure for future H_2 transmission and distribution is addressed, and H_2 clusters are seen as an important step towards H_2 use, both in industry, and in regional H_2 networks.

Several country strategies address the “**color**” of H_2, i.e., its origin, and some focus on “green” H_2 while others include a broader range, especially “blue” H_2.

In general, H_2 country strategies do not only concern H_2 as such but include derived products such as ammonia or synthetic methane (SM), and some recognize other renewable gases such as biogas, and biomethane.

The synopsis of quantitative H_2 production targets (Table 1) indicates that for the year 2030 time horizon, several country strategies and roadmaps are quite ambitious.

For the year 2050, five out of the 22 countries included in the analysis provide targets, with one of them only addressing exports.

Finally it should be noted that in **all** country strategies and roadmaps, targets and levels of ambition regarding ex- and imports are **subject to significant advances in cost-reduction** for low-carbon and “green” H_2:

Target levels for 2030 are in the \$2 – \$5/kg H_2 range, with prospects for a \$1 – \$2/kg H_2 range by 2050. The strategies and roadmaps also commonly assume that market introduction and support schemes for H_2 as well as increased R&D are needed over the next decade to deliver on the expected H_2 cost reduction.

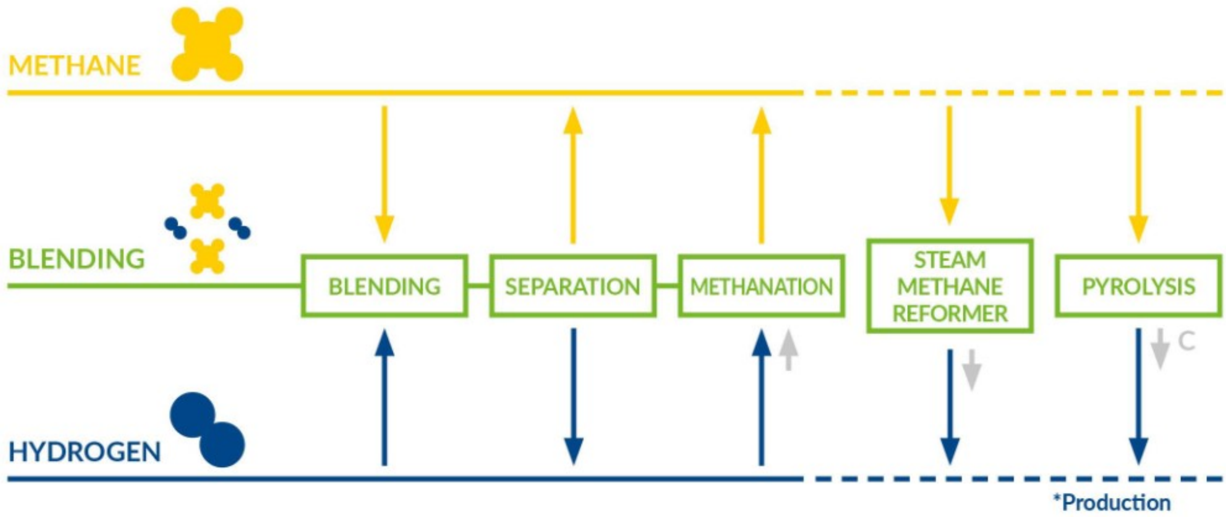
3. Renewable gases in gas grids: Options and obstacles

As depicted in Figure 4, the IEA projects a rising contribution of renewable gases in gas grids, both for biomethane and synthetic methane, and H_2.

Today, the majority of H_2 is produced and consumed directly in industrial clusters, e.g., chemical industry, and refineries. In few other cases, H_2 is transported in dedicated H_2 pipelines to large consumers, but the overall dedicated H_2 pipeline infrastructure is rather small.

The following section discusses existing and emerging (innovative) technologies for adding low-carbon H_2 to existing gas grids, with a focus on blending, separation, and methanation, and biomethane (not shown in Figure 8).

Figure 8 Schematic interaction between methane (CH_4) and H_2 in gas grids



Source: Gómez (2020); note that biomethane is not included in the scheme

The production of H_2 from methane (dashed lines on the right side of Figure 8) is, together with H_2 from electrolysers, briefly covered in Section 3.6.

3.1 Upgrading biogas to biomethane and injection into natural gas grids

Biogas, a mixture mainly of CH_4 and CO_2, is a well-known renewable gas from anaerobic digestion with significant potential (IEA 2020b)[33]. Given the decentral nature of biogas plant often located in rural areas, most biogas is currently used for power (co-)generation in internal combustion engines (IEA Bio 2021a). This implies that a significant share of the biogas energy content is lost due to missing local heat demand, and low electric efficiency[34].

[33] Note that biomethane can also be produced from gasification of lignocellulose and methanation of the syngas, see IEA Bio (2018).

[34] There are highly efficient electricity generation options from biogas, though: Modern medium-to-large-scale turbocharged gas motors, tri-generation systems (electricity plus combined heating & cooling), and solid oxide fuel cells - the latter can be combined with steam turbines to increase electric efficiency beyond 60 % (based on LHV).

To improve biogas use, the upgrading to biomethane through removing CO_2 gives a product similar to natural gas (> 95% CH_4 content) that can be directly injected into existing gas infrastructure and used by natural gas end-use appliances without the need for any change (IEA Bio 2018). Biogas and biomethane are key options for energy system flexibility (Schildhauer et al. 2021).

3.2 H_2 as a booster for biomethane

A possibility to increase renewable methane yield is to **co-process** biogas and H_2 in hybrid plants which integrate an electrolyser for H_2 production, and biological methanation (Section 3.5). The resulting renewable methane is a composite of biomethane and H_2 and can be directly injected into the existing gas grids, avoiding the cost for separate biogas upgrading.

This option can be seen as a **near-term route** to integrate decentral H_2 production into existing local gas grids without compatibility problems for distribution infrastructure or end-use appliances.

As the resulting renewable methane can also be stored locally, it may help to balance intermitting renewable electricity generation (IEA Bio 2018).

3.3 H_2 injection into natural gas grids

As IEA (2019) pointed out, *existing* natural gas grids could be used to transport H_2 at much lower costs than those of new dedicated H_2 pipelines. Yet, H_2 injection into the gas grid (HIGG) may cause compatibility issues with pipelines, end-use appliances, and metering systems.

Already in 2006, the European gas industry prepared recommendations for the injection of gases from “non-conventional” sources into gas networks (Marcogaz 2006), which was followed by analysis of the effects of H_2 injecting (Marcogaz 2018) and a discussion of test results and regulatory limits for H_2 admission into existing natural gas infrastructure (Marcogaz 2020)[35].

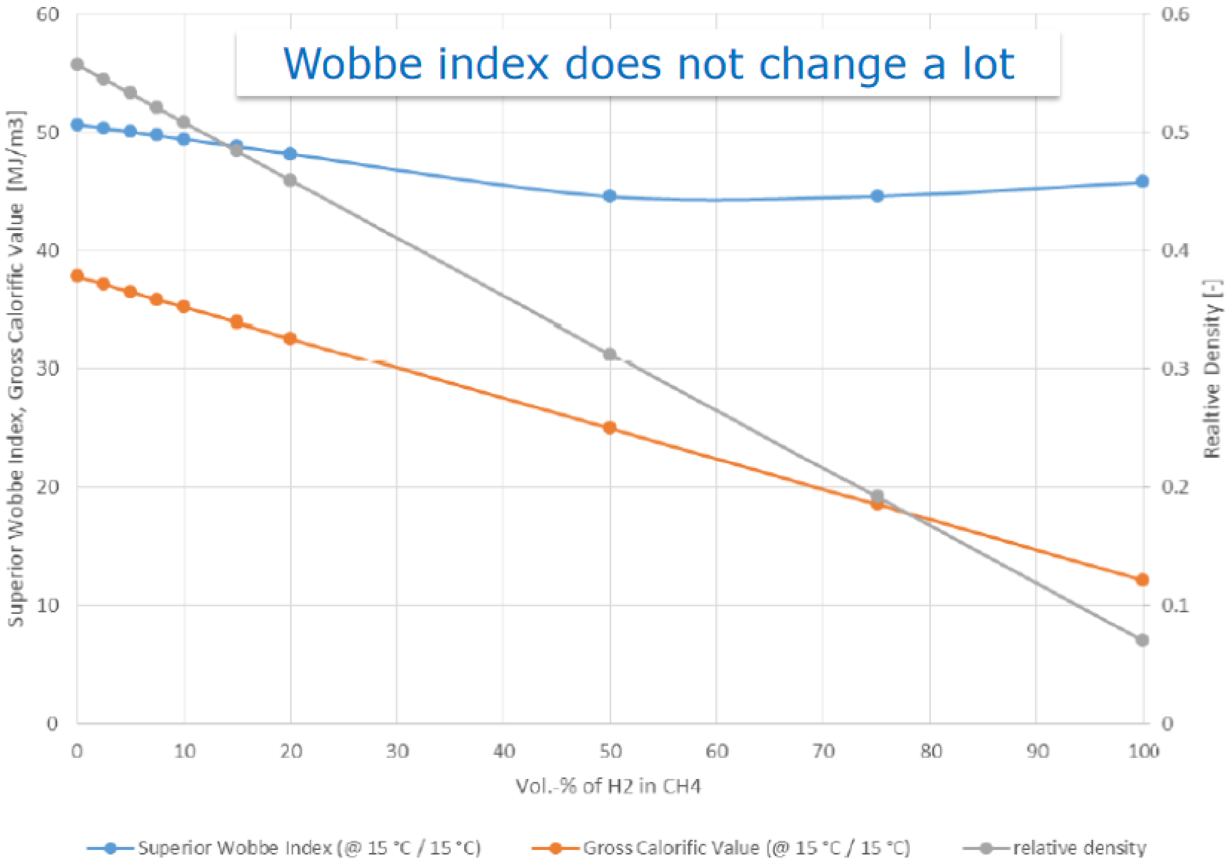
From 2004 onwards, the *NaturalHy* EU project analyzed effects of H_2 injection into the gas grid (de Vries, Florisson & Tiekstra 2007; NaturalHy 2009). A comprehensive review of the status of HIGG and its perspectives is given by Quarton & Samsatli (2018).

A key parameter for H_2 compatibility with natural gas infrastructure is the so-called Wobbe Index (WI) which measures the interchangebility of gases, expressed in MJ/Nm^3. As H_2 has an approx. 10% lower WI than natural gas, adding H_2 to the gas grid will result in a lower WI.

[35] In the US, only few studies looked into the issue, but are rather comprehensive (see Nexant 2008; NREL 2013).

If the H_2 injection remains below 20 vol%, only very small effects on the WI will occur[36], as indicated in Figure 9.

Figure 9 Effect of the H_2/CH_4 mixing ratio on the Wobbe Index



Source: Linke (2020)

3.3.1 Gas Transmission

As Majumdar et al. (2021) indicate, the comparatively low volumetric energy density of H_2 (approx. 30 % of natural gas) requires to either increase the H_2 flow velocity or its pressure by a factor of about 3 to match the energy delivery rate of natural gas. This will increase the cost of compressors beyond those used in natural gas pipelines[37], but industry recently presented options to overcome this barrier and assured that existing steel pipelines for high-pressure H_2 transport are able to handle H_2 up to 20 vol% with practically no risk of embrittlement (Adam et al. 2021; COWI et al. 2020).

A US review of H_2 impacts on pipelines showed that small partial pressure of H_2 can have substantial effects on fracture and fatigue of steels, while O_2 present in the natural gas can mitigate effects of H_2 in ferritic steels (Ronevich & San Marchi 2019).

[36] It should be noted that H_2 addition to natural gas also affects other gas quality parameters (e.g., flammability, methane number, relative density). Furthermore, gas metering and respective billing systems need adjustment for the H_2 content.

[37] See Section 3.6 for a discussion of cost impacts.

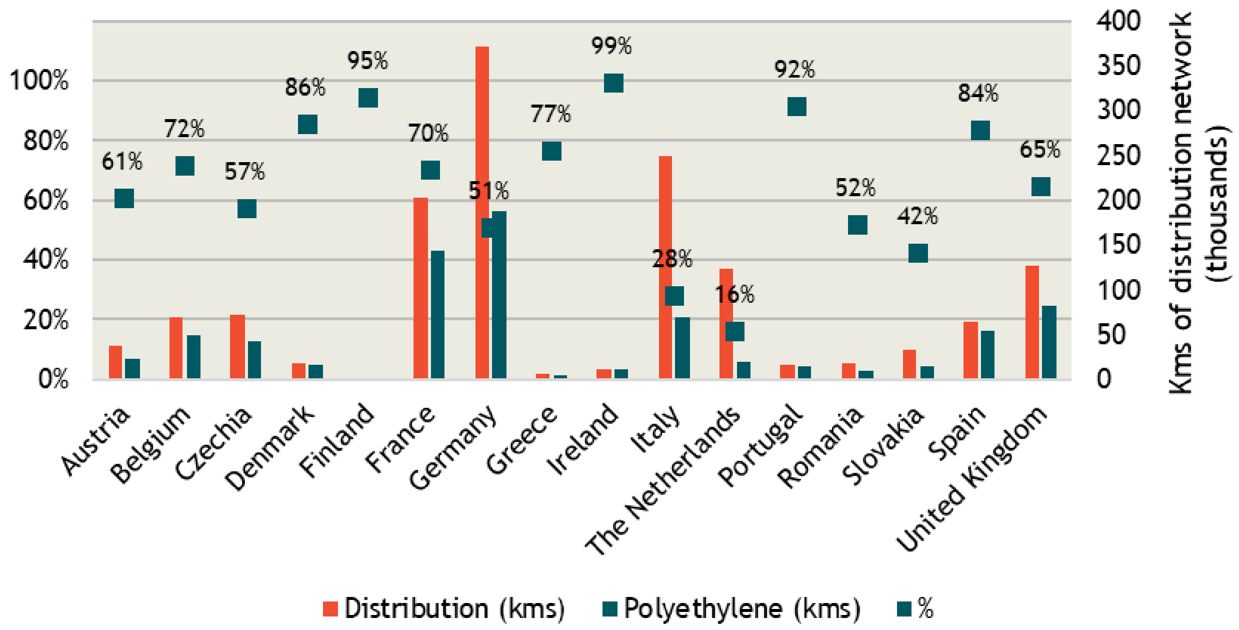
For Russia, an addition of up to 20 vol% H_2 in existing gas infrastructure systems is seen as a conservative assessment, and the Nord Stream I and II pipelines have been tested for 70 vol% H_2 (Gazprom 2018).

The stationary gas engines and gas turbines used for compressing natural gas in transmission systems need adjustment and/or modification to the H_2 addition, but this is not seen by industry as a major issue (Adam et al. 2021; Zabrzeski et al. 2019).

3.3.2 Gas distribution

Nowadays, polyethylene, which is not susceptible to H_2 embrittlement, is being used more commonly in distribution networks. Most EU countries can use existing gas infrastructure as basis for H_2 **distribution**, as indicated in the following figure.

Figure 10 Share of polyethylene pipelines in European distribution systems



Source: Gérard et al. (2020)

HIGG projects exist in many countries and provide a growing evidence base:

- **Australia** carried out research on impacts of H_2 additions to gas distribution networks (GPA 2019a) and on respective impacts on downstream installations and appliances (GPA 2019b). Australia currently explores the feasibility of blending 10 vol% H_2 into natural gas networks for selected regional towns in South Australia and Victoria and is undertaking a project on blending 5 vol% of "green" H_2 into a natural gas network which will be operational by mid-2020.

- In **France,** a consortium of gas system operators provided an overview of French HIGG projects[38] and respective research, concluding that the system would tolerate up to 10 vol% H_2 without modification, and that for up to 20 vol% of H_2, only minor adjustments would be needed (GRTgaz et al. 2019).
- In **Germany**, various projects demonstrated that the national gas grid is H_2-compatible up to 10 vol% without modification, and a practical test confirmed that the system could be operated with minor adjustments up to a blending concentration of 20 vol% (DVGW 2020). The Federation of the German Heating Industry confirmed that the appliances available on the heating market can be operated safely and efficiently with a H_2 share of 10 vol% without major technical modifications and assumes that 20 vol% can be achieved within a few years (DVGW 2020). For H_2 admixtures > 20 vol% or pure H_2 supply via the upgraded gas distribution network, end consumers' gas appliances will either need to be converted or replaced by new appliances. Recent research indicated that at least some parts of the German gas distribution system are "H_2-ready" (Ready4H2 2021).
- In the **Netherlands**, a smaller-scale pilot project on 20 vol% H_2 injection in the natural gas grid of the Ameland island showed after several years no effects on the distribution system, on functionality and safety of appliances, and no visible damage of components in appliances (Kippers et al. 2011; Harcus 2017).
- In **Switzerland**, recent work identified H_2 injection into gas transport pipelines and distribution grids as possible for up to 20 vol%, and considers to increase the injection share to 30 vol% (Bordenet & Hafner 2021; VSG 2021)
- The **United Kingdom** has extensive work on HIGG: The H21 Leeds CityGate project researched converting an existing natural gas network to 100% H_2, and the HyDeploy[39] programme investigates supply of H_2 blends to an existing gas network, demonstrating that a blend of hydrogen up to 20 vol% can be safely distributed and utilized (Isaac & Lewis 2021). It further concluded that UK appliances are capable of safely operating with a 20 vol% H_2 blend and with good performance and without the need for adjustment, which was confirmed earlier by Hodges et al. (2015). In consequence, the UK H_2 strategy pointed out that the government will engage with industry and regulators to develop the safety case, technical and cost effectiveness assessments of blending up to 20

[38] See GRTgaz et al. (2019) which provides an overview of French projects in the Annex.

[39] See https://hydeploy.co.uk/

vol% into the existing gas network and to provide a final policy decision on H_2 blending levels in late 2023 (UK 2021).

Adding H_2 to natural gas will decrease the *Wobbe index* (see Figure 9), and the thermal power of gas utilization equipment. Thus, the Wobbe index of mixtures of H_2 and natural gas must remain above that of the lower Wobbe limit of the range for natural gas[40]. From this it can be concluded:

- The maximum H_2 concentration for the domestic market in a country is determined by the safe operation of properly adjusted conventional domestic appliances as well as by the local conditions of natural gas quality (range and current value of Wobbe Index);
- for properly adjusted appliances and favorable conditions of natural gas quality, conventional domestic appliances can accommodate up to 20 vol% H_2.

In summary, HIGG could provide a steppingstone for developing a H_2 infrastructure with adding up to 20 vol% of H_2 to the gas grid, i.e. about 7 % by energy content. An ongoing EU project will provide empirical data on the impacts of higher levels of H_2 on the gas infrastructure, its components and its management[41].

3.4 H_2 separation from natural gas grids

Given the concerns about compatibility of higher (> 20 vol%) H_2 shares in the gas grid with end use equipment (appliances, metering etc.), concepts to use the high-pressure gas pipeline system **for H_2 transport only** (e.g., for ex- or imports) and to **separate H_2** from transported natural gas **before** it is distributed to end-users.

There are several technologies to extract H_2 from gas mixtures, including pressure swing adsorption (PSA), and H_2-selective membranes (Lu et al. 2021). PSA and membrane hybrid systems could operate at an electricity demand of 0.8 - 1.5 kWh/m^3 H_2 (Liemberger et al. 2017), i.e. 8 – 15 kWh/kg H_2.

The EU-sponsored HyGrid project researched innovative technologies for H_2 separation from natural gas grids through a combination of membranes, electrochemical separation, and temperature swing adsorption[42]. As Nordio et al. (2021) reported, the various technology configurations resulted in high-purity H_2 (> 99.9 %) with electricity demands of 4 - 6 kWh/kg H_2, and in some cases thermal demands of about 11 kWh/kg H_2. A typical electrical demand of 8 kWh/kg H_2 was determined, compared to approx. 20 kWh/kg H_2 for small-scale PSA systems (Nordio 2020).

There are various industry activities to further develop and demonstrate H_2 separation with membranes (e.g., DVGW 2021; DBI-GUT 2021; Evonik 2020; IKTS 2021)

40 Note that as of now, there is no harmonization of the lower WI limit between EU countries (see Section 5).

41 See https://www.higgsproject.eu

42 See https://www.Hygrid.eu for details.

so that by 2030, commercial applications can be expected. The additional H_2 separation costs are in the range of \$5 - \$7 per kg of H_2 (Weeks 2014) which could be reduced to \$2 - \$4 per kg of H_2 in the longer-term (Nordio et al. 2021).

3.5 From H_2 to SM: The next step towards renewables gases?

A potential alternative to HIGG (and later separation) can be seen in the production of **renewable synthetic methane** (SM)[43]. The methanation of H_2 to CH_4 makes it 100% compatible with existing natural gas infrastructure and end uses, similar to biomethane. This advantage[44] comes at a cost, though:

- SM requires to convert H_2 and CO_2 into CH_4, and to ensure carbon neutrality, the CO_2 source must be either biogenic, or from the atmosphere[45].
- Converting H_2 and CO_2 to SM currently implies a loss of about 20% of the H_2 heating value, which – in addition to investments – raises SM cost accordingly.

There are two major methanation technologies (Thema, Bauer & Sterner 2019; Rasmusson et al. 2020):

Biological methanation uses microorganisms for the conversion of H_2 and CO_2 at low temperatures (30 - 70° C) and low pressures. It has a TRL of 7 (pilot and demonstration scale), and a larger industrial-scale plant (TRL 9) is under contruction[46]. The system efficiency reaches up to 80%. It requires a high numbers of reactors (or fewer reactor with large volumes), but is dynamic, i.e., allows fast start-up and shut-down[47].

Catalytic methanation is a thermochemical conversion with catalysts at high temperature (200 - 700 °C) and pressure (up to 100 bar). It is near-commercial (TRL 8) with a system efficiency of 80%. With heat recovery, efficiencies > 90% are possible. Yet, as catalytic methanation is not very flexible, it requires rather stable operation.

The STORE&GO project estimated methanation investment cost for smaller scale (< 1 MW) as 250 €/kW CH_4 for 2030 and 100-200 €/kW CH_4 by 2050 (van Leeuwen & Zauner 2018; Zauner et al. 2019) which is in the range of 100 – 180 €/kW CH_4 given by Kober et al. (2019)[48].

43 SM is also known as synthetic natural gas, or renewable natural gas. The acronym varies accordingly (SNG, RNG, P2G, etc.). It should be noted that as of now, the term is rather poorly defined (IEA H2 2020).

44 Methanation offers further benefits, e.g., O_2 from electrolysis for wastewater treatment.

45 Direct Air Capture (DAC) is under development, with a first pilot plant being operated since August 2021 in Iceland, and small-scale demo plants in Switzerland since 2019. For more details see e.g., Bajamundi et al. (2019); Deutz & Bardow (2021), and Hanna et al. (2021).

46 See https://www.powertogas.ch/

47 Biological methanation can be *in-situ*, i.e., H_2 is injected directly into the biogas plant and combines with the CO2 of the biogas, or *ex-situ* in which both H_2 and CO_2 are converted in an external reactor (IEA Bio 2018).

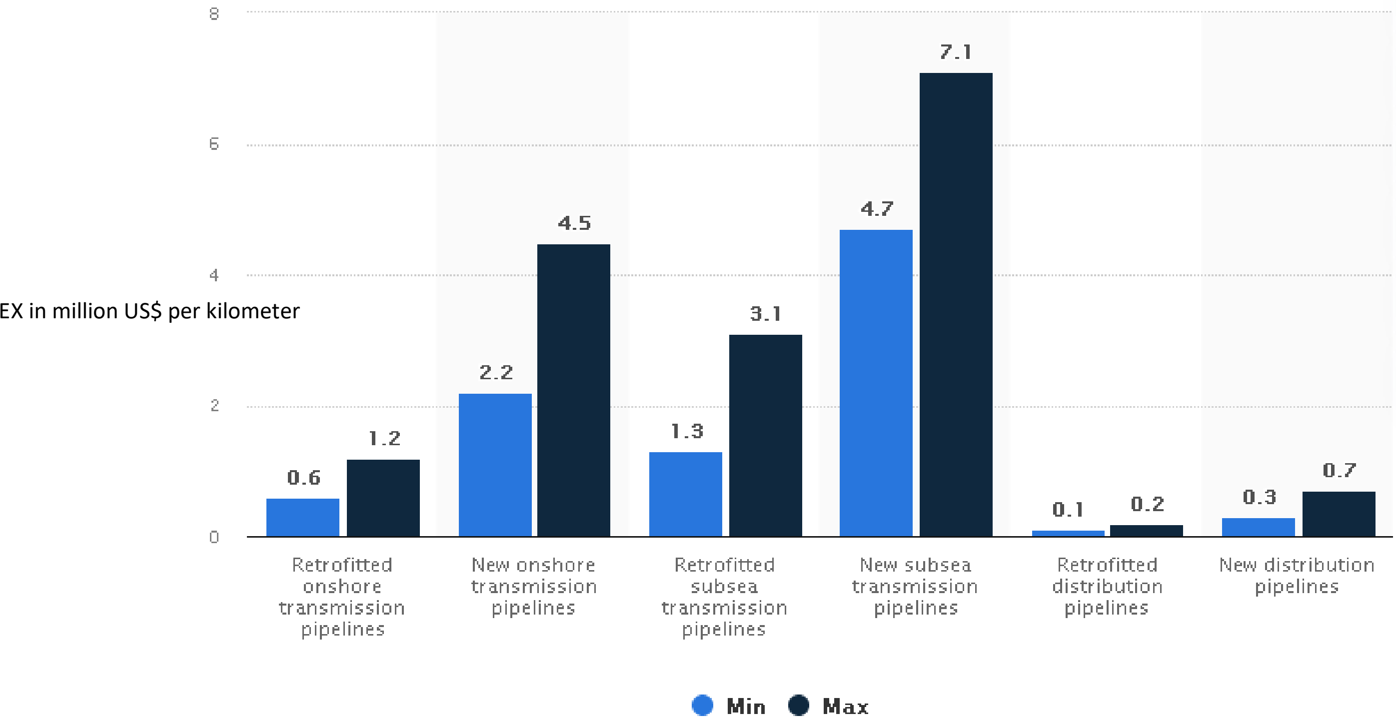
48 Balducci et al. (2020) estimated investment cost in the range of 330 – 780 \$/kW H_2 for biological and of 450 – 560 \$/kW H_2 for catalytic methanation, given current technology. The lower STORE&GO data of approx. 150 – 300 \$/kW H_2 for 2050 assume technological learning.

The conversion of H_2 to synthetic CH_4 adds approx. € 36 – € 39 per MWh of CH_4 to the H_2 costs, i.e., $1.8 - $2/kg of H_2 (FE & IAEW 2019, Dias et al. 2020). Thus, methanation is about 50% of the longer-term additional cost of H_2 separation (Section 3.4).

3.6 Dedicated H_2 grids

There are several means to transport H_2, and pipelines have been found to be most cost-effective over long distances (JRC 2021)[49]. The cost for new dedicated H_2 pipelines is 110 - 150% of the costs for natural gas systems (IRENA 2021b; Wang et al. 2020), but pipelines can be repurposed to transport H_2 at lower cost (Figure 11).

Figure 11 Estimated capital costs of new and retrofitted pipelines for H_2



Source: *https://www.statista.com/statistics/1220856/capex-new-retrofitted-h2-pipelines-by-type/*

The capital cost (CAPEX) range for onshore transmission networks (incl. compression) given in Figure 11 is the same as in the literature (e.g., Cerniauskas et al. 2020; ENTSOG, GIE & HE 2021; HC 2021).

For the conversion of existing gas pipeline to H_2, Reinertsen (2021) reported cost of € 0.05/kg H_2, and of € 0.1/kg H_2 for new dedicated H_2 pipelines. ACER (2021) found that the cost of repurposing natural gas pipelines is 15 – 33 % less than those of dedicated H_2 pipelines with similar diameter, with optimistic views of only 10 % by the German Association of Gas Transmission Operators.

[49] A very early study found that H_2 pipelines would cost about 40% more than those for natural gas (Beghi et al. 1974), but the more recent studies (see text) found that these results are rather outdated.

As a share of about 75 % of future H_2 pipelines in Europe could come from repurposing existing natural gas pipelines (ACER 2021; Jens et al. 2021), and it is argued that a “no-regret” European H_2 backbone strategy would **not need any** new H_2 pipeline at all (Andreola et al. 2021), the range of future investment for new dedicted H_2 pipelines until 2030 seems rather narrow.

3.7 Summary on renewable gases in gas grids

Biomethane is the most versatile renewable gas for grid injection as it requires **no modification** of gas infrastructure, i.e., it could replace natural gas up to 100 vol%. Given the limits of sustainable global biomethane potential, it may contribute up to 20% (energy share) of the 2050 (reduced) gas demand, as indicated in Figure 4.

To increase near-term renewable methane production, H_2 could be a booster by **co-processing** biogas and H_2 in hybrid plants (electrolyser plus methanation).

Next to that, H_2 injection in gas grids (HIGG) could provide a steppingstone for developing a H_2 infrastructure with adding up to 20 vol% of H_2 to the gas grid, i.e., about 7 % by energy content.

To achieve higher shares of H_2 without compromising downstream gas distribution and end-uses, the pipeline system could be used **to transport H_2** which then could be **separated** from transported natural gas **before** it is distributed to end-users. H_2 separation would add \$2 - \$4 per kg of H_2 in the longer-term.

A potential alternative to HIGG (and later separation) is to convert H_2 into **synthetic methane** (SM) which makes it 100% compatible with the existing natural gas infrastructure and end-uses. H_2 methanation costs about 50% less than the longer-term additional cost of H_2 separation and could help balancing the electricity system and longer-term storing of renewable electricity.

Converting existing natural gas **transmission** pipelines to H_2 (“repurposing”) is possible in many cases and can make use of inhibitors to reduce H_2 embrittlement, and corrosion. Cost of doing so would add approx. 0.05 \$/kg H_2, while cost for new dedicated H_2 pipelines are twice as high. Costs to convert the gas **distribution** to be fully H_2-compatible are about 20 % of repurposing transmission pipelines, and approx. 1/3 of new dedicated H_2 pipelines, but strongly depend on the geographical distribution of end-users.

In summary, biomethane and renewable synthetic methane (RM) can **already** be carried by the existing gas network infrastructure without any problems. The injection of larger quantities of H_2 and the transition to 100 vol% H_2 will require step-by-step technical modification or further development of the gas distribution networks and the customer facilities connected to them.

As BMWI (2021b) states, work must start now to ensure that a properly functioning system with full area coverage is available by 2050 at the latest.

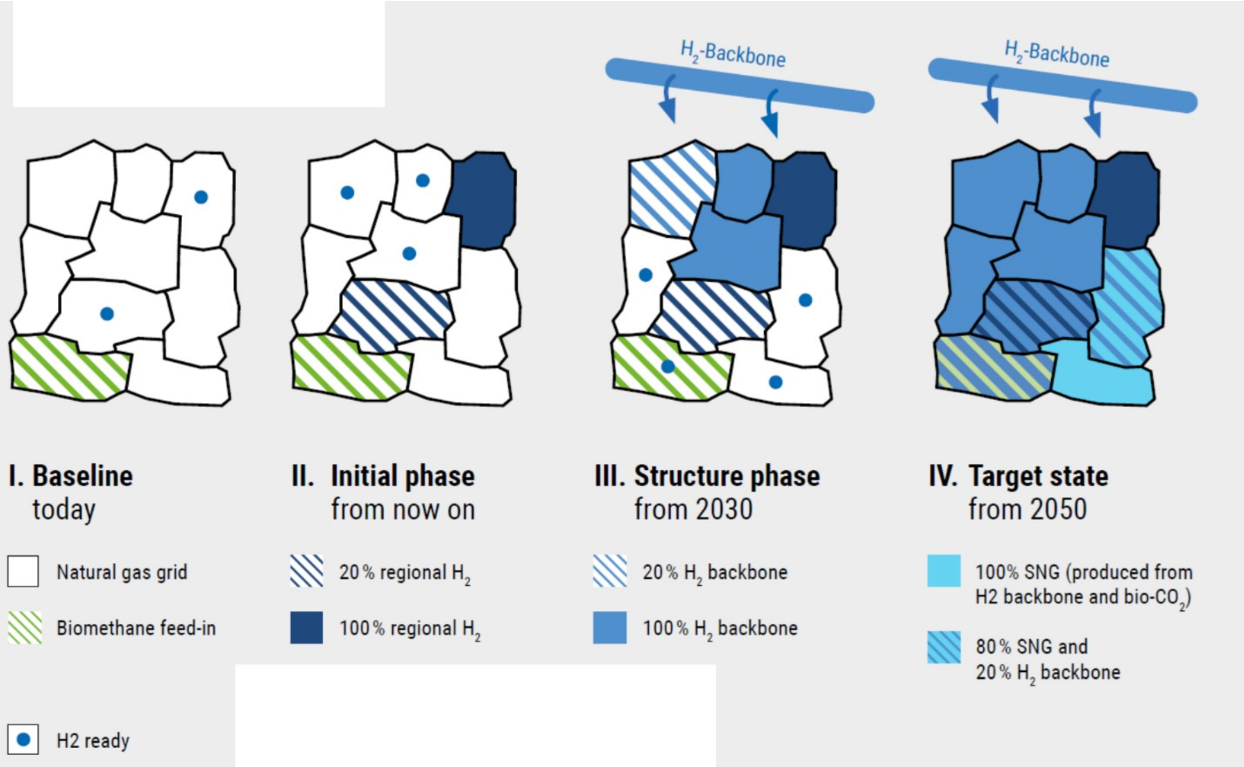
4. The transition logic: from natural to renewable gases

As indicated in the previous section, there are several options to make renewable gases compatible with natural gas grids, or to convert the gas system towards H_2 compatibility.

Since several years, discussions and studies especially in Europe developed a “vision” on how biomethane, synthetic methane, and H_2 together could transform the gas system, and integrate it with the (decarbonized) electricity system[50].

This vision includes a **transition logic** which links the various technology options to a dynamic view, and considers the possible evolution of demand and supply, as shown in Figure 12.

Figure 12 Gradual transition of the grid from natural gas to 100% H_2



Source: ERIG (2021); SNG = synthetic natural gas, i.e., synthetic methane (SM)

4.1 The 2030 perspective: HIGG, islands, and some SM

In the 1st phase of the transition, **all** gas users will benefit from biomethane injection and HIGG which, depending on the country’s infrastructure, could replace up to 20 vol% of natural gas in the existing grid, representing about 7% of the gas energy content.

[50] See e.g. ERIG (2021); ETC (2021); GasNaturally (2019); Peters et al. (2020); PwC (2021); UN-ECE (2020); Wang et al. (2020+2021)

In parallel, decentral H_2 production will feed into individual grid areas where the gas infrastructure and end-use appliances can tolerate 100% H_2 supply (so-called H_2 "islands").

Some of the larger H_2 islands, together with larger-scale direct H_2 users in industry (see subsection on "hubs" below), could be fed by 100% H_2 from segments of the high-pressure gas transmission grid either repurposed or retrofitted to transport 100% H_2 ("backbone") from centralized production plants, or from international trade.

With that, a H_2 share of about 10 – 15 % (energy-based) in gas consumption could be achieved in the near-term. When factoring-in supply of biomethane (Sections 3.1 and 3.2) and SM (Section 3.5), the overall share of renewable gases could increase further.

4.2 H_2 hubs: An interim step

Hubs are regions where various H_2 users across industrial, transport and energy markets are **co-located**, i.e., hubs aggregate the individual users into one H_2 cluster.

The concept was presented by IEA (2019) and followed-up in several H_2 country strategies and roadmaps which identified hubs (or clusters) as a viable interim option to stage 100 % H_2 supply and use in a **limited area**, thus reducing risks for the overall gas infrastructure.

If quantities of H_2 available in a country (e.g., by imports) exceed the limits of gas distribution for HIGG, additional demand from H_2 clusters could be met by a higher volumetric share of H_2 in **selected** transmission pipelines and taking the additional H_2 out before the gas mix is distributed further (H_2 separation, see Section 3.4).

The separated H_2 would be delivered to the hubs through short-distance dedicated (or repurposed) H_2 pipelines. This allows to transport more H_2 through the transmission system than the overall distribution system or end-uses can tolerate, facilitating the co-existence of traditional natural gas uses, and 100% H_2 uses.

4.3 The 2050 perspective: H_2 backbones

In the longer-term, most country strategies and various studies envision an *integrated gas system* able to handle 100% H_2 on **all** levels, and in **all** areas served.

This would require replacing or refurbishing all gas distribution systems, end-uses appliances, and metering equipment as well as gas storage facilities to operate at 100 % H_2, and the gas transmission system would consist of several backbones to supply large H_2 quantities downstream.

Depending on the future needs for medium- and longer-term electricity storage and the evolution of electric storage technologies, SM could also play a role to balance seasonal demand and supply variation using existing gas storage systems.

5. Regulatory issues for H_2 in the grid

The implementation of H_2 in the grid over the coming decades will be shaped by successes in lowering the cost of H_2 production, as expected in all H_2 country strategies and roadmaps, and by national and international **policies** (COWI et al. 2019).

The formulation of supportive policies has started already, as the country strategies and roadmaps indicate, and can draw from the experience with regulating the natural gas markets, e.g., regarding grid access and competition.

Yet, H_2 in the grid is a rather new issue, the transformation of the gas system and "coupling" with other energy sectors is quite complex, and the international dimension of trade, especially when including climate policies, is challenging.

The regulatory discussion on H_2 does not start from zero[51], but a review by the IEA Hydrogen TCP found that

"only a few countries are implementing legal frameworks for hydrogen applications" (IEA H2 2020)[52],

and the IEA wrote in its H_2 report for the G7:

"Blending would be considerably easier to implement if steps were taken to clarify existing national regulations on hydrogen in natural gas and to harmonise regulations across borders" IEA (2019).

More recently, IEA stated in its Global Hydrogen Review:

"Governments are starting to announce a wide variety of policy instruments, including carbon prices, auctions, quotas, mandates and requirements in public procurement. Most of these measures have not yet entered into force. Their quick and widespread enactment could unlock more projects to scale up hydrogen demand" (IEA 2021b).

Key policy recommendations on the international level are also given in IRENA (2021a). The following focusses on the European context[53].

In the EU[54], it is doubted that the current regulatory frameworks can deliver decarbonized gas by 2050 (Barnes & Yafimava 2020) – this view is supported by a recent survey on network adaptation needs for renewable gases (ACER 2020).

Sector integration, in particular of the power and gas sectors, is needed, and the EU strategy on *energy system integration*[55] indicated first steps in that regard.

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[51] See e.g., Barnes & Yafimava (2020); IEA (2019); IEA H2 (2020) and IRENA (2021a+b). For the EU, the HyLAW project compiled national and international H_2 legislation from 2017-2018 which is available in an online database, see https://www.hylaw.eu. The IEA maintains an online database on national policies, including regulation and policies on H_2 (https://www.iea.org/policies?qs=hydr&technology=Hydrogen).

[52] The IEA Hydrogen report analyzed the legal situation in 12 countries: Argentina, Austria, Belgium, France, Germany, Italy, Japan, New Zealand, Norway, Spain, The Netherlands, and the United Kingdom.

[53] For a broader review of H_2 policies and country activities as well as respective policy recommendations, see IEA (2021b).

[54] Th following text focuses on Europe – for a brief discussion of regulatory issues for H_2 transmission and distribution in the US see US-CRS (2021), and the country H_2 strategies presented in Sections 2.

[55] See EC (2020) EU strategy on energy system integration COM(2020) 299 final. European Commission. Brussels https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:299:FIN

The EU HyLAW project found a variety of fundamental legal and administrative barriers which **hinder** the H_2 injection into the gas grid, especially legal complexity or absence of permitting rules, divergent regulation on H_2 concentration levels in gas grids, contracts and billing arrangements based on calorific value or Wobbe Index, safety requirements for connection/injection of hydrogen, and for all types of end-user equipment (Floristean 2019a).

HyLAW also provided a list of EU legislative acts that affect rules and processes applicable to H_2 technologies (Floristean 2019b).

As regards developments of standards, CEN - CENELEC operates a H_2 working group which made various recommendations (Weidner et al. 2016; JRC 2019)[56]. The working group found that standardization related to the admixture of H_2 to natural gas is a key issue, as there is still no understanding of an acceptable H_2 concentration in the natural gas system at European level[57]. Respective standardization – including e.g., gas quality, compressor stations, metering – should be developed in the 2022-2025 timeframe (JRC 2019).

From the industry side, Hydrogen Europe recently called for the creation of an *EU Hydrogen Act* to legally substantiate the EU H_2 strategy (HE 2021b)[58].

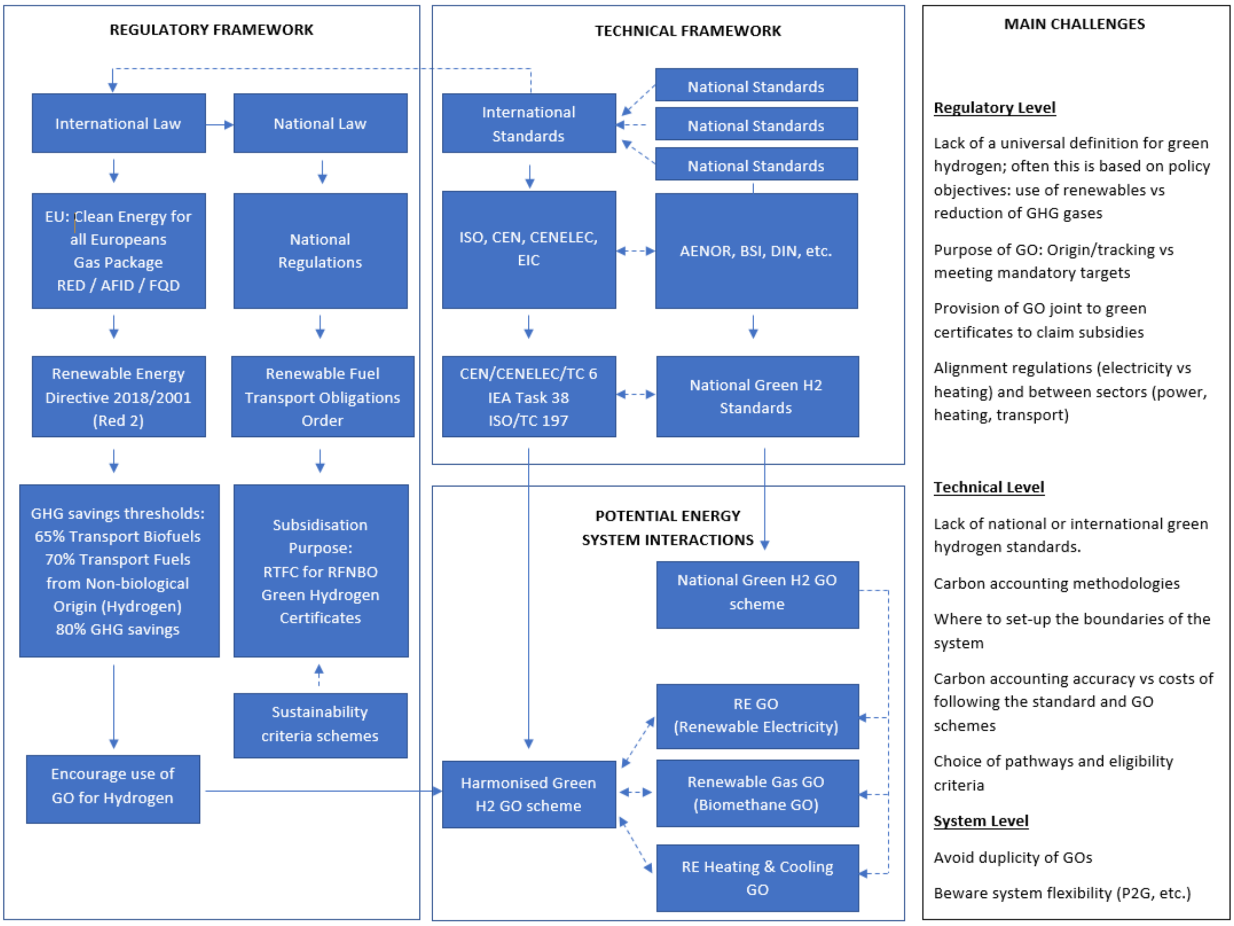
Figure 13 summarizes the regulatory and technical challenges related to H_2 as seen from a European point of view but considering international linkages.

[56] Note that CEN-CENELEC is working also several H_2-related standards, e.g., concerning gas infrastructure (CEN/TC 234), Guarantee of Origin, and H_2 safety (CEN/CLC/JTC 6), see https://standards.cencenelec.eu/dyn/www/f?p=205:105:0::::

[57] IEA (2021b) found that the establishment of a legal framework for injecting hydrogen into natural gas systems (at both distribution and transmission levels) is critical for the further development of H_2.

[58] In the EU, the Member States are legally required since 2008 to harmonize regulation if it concerns the internal EU market, see https://ec.europa.eu/growth/single-market/goods/new-legislative-framework_en

Figure 13 Regulatory and technical frameworks for H_2 and main challenges



Source: Abad & Dodds (2020); note that under current EU RED, GOs are meant only to inform customers about the origin of a product, not for "tracking"; under the EU RED, renewable transport fuels from non-biological origin include hydrogen and other synthetic gases as well as power-to-liquids

5.1 The "color" and origin of H_2

One key area of future H_2 regulation is agreement on reliable **international sustainability standards** and (proof of) origin for electricity from renewable energy sources and for green H_2 and its derivatives (IEA 2021b).

Related to the challenging definition of H_2 "colors" is **to set GHG emission thresholds** for the various H_2 production methods and national contexts:

- Countries such as France, Japan, Korea, Norway and Russia consider a range of low-carbon H_2 production methods, including large hydro and nuclear power, while
- others focus on green H_2, e.g., Germany's *H2 Global* support scheme for long-term and market-based imports will **exclusively support** H_2 from renewable electricity (BMWi 2021b).

The EU's H_2 strategy announced that the EC will adopt a "*common low-carbon threshold/standard for the promotion of hydrogen production installations based* *on their full life-cycle greenhouse gas performance (…) and a comprehensive terminology and European-wide criteria for the certification of renewable and low-carbon hydrogen*" (EC 2020)[59].

As a first step, the EC detailed in a Delegated Regulation that for H_2 production to be considered as sustainable under the EU Taxonomy[60], it has to meet an emission threshold of 3 t CO_2/t H_2 (EC 2021b). This way, "blue" H_2 could qualify as "sustainable" under the EU Taxonomy as well. Furthermore, the taxonomy allows blends of H_2 and natural gas to be eligible, subject to meeting the GHG emission threshold.

With investments in potential H_2 export countries (both within and outside of the EU) as part of bi- and multilateral cooperation agreements becoming a reality, regulatory standards on the GHG intensity of H_2 are urgently needed at least at European level for its entire single market but given that international H_2 trade is expected beyond Europe, a broader international scheme will be required in the medium-term.

To ensure the low-carbon origin of H_2 and its GHG footprint, a certification mechanism should be defined and established (IEA H2 2020), with a *Guarantee of Origin* (IRENA 2021a). In the EU, the CERTIFHY project established the first Green Hydrogen Guarantee of Origin (GO), distinguishing between renewable and low-carbon origins[61].

H_2 certification system also exist in France, Germany and California, and the European Committee for Standardization (CEN-CENELEC) is developing a standard on Guarantee of Origin[62] for production of hydrogen, as indicated in Table 4.

Given the importance of the issue, several countries agreed on a *Hydrogen Production Analysis Task Force* to reach consensus on a methodology and analytical framework for determining GHG emissions related to one unit of produced H_2 (IEA 2021b). This group operates under the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), and is expected to deliver a proposal in 2022.

[59] A recent resolution, the European Parliament calls for "(…) *stepping away from the commonly used colour-based approach; is of the opinion that this classification should be based on the life cycle greenhouse gas emissions throughout hydrogen's entire production and transport process*" (EP 2021).

[60] The Taxonomy is the EU's classification system for green investments, as legally enacted through Regulation (EU) 2020/852 on the establishment of a framework to facilitate sustainable investment. The taxonomy's technical screening criteria are set out in acts that define which investments in technologies across the energy, chemical, waste, and other sectors can be marketed as aligned with EU climate policy standards for adaptation and mitigation. For the public sector, the EU Taxonomy regulation will be used for delivering the EU's economic recovery from the pandemic, and respective funding, i.e., setting the rules governing the €724 billion Recovery and Resilience Facility, part of which is earmarked to fund energy transitions in EU Member States.

[61] See https://www.certifhy.eu/ , and ECOS (2020) for a critique of the approach.

[62] For a more detailed discussion of GOs see FaStGO (2020).

Table 4 Green hydrogen characterization initiatives worldwide

Body (Country)	Type	Baseline GHG threshold	Qualification level	System boundary
AFHYPAC* (France)	GO scheme (proposal)	None	Must be 100% renewable	Point of production
California LCFS	Regulation (active)	WTW** emissions from new gasoline vehicles	30% lower GHG and 50% lower NO_X emissions (on WTW per mile basis) for fuel cell vehicles	Point of use
CEN/CENELEC CLS JCT 6 WG1 / WG2 (International)	International Standard (in prep.)	Adopted from CertifHy	Adopted from CertifHy	Adopted from CertifHy
CERTIFHY (EU wide)	GO scheme (testing)	H_2 from SMR of natural gas	At least 60% lower than SMR for past 12 months	Point of production
Taxonomy (EU wide)		Hydrogen (all sources)	≤ 3 t CO_2/t H_2	Point of production
TÜV SÜD (Germany)	National Standard (active)	Hydrogen from SMR of natural gas	35-75% emissions reduction below baseline (83.8 - 89.7 g CO2e/MJ), depending on production process	Point of use

*Source: adopted from Abad & Dodds (2021), and updated; * = L'Association Française pour l'Hydrogène et les Piles à Combustible (https://www.afhypac.org); ** = well-to-wheel (life-cycle)*

The recent **EC proposal** for a Directive on common rules for the internal markets in renewable and natural gases and in hydrogen (EC 2021e) includes in its § 8 the **mandatory certification** of H_2 to demonstrate a GHG emission reduction of at least 70%. This obligation

"…shall apply regardless of whether low carbon fuels are produced within the Union or are imported. Information about the geographic origin and feedstock type of low carbon fuels or low carbon hydrogen per fuel supplier shall be made available to consumers on the websites of operators, suppliers or the relevant competent authorities and shall be updated on an annual basis" (EC 2021e).

The proposal is surely an important input to the international discussion – yet, it includes the provision that by 31 December 2024, the EC shall adopt delegated acts to specify the methodology for assessing GHG emissions savings from low carbon fuels, ensuring that credit for avoided emissions is not given for CO_2 which has already received an emission credit for capture (via CCS).

This means that there will be sufficient time to develop the EU methodology harmonized with international activities.

5.2 Additionality of "green" H_2

As long as the electricity mix is not fully decarbonized, a relevant regulatory question related to the H_2 potential to contribute to decarbonization is whether the electricity needed for "green" H_2 production is diverted from current production, or "additional" (IRENA 2021a). Only the latter will ensure GHG reductions through new (or uncurtailed) renewable electricity generation[63].

To clarify this, the EC has to adopt two Delegated Regulations under the RED II:

- A methodology to determine GHG emissions savings from renewable liquid and gaseous transport fuels, including H_2, and detailed rules on how electricity for H_2 production obtained from direct connection to an installation generating renewable electricity may be fully counted as renewable electricity where it is used for the production of *renewable liquid and gaseous transport fuels of non-biological origin* (which includes H_2), and
- how electricity that has been taken from the grid may be counted for this purpose.

H_2 under the EU RED II is part of "*renewable fuels of non-biological origin*" (RFNBO) but the above mentioned GHG emissions benchmarks, definitions for additionality, geographical and temporal correlation to be specified in EC Delegated Acts are still pending. The additionality requirements under the current regulation in the RED II have been criticized recently as too complex (Pototschnig 2021).

5.3 Access to the gas grid and grid development planning for H_2

The transformation of the gas grid towards H_2 will occur in steps over time, as depicted in Section 4, and implies investments of the transmission and distribution system operators. The regulation of respective planning and cost recovery is yet unclear, and applicability of the existing regulatory frameworks for natural gas in IEA countries to H_2 is questionable (IEA 2019).

For example, Germany's Federal Network Agency recently cleared two dozen natural gas transmission pipelines for future conversion to transport H_2, with some legislative and regulatory steps still necessary before the pipelines can be converted, though. The agency allowed the pipelines to be taken out of the current natural gas infrastructure and be added to a future hydrogen grid – so long as the performance of the current gas grid is left uncompromised.

[63] See ECOS (2020) for Europe, and RNE (2020) for Germany. Similar considerations have been made by Shibata et al. (2020) in the context of a prospective H_2 sustainability certification scheme for Germany and Japan.

However, the agency also clarified that the hydrogen network **cannot** be part of the natural gas grid development plan, and **new rules** have to be established **first**[64].

In a study for the EC on a regulatory framework for H_2, the authors concluded:

"Since it is expected that the hydrogen markets will initially develop in smaller clusters which will be interconnected only gradually, the rules setting up a framework for EU-wide internal market for hydrogen do not have to be introduced in the short term. However, the rules for cross-border capacity allocation should be defined by 2030, when more substantial interconnection can be expected for the MSs following more ambitious pathways (...) Further harmonisation of market rules and regulation of organised markets will be necessary by 2030 or only in the long term, when the cross-border trade will reach a more significant volume" (van Nuffels et al 2020b).

The recent EC proposal for a regulation of low-carbon H_2 and respective infrastructure (EC 2021d) is an important step in that regard. It needs to be seen how the negotiations between the EC, the European Parliament and the European Council will proceed-

5.4 H_2 safety

Last but not least, the issue of H_2 safety will have to be regulated to minimize risks for investors, and facilitate planning procedures, e.g., through agreement on consistent safety distances from H_2 or blended infrastructure.

International research on the potential safety risks associated with H_2 blending of up to 25 vol% indicated no (or very minor) safety effects (Polman et al. 2003), and later work in the EU project *NaturalHy* supported this view (de Vries, Florisson & Tiekstra 2007) and showed that the severity of explosions in buildings increases if H_2 is added to natural gas, but the increase is small for H_2 addition of 20 vol% (NaturalHy 2009)[65].

Empirical studies by Askar et al. (2016) and HYPOS (2021) found that adding up to 10 vol% H_2 to natural gas had nearly no effect on the safety characteristics, while more significant effects were observed at >25 vol% of H_2. For the UK, no higher risks of fire and explosion hazards are expected from H_2 mixing into the natural gas grid up to 20 vol%, compared to natural gas (Hodges et al. 2015).

In the US, a recent review of the release behavior of H_2 and natural gas blends from pipelines indicated that leakage and respective risk of explosions and fire are similar for H_2 blends of 20 vol% and natural gas, but very few empirical data exist (Baird, Glover & Ehrhart 2021; US-CRS 2021).

64 See https://www.cleanenergywire.org/news/german-regulator-paves-way-converting-natural-gas-infrastructure-hydrogen

65 Until 2008, the EC Network of Excellence for Hydrogen Safety "HySafe" analyzed a variety of safety issues , see http://www.hysafe.net

Thus, there is (some) agreement that H_2 blends with natural gas of up to 20 vol% poses no additional safety risks, but regarding the longer-term transition towards 100% H_2 infrastructure, the safety issue will have to be researched more (Messaoudani et al. 2016) and respective regulation be implemented (EP 2021).

Internationally, it is worth mentioning that the IEA Hydrogen TCP[66] is developing a new Task on "Safety and RCS of Large Scale Hydrogen Energy Applications" targeted to start in 2022.

[66] It should be noted that IEA Hydrogen operated Task 37 on Hydrogen Safety from 2015 to end of 2021, see https://www.ieahydrogen.org/task/task-37-hydrogen-safety/

6. Open questions on H_2 in the grid

Besides the regulatory and safety issues mentioned before, open questions on *H_2 in the grid* concern mainly two issues:

- Will H_2 be a competitive option for heat and road transport, compared to direct-electric alternatives?
- Are the various options to add H_2 to the gas grid suited better for decarbonization than SM (including biomethane) schemes?

6.1 H_2 versus direct electricity use

The future use of H_2 to decarbonize the **non-industrial** heating sector (H_2 boilers[67]) and road transport (fuel-cell vehicles, respective refueling stations) will determine if – in the longer-term - 100% H_2 distribution grids will be needed, as these end-uses are **distributed**.

Direct H_2 use in these sectors **competes** with **direct electricity** use[68], and the review of national H_2 strategies and roadmaps (Section 2) indicated that so far, most countries focus on hard-to-abate sectors and non-road (or longer-haul) transport for H_2 implementation. In IEA's NZE, H_2 will contribute a rather low share of the heat demand (6% by 2050, see IEA 2021a).

Some authors argued that H_2 could well compete with electricity in the heating sector (e.g., Bothe et al. 2021; Gatzen & Lenz 2021), while others find that direct use of low-carbon and renewable electricity would allow to decarbonize heat more cost-effectively (AVERE et al. 2021; Baldino et al. 2021; ICCT 2018; Ueckerdt et al. 2021).

For road transport, the competition between battery-electric (BEV) and fuel-cell electric vehicles (FCV) is not only determined by the dynamics of storage cost and delivered vehicle range but also by the infrastructure cost: A wide distribution of charging stations for BEVs implies at least some extensions in low-voltage local infrastructure, and H_2 refueling stations for FCVs are yet quite rare but many of the national H_2 strategies and roadmaps foresee a significant increase over the next decades. The "chicken-and-egg" question for FCVs is more prominent than for BEVs, as meanwhile, many car manufacturers have dedicated to BEV[69].

[67] Note that there is much agreement in country strategies and roadmaps on the potential role of H_2 for smaller-scale local cogeneration using high-efficient fuel cells (IEA 2021b). In such cases, H_2 could be either produced on-site or – for larger systems – through dedicated H_2 pipelines (or H_2 separation), see Section 4.2.

[68] New busses, cars and light-duty vehicles as well as medium-range trucks would be driven by electricity stored in on-board batteries. New (low energy) buildings would use electricity through heat pumps. There will also be (some) competition with other renewables: Biomass-based fuels in transport and bioenergy, geothermal and solar energy for direct heating.

[69] Note that this mainly concerns light-duty vehicles, not heavy-duty ones such as long-haul trucks.

As the transition logic for natural gas grids to H_2 requires overall conversion of the gas distribution system only in the longer-term (see Section 4), the question of actual need to do so can remain open up to 2030 and further research and demonstration should be carried out to clarify the issue.

In that, the issues of future development of abatement cost, uncertainty in cost reductions, availability of large-scale renewable electricity and resource efficiency of conversion routes should be dealt with, considering also potential lock-in effects (Ueckerdt et al. 2021).

6.2 Beyond 2030: H_2 or SM?

The second open question on H_2 in the grid also concerns the post-2030 timeframe: Will H_2 be widely used, which implies infrastructure adjustment, or will – beyond H_2 clusters – renewable synthetic methane (SM) become more important?

For **both**, the cost of low-carbon (especially renewable) H_2 will be a decisive factor, and the availability of large amounts of (low-cost) renewable electricity generation.

By 2030, H_2 costs are estimated at \$1- \$2 per kg for low-carbon H_2, and \$2 - \$3 per kg for green H_2 by 2030 with a perspective of further reductions to \$1 - \$2 per kg by 2050 (HC 2020; IEA 2021a+b; IRENA 2020)[70].

The screening of options to inject H_2 into gas grids beyond 20 vol% (see Section 3) indicated that this would imply comparatively low additional cost (except for H_2 separation), while conversion of H_2 to the more compatible SM adds up to \$2 per kg of H_2.

This simple comparison ignores that SM offers other "services", though:

- With high shares of renewable electricity generation (needed for both H_2 and SM), balancing the electricity grid and storing electricity over longer periods become major issues, and SM offers a pathway to make use of **existing** natural-gas-based systems to deliver **on both**.
- In that, SM helps maintaining the economic value of such infrastructure[71], and avoids investment in costly electricity storage. On the other hand, H_2 could also make use of (refurbished) gas infrastructure to provide services to the electricity system[72], but at a cost for the refurbishing.

[70] Note that the US "Hydrogen Earthshot" initiative for H_2 aims at low-carbon or renewable H_2 cost of \$ 1 per kg already for 2030 (US DOE 2021).

[71] With natural gas use significantly decreasing in many IEA countries in the coming decades, cost recovery for gas infrastructure may become an issue. If SM contributes to make use of such infrastructure, stranded assets might be avoided to some extent, which implies an economic benefit for the gas system operators.

[72] Both H_2 and SM use to provide electricity services implies efficiency losses, though: Re-converting H_2 or SM to electricity looses 50 – 60 per cent of the energy content, depending on the electricity generation technology (combined-cycle gas turbine or solid-oxide fuel cell).

The advantage of SM to use the existing infrastructure will be reduced over time, as (re-)investment cycles will be adapted to future demands.

Thus, the level of **integration** of the electricity and the gas system and its economic implications will determine whether H_2 or SM will have a more prominent role in the renewable gas game.

Further research and development is needed to clarify which costs can be achieved, and which economic value the electricity services from renewable gases will have.

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