



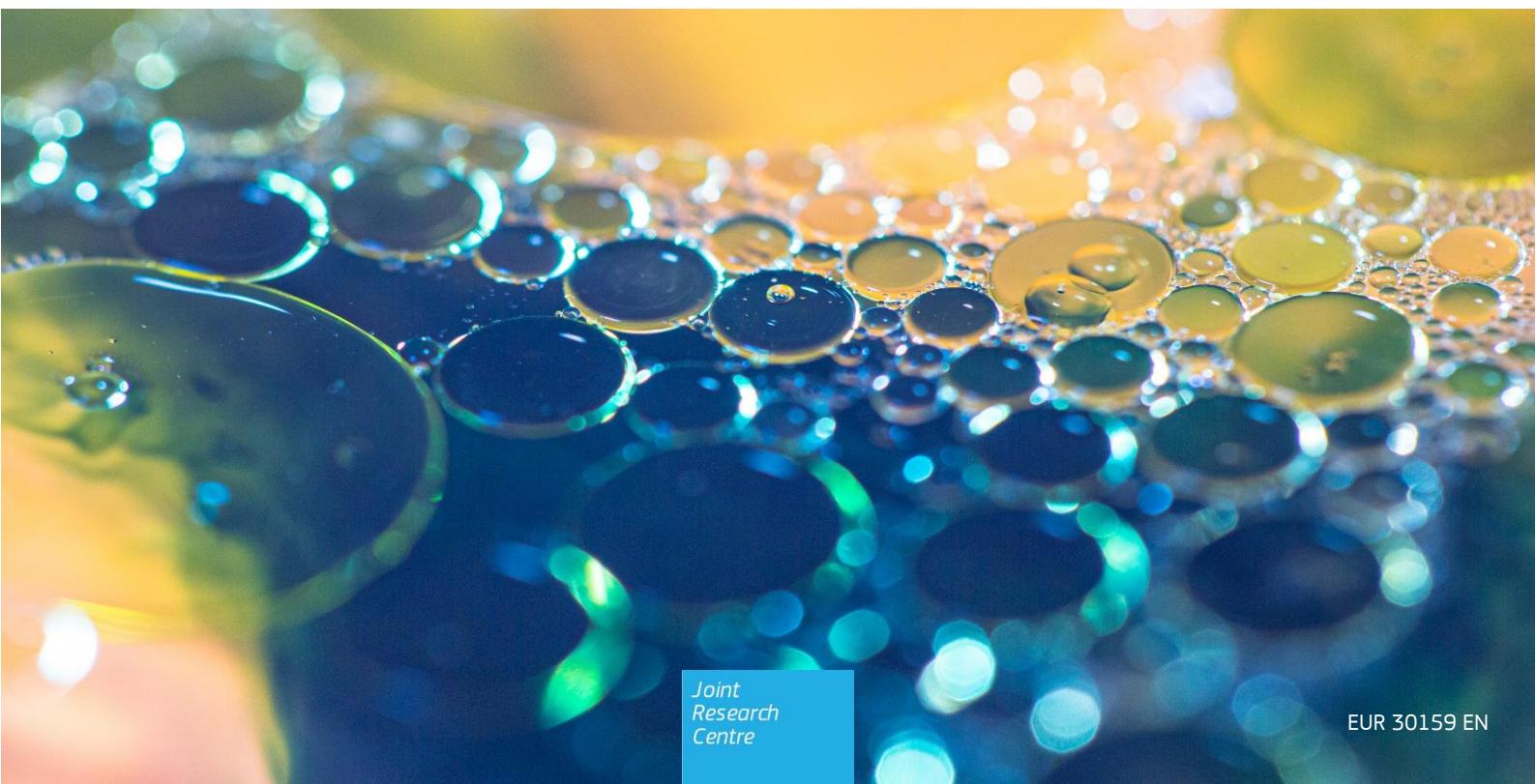
JRC SCIENCE FOR POLICY REPORT

Current status of Chemical Energy Storage Technologies

*Trends in research,
development and deployment
in Europe and the rest of the
world*

Davies, J., Dolci, F., Klassek-Bajorek, D., Ortiz Cebolla, R., Weidner, E.

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Abstract

The aim of this report is to give an overview of the contribution of EU funding, specifically through Horizon 2020 (H2020), to the research, development and deployment of chemical energy storage technologies (CEST). In the context of this report, CEST is defined as energy storage through the conversion of electricity to hydrogen or other chemicals and synthetic fuels. On the basis of an analysis of the H2020 project portfolio and funding distribution, the report maps research activities on CEST at the European level. In addition, projects funded at national and international level, occurring within the same timeframe, have been considered.

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Authors

Jonathan Davies, Francesco Dolci, Dominika Klassek-Bajorek, Rafael Cebolla Ortiz and Eveline Weidner.

Executive summary

The aim of this report is to give an overview of the contribution of EU funding, specifically through Horizon 2020 (H2020), to the research, development and deployment of chemical energy storage technologies (CEST). In the context of this report, CEST is defined as energy storage through the conversion of electricity to hydrogen or other chemicals and synthetic fuels. On the basis of an analysis of the H2020 project portfolio and funding distribution, the report maps research activities regarding CEST at the European level. In addition, projects funded at national and international level, occurring within the same timeframe, have been considered. For each of the technologies and processes described, key performance indicators are defined, and the state-of-the-art is assessed.

Policy context

The Paris Agreement requires actions to reduce greenhouse gas emissions, in order to keep the global temperature increase to well below 2°C. The transformation of the energy system required to meet 1.5°C or 2°C scenarios is substantial. The EU has issued a number of policies to support the reduction of greenhouse gas emissions and has set increasingly ambitious objectives. However, according to the recently published communication "A Clean Planet for all", these policies are not sufficient for the EU to contribute to the Paris Agreement's temperature goals, as the EU should aim to achieve greenhouse gas emissions neutrality by 2050. That communication highlights energy storage as a key enabling technology to provide the necessary flexibility for integrating increasing amounts of variable renewable electricity into the grid. Hydrogen is also considered an important instrument for reaching the European Green Deal objectives.

Key conclusions

The report concludes that chemical energy storage technologies can support the integration of renewable electricity and help decarbonise various end-use sectors. The key role hydrogen can play in a future carbon neutral energy system, either as an energy carrier, molecule, feedstock, or in its derivative chemicals, is due to its ability to link the electricity sector to transport, industry and – in principle – commercial/residential sectors. This implies that there are a large variety of pathways, which are at different levels of technological readiness, efficiency and performance, and which might need further public support. We recommend to perform an assessment of the decarbonisation potential and overall sustainability to determine which of these pathways and technologies should receive support.

Main findings

CEST are likely to have a key role in the decarbonisation of the future energy system, and this has been reflected in current and previous research framework programmes. Public funding for R&D on CEST has been of the order of €180 million, of which 60% has been awarded to private companies. Half of the H2020 funding has been given towards research on electrolysis, where most projects are in the demonstration phase, which is an indication of a high technical maturity of this technology. Hydrogen-to-X projects are typically at the level of field tests. Fundamental research generally received less support with respect to other CEST projects. Almost half of the funding has been awarded through the FCH 2 JU programme, followed by LCE calls (22%). Sustainability and performance of different CEST options vary and they should be considered on a case-by-case basis. The reduction of the cost of all technologies will need further investment, in particular through the development of manufacturing processes and increasing their capacity.

Related and future JRC work

It is recommended that specific energy system modelling studies should be performed in order to assess the role of CEST in a future energy system. In addition, appropriate assessment methodologies should be developed and further studies (LCA, techno-economic assessment) performed in order to identify the most advantageous uses of green hydrogen in terms of limiting pollution, CO₂ abatement potential, critical raw materials use, overall environmental impacts and cost.

Quick guide

On the basis of an analysis of the H2020 project portfolio and funding distribution, the report maps research activities on CESTs at the European level. In addition, projects funded at national and international level, occurring within the same timeframe, have been considered. This analysis was coupled to the technical description of current state-of-the-art options for CEST technologies.

1 Introduction

The aim of this report is to give an overview of the contribution of EU funding, specifically through Horizon 2020 (H2020), to the research, development and deployment of chemical energy storage technologies (CEST). **In the context of this report, CEST is defined as energy storage through the conversion of electricity to hydrogen or other chemicals and synthetic fuels¹.** On the basis of an analysis of the H2020 project portfolio and funding distribution, the report maps research activities on CESTs at the European level. In addition, projects funded at national and international level, occurring within the same timeframe, have been considered.

The Paris Agreement requires actions to reduce greenhouse gas emissions, in order to keep the global temperature increase to well below 2°C. The transformation of the energy system required to meet 1.5°C or 2°C scenarios is substantial. The EU has issued a number of policies to support the reduction of greenhouse gas emissions by setting increasingly ambitious objectives, which are projected to reduce emissions by around 45% by 2030 and 60% by 2050, compared to 1990 [1]². However, according to the recently published communication "A Clean Planet for all" [1] (or Long Term Strategy, LTS), these policies are not sufficient for the EU to contribute to the Paris Agreement's temperature goals, as the EU should aim to achieve greenhouse gas emissions neutrality by 2050. That communication highlights energy storage as a key enabling technology to provide the necessary flexibility for integrating increasing amounts of variable renewable electricity into the grid. In 2019 the European Commission presented the European Green Deal, setting up a framework of regulation and legislation with clear overarching targets to reach net zero global warming emissions by 2050. Hydrogen is considered an important instrument for meeting the Green Deal objectives.

Energy storage is often understood to be synonymous with electrical power storage, and is typically provided through mechanical, electrical and electrochemical³ storage systems. In the current energy system, grid-scale energy storage is typically short-term and used to maintain stability, in order to address peaks (i.e. on the minute and hour scale) up to daily imbalances [2]. Seasonal storage may be needed in the future for high levels of renewable generation based mainly on solar and wind generation, and can be provided at terawatt (TW) level through hydrogen or synthetic methane (see Figure 1).

Two EU legal definitions of energy storage are currently available:

- as proposed in SWD(2017)61 [3], as well as in Proposal for a Directive of the European Parliament and of the Council on common rules for the internal market in electricity COM(2016) 864 final/2 [4]:

'energy storage' means, in the electricity system, deferring an amount of the electricity that was generated to the moment of use, either as final energy or converted into another energy carrier.

- as published in policies, information and services section of Related legislation on Electricity Market Design [5], and as incorporated in text of Directive on common rules for the internal market for electricity [6]:

'energy storage' means, in the electricity system, deferring the final use of electricity to a moment later than when it was generated, or the conversion of electrical energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into electrical energy or use as another energy carrier;

Chemical energy storage technologies involve the conversion from electricity to another energy carrier, which is reflected in the second of the definitions of energy storage. In the LTS, new energy carriers such as hydrogen are considered for energy and industrial applications where it is difficult to replace fossil fuels, and because of their chemical and physical properties. Hydrogen can take the role of an energy vector beyond its potential role in providing chemical storage of electricity. As hydrogen is versatile, it can also contribute to the decarbonisation of transport, buildings or industry. This concept is also referred to as sectoral integration, the linking of energy (electricity, gas and heat), transport and industrial sectors and infrastructures. It can be considered an economic necessity that many of today's energy network infrastructures will still be operational in 2050. The LTS considers that during the energy transition, the existing gas (and oil) infrastructure should be used, as it is able to distribute and store substantial amounts of energy.

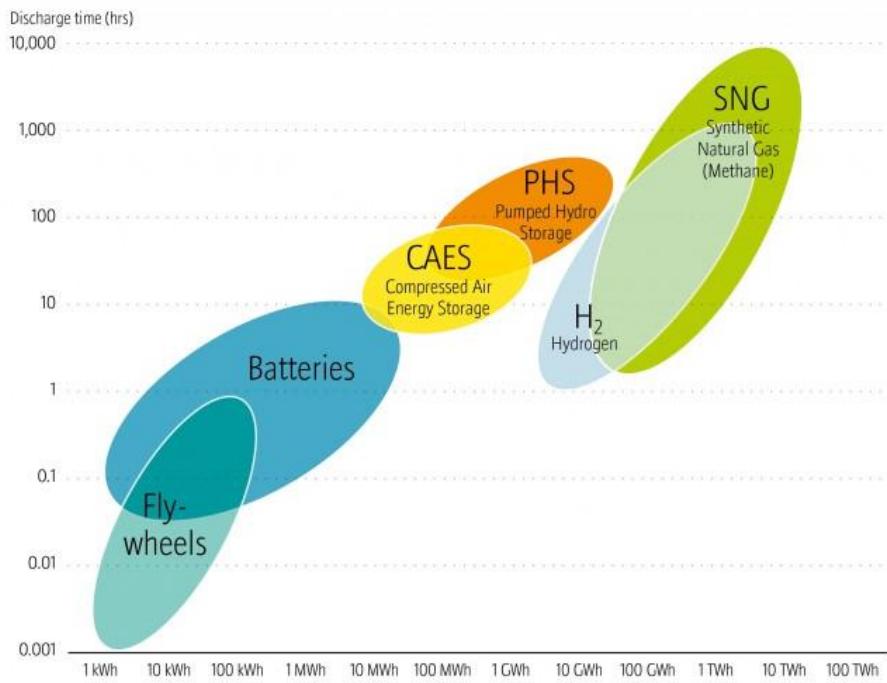
¹ Therefore chemical energy storage in the form of natural gas to enable security of energy supply is not considered here.

² As set out in the 2030 Energy Strategy, first published in 2015 and recently partially updated with the third Clean Energy Package legislation in December 2018.

³ Flow batteries are considered as part of electrochemical, rather than chemical energy storage technologies in this report.

Figure 1 Electricity storage applications and technologies.

Overview storage capacity of different energy storage systems



Source: [7]

CEST are likely to have a key role in the energy transition, which has been recognized in current and previous EU research framework programmes. A significant investment of public funding has been made into the development and improvement of the relevant technologies. This report aims to provide an assessment of the progress made through EU funding provided during the 2014-20 research programme, H2020. 55 projects were identified as targeting CEST as their main focus. During the same time period, a large number of CEST projects were publicly supported at national level. National funding programmes and projects have also been assessed.

In Chapter 2 of this report, a description of the scope of technologies covered and of the methodology used is presented. For each of the technologies and processes described, Key Performance Indicators (KPIs) are defined, and the State-of-the-Art (SoA) is assessed (Chapter 3). The technologies considered are electrolysis, various storage and distribution options, as well as technologies and processes for the conversion of hydrogen to methane or other chemicals⁴. Chapter 3 also provides a short summary of the scope of the CEST projects funded under H2020. An analysis of the funding available under H2020 for CEST technologies is provided. An overview of national funding programmes is given in Chapter 4, and standardisation activities and international initiatives with a scope related to CEST are described. The report gives an indication of the differences in relative positioning of CEST at European and international level. Based on this assessment, recommendations for the next European framework programme are provided in Chapter 5 which also compares the European programme to those at a national and international level. In the Annex, tables with EU funded and nationally funded projects are provided.

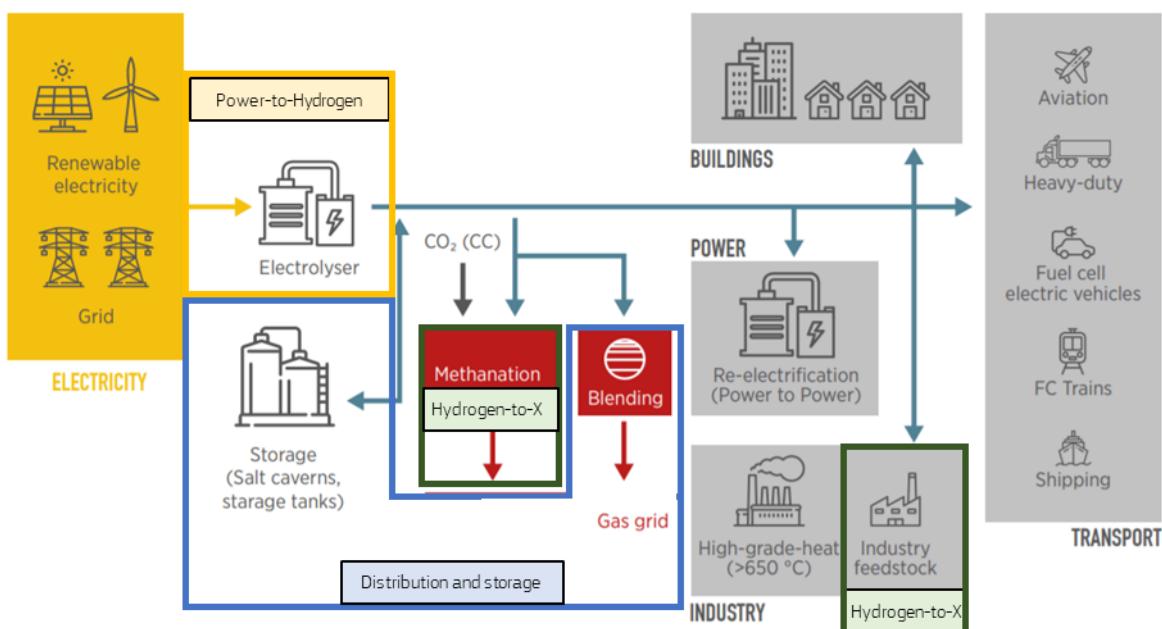
⁴ The end-use of hydrogen or synthetic methane is not part of the scope.

2 Scope, methodologies and data sources used

2.1 Scope and terminology

This report assesses the state-of-the-art and key performance indicators (KPIs) of the main chemical energy storage technologies (CEST). The scope of this study is depicted in Figure 2, as well as the links to other technologies and applications. The H2020 project portfolio on related topics was analysed and put into context of activities at member state and international level within the same period. Specifically, the report covers the time period from 2014-2018, but for the overviews on member state and international funding schemes, the time frame was extended to include 2019, to incorporate important recent developments.

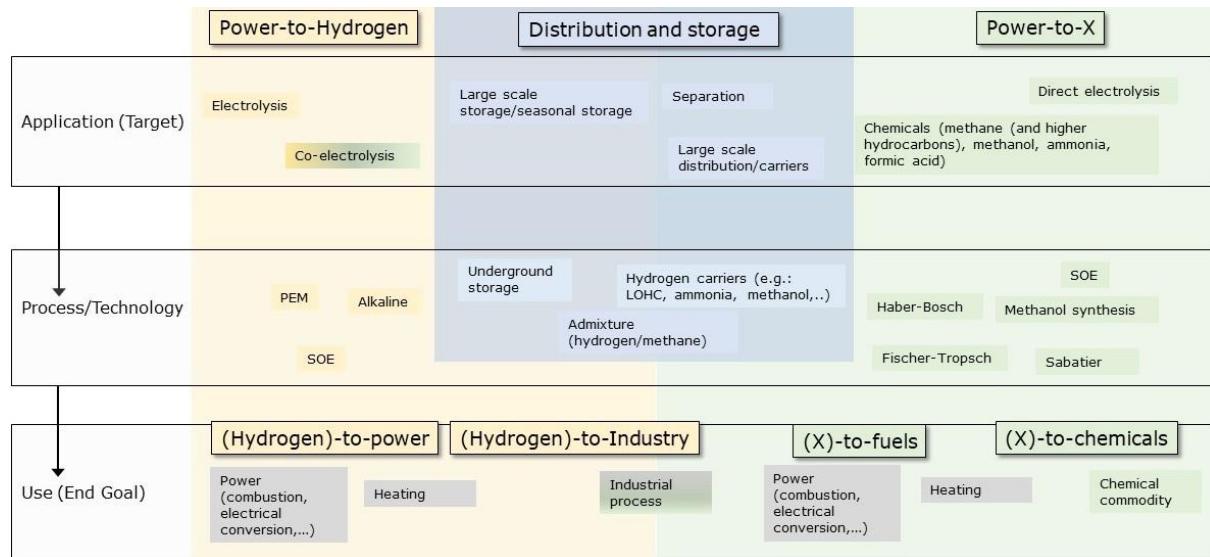
Figure 2 Integration of renewable energy sources through conversion of electricity to hydrogen. The coloured boxes indicates the focus of the report, see also Figure 3.



Source: Adapted from [8]

Figure 3 provides a more detailed overview schematic of the various technologies, conversion processes and applications analysed for this report. The yellow area indicates production and direct use of hydrogen, the blue area highlights storage and transport applications, and the green area highlights chemical uses and conversion options. Grey boxes are used for final conversion steps that are outside the scope of this report, but included in the figure to provide a complete picture. Outlined boxes identify the terminology used in this document.

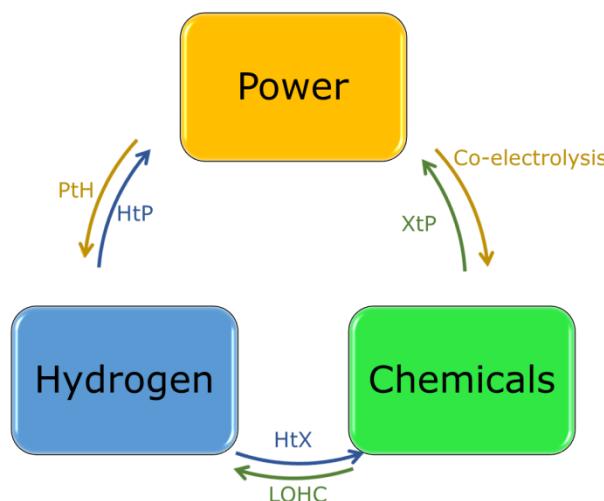
Figure 3 Scope and terminology schematic.



Source: JRC, 2020

The conversion of electricity to hydrogen or synthetic methane is often referred to as Power-to-Gas (PtG). The term power-to-gas is generally used in an ambiguous manner, sometimes referring to the production of synthetic methane or sometimes to the admixture of hydrogen, and is therefore avoided in this report when assessing the projects under the H2020 programme. For describing programmes and initiatives at national and international level the term power-to-gas has been replaced wherever possible with less ambiguous alternatives. This is not always possible, for example where power-to-gas is in the title of a project, or where the specific process is unclear. In this report a terminology was adopted, based on the clear definitions developed in IEA Task 39 [9]: Power-to-Hydrogen (PtH) refers to the conversion step to hydrogen only, while Hydrogen-to-X (HtX) refers to all further conversions, including methanation. The conversion steps are also depicted schematically in Figure 4.

Figure 4 Schematic of possible pathways and conversion steps for sector coupling through hydrogen.



Source: JRC, 2020

These conversion processes are at the heart of Chemical Energy Storage Technologies (CEST), and are covered in the two main sections of Chapter 4. The distribution and storage of hydrogen (D&S), focussed on those technologies relevant to the scope of the report (which excludes the end-use of hydrogen), links the PtH and HtX sections. Storage and distribution/transport of hydrogen, synthetic methane or other hydrogen carriers are

a key element to enable chemical energy storage. This includes the distribution of hydrogen or synthetic methane through pipelines, the admixture of hydrogen to natural gas, the separation of hydrogen from a mixture of natural gas and hydrogen, as well as the large scale storage of hydrogen underground or as liquid hydrogen (LH₂). Hydrogen carriers such as Liquid Organic Hydrogen Carriers (LOHC) are covered, as they enable the transport of large quantities of hydrogen over long distances.

Topics that have been excluded from the scope of work:

- The end-uses of hydrogen, for example for mobility purposes.
- The use of hydrogen for the production of chemical commodities in general, or for use in refineries or metallurgy.
- The reconversion to electricity of hydrogen, synthetic methane or chemicals.
- CO₂ capture and handling technologies (CCS and CCU).
- Hydrogen production other than water electrolysis (i.e. SMR, solar water splitting, hydrogen production from biomass, coal gasification, pyrolysis, etc.).
- Smart grid concepts or grid management.
- Supporting activities such as training and education, or hydrogen safety.

These topics are not covered in order to keep the focus of the report on the basic concept of chemical energy storage. Therefore all end-use applications for hydrogen have been excluded, and HtX is only included up to the point where (electrolytic) hydrogen is used to produce a chemical product, but not the further utilisation of that product itself. Other hydrogen production routes are not directly related to the chemical energy storage approach as outlined above, where the conversion of electricity to hydrogen plays a central role.

2.2 Methodology

In this report, the focus is on the state-of-the-art, KPIs, ongoing relevant R&D efforts and on R&D needs for the CEST identified as part of the scope. The basic approach of this work takes the methodology developed by the JRC for the Low Carbon Energy Observatory into account, but has been adapted further to account for the wide variety of technologies, applications and pathways addressed. To identify the relevant projects under H2020, the CORDIS and CORDA databases⁵ were searched for a number of keywords, such as hydrogen, methanation, electrolysis, membrane, separation, sector coupling and power to gas. Only the projects falling within the scope as defined in Section 2.1 were assessed further. The database searches were conducted in July 2019, so projects starting thereafter were not considered. These projects were categorised by keywords relating to the project topic as shown in Table 1. The first level of keywords relates to whether the project is focusing on the conversion of electricity to hydrogen (PtH), to the distribution and storage of hydrogen (D&S) or the conversion of hydrogen to chemicals/fuels (HtX). The second keyword was assigned according to the technology or process, for example electrolysis or methanation. A third level keyword was assigned only to the electrolysis projects, based on the type of electrolyser or component developed, namely PEM Electrolysis (PEMEL), Alkaline Electrolysis (AEL), Solid Oxide Electrolysis (SOEL). The first level of keywords is the basis for the analysis of the funding provided to H2020 projects. The second and third level keywords were used to structure the subsections in Chapter 4.

Table 1: Keyword level structure used in the categorisation of projects

Keyword level 1	Keyword level 2	Keyword level 3
PTH	Electrolysis	PEMEL
PTH	Electrolysis	AEL
PTH	Electrolysis	SOEL
PTH	Electrolysis	PEMEL/AEL
PTH	Electrolysis	Other
D&S	Separation	
D&S	LOHC	
HtX	FT and co-electrolysis	
HtX	Methanation	

⁵ The Community Research and Development Information Service (CORDIS) is the European Commission's primary source of results from the projects funded by the EU's framework programmes for research and innovation (FP1 to Horizon 2020). CORDA is the European Commission's database of projects.

Keyword level 1	Keyword level 2	Keyword level 3
HtX	Methanol	
HtX	Methanol derivatives	
HtX	Formic Acid	
HtX	Formic Acid/Methanol derivatives	
HtX	Strategy/Roadmap	

Source: JRC, 2020

The main sources of information for assigning these keywords were the project abstract and project website (where available). For some projects, publically available deliverables were consulted.

Based on this information, projects were further analysed in terms of the type of research or demonstration activity performed and assigned a Project Class. The available sources were analysed for information regarding the stage of the project within the overall development of the technology. For example, terms such as "R&D; Materials; Component; Prototype; Proof of Concept" suggested a project in the earlier stage of development, whilst phrases such as "System; Field Test; Demonstration; Plant; End-User" suggested a project much closer to real-world application. In order to classify each individual project, a Project Class was defined as shown in Table 2. Eight project classes (A-G) ⁶were used to define the projects with the aim to capture the range of activities undertaken in that project⁷.

Table 2: Definitions of Project Class

Class	Project Class
A	Fundamental Research
B	Research to Prototype (Testing of a Technology Component)
C	Technology Validation via Field Test (Field test of a technology in a full System environment)
D	Large Scale Demonstration
E	Manufacturing
F	Diagnostics
G	Re-Normative Research (PNR), Regulations, Codes and Standards (RCS)
H	Strategic planning, roadmaps

Source: JRC, 2020

It should be noted that the allocation of a Project Class is subjective and not ideal, but still enables a descriptive classification of projects (to a greater degree of detail than simply "Research" or "Demonstration") in order to demonstrate some overall trends. Ideally, the Project Class could be replaced, for example, using the Technology Readiness Level (TRL). This has been attempted for Horizon 2020 projects funded through the European Public-Private Partnership Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU), where the initial and target TRL are defined within most call topics. However, even in this case, a TRL range is often given in the call and multiple technologies investigated within a given project may be at different TRL. Furthermore, some projects may only attempt to further a technology by a single TRL whereas other projects may be trying to progress a technology 3 or even 4 levels. Therefore, it is often difficult to make a clear connection between Project Class and TRL.

⁶ As originally defined in the report "Keyword Analysis and Project Classification of FCH 2 JU Projects" by J.C. Davies, prepared for the FCH 2 JU. The public version of this document will be released in 2020.

⁷ The most applicable Project Class was assigned to each project. Multiple assignments to an individual project were not permitted. Some classes are listed here for the sake of completeness, even if no projects were labelled as falling under that category.

For H2020 projects, in particular those not funded by the FCH 2 JU, it should be noted that the amount of public information available varies greatly, and in many cases nothing more than the project abstract was accessible.

For the FCH 2 JU projects, the JRC was able to draw upon additional information regarding project activities on LCA. In 2018, the JRC delivered the report "Life cycle assessment of Hydrogen and Fuel Cell Technologies - Inventory of work performed by projects funded under FCH 2 JU": which provides an overview of the progress achieved so far and an analysis on LCA for various hydrogen technologies and processes [10]. These LCAs have been assessed regarding adherence to guideline recommendations (e.g. reported properties, system boundary definitions, goal and scope definitions), methodology and overall quality of the work. A public version of this report was prepared in 2019 [11]. Based on the outcome of this analysis, a harmonisation effort in the approach to LCA for the FCH 2 JU funded projects was proposed, and a workshop organised in 2019. The goal of the workshop was to identify critical requirements, to discuss a common approach to LCA of Fuel Cells and H2 Technologies and to propose the creation of a Life Cycle Inventory (LCI) database useful for the projects performing LCAs [12]. Relevant outcomes of this work are taken into account for this report on CEST.

For the national programmes it is quite difficult to provide a comprehensive overview on funding for CEST projects. In some member states there are national project databases, similar to CORDIS, in which a keyword-based search could be performed. Based on the number of projects found, a cut-off (minimum project funding) was defined for inclusion of projects in the overview tables in Annex B. This value varies from country to country, as for example Germany is funding CEST projects at a much higher level than other countries. Also the type of information provided through the databases is not consistent, therefore the details provided in the tables in Annex 6.2 has been adapted accordingly. For example, in some cases the total cost of the project is not available. For many other national programmes, information on research projects was not readily accessible through one central database and the sources only mentioned selected or individual projects. Some relevant projects may therefore have been overlooked. Only a few privately funded projects have been mentioned, as information on these is difficult to find.

To improve readability, project names have been capitalised throughout the document.

2.3 Data sources

In addition to information from CORDIS, the following data sources have been used for the H2020 projects:

- FCH 2 JU - programme review and public project deliverables
- JRC review of FCH JU project deliverables on LCA, expert workshop on LCA held 2019
- Project websites, where available
- Connecting Europe Facility website [13]

To describe national and international programmes:

- Literature (studies, papers, review articles)
- National funding databases, if available
- Databases on power-to-gas projects: European Power-to-Gas Platform, IEA Hydrogen Task 38 data and DOE Energy Storage database for international projects

For assessing the SoA and KPIs of technologies/processes:

- Literature (studies, papers, review articles)
- Manufacturer information
- FCH 2 JU programme review, as performed by the JRC since 2017
- JRC expertise

3 Chemical energy storage technologies KPIs, state of the art and research orientations

In the following sections, an overview of the main technologies and processes for chemical energy storage is provided. The content is divided into three main subsections (see also Figure 3): the conversion of electricity to hydrogen (power-to-hydrogen, subsection 3.1), the distribution and storage of hydrogen, subsection 3.2 and the conversion of hydrogen to chemicals or fuels (hydrogen-to-X, subsection 3.3). Most of the subsections are further broken down, focussing on a particular technology or process. Each of these subsections provides a definition of key performance indicators, the current state of the art, and an overview of projects funded through the Horizon 2020 programme (if any). The review begins with the topic of electrolysis, as hydrogen is the starting point for the other technologies. Next the topic of hydrogen distribution and storage is assessed as relevant to the scope of the report (e.g. on-board hydrogen storage for FCEV is out of scope). Hydrogen-to-X applications are covered in as far as they can be considered as options for energy storage, but no re-conversion of chemicals to energy will be discussed in detail here. Some pathways (e.g. electrofuels) will be covered inasmuch as they provide a method for storing energy and not in their actual fuel role. In subsection 3.2.4.3, a project funded through structural funds is described, as it falls under the scope of the report.

3.1 Power-to-Hydrogen (electrolysis)

The use of electrolysis for producing hydrogen from available electricity coming from renewables (mainly wind and solar) can be considered as the fundamental technical foundation for any application exploiting the concept of a general power-to-hydrogen, or power-to-methane chain. In the following Section 3.1.1, electrolysis will therefore be described in detail, since it is currently the most mature and practised path for directly converting electricity into a useful molecule. Hydrogen can then be further converted to other chemical compounds (hydrogen-to-X, see Section 3.3), or converted back to power or heat (hydrogen-to-power and hydrogen-to-heat). The latter two paths are outside the scope of this report.

3.1.1 Electrolysis KPIs

In the following tables, the state of the art and future targets for specific quantitative Key Performance Indicators are given for the three main electrolyser technologies. These values are taken from the Addendum to the Multi-Annual Work Plan 2014-2020 of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) from 2018 [14]. Table 3 shows the values for Alkaline Electrolysers, Table 4 for PEM Electrolysers and Table 5 for Solid Oxide Electrolysers.

Alkaline electrolysers are a relatively advanced technology, particularly in the case of stationary hydrogen generation in an industrial environment. However, they are mainly suited to continuous operation, and have historically had issues when being operated under dynamic or discontinuous conditions, which will be necessary, for example, for coupling with dynamic energy sources such as wind or solar. Therefore, the main areas requiring improvement are operational flexibility and hot/cold start routines. The FCH 2 JU is funding projects to overcome these issues. From the targets set by the FCH 2 JU, a modest increase in terms of efficiency (expressed as the electricity consumption at nominal capacity in kWh/kg produced hydrogen) and degradation (%/1000 hrs) are expected, which reflect the already more advanced nature of this technology. In general, the more ambitious targets relate to cost reduction in terms of CAPEX and O&M (excluding electricity) costs. Further targets relate to increasing the current density and reducing the use of cobalt (alkaline electrolysers do not use precious metals).

PEM electrolysers have the advantage of operational flexibility and therefore have considerable potential for coupling with renewable energy sources such as solar and wind. PEMEL can deliver hydrogen under pressure and with high overload capability. The current issues with the technology relate to degradation and high capital cost. The FCH 2 JU targets reflect that this technology is not at such an advanced stage of development as alkaline electrolysers and therefore greater potential is observed for improving efficiency and durability. Challenging targets have been set for reduction in CAPEX and O&M costs, while specific KPIs have been set for the reduction in the amount of precious metal catalysts (e.g. platinum and iridium) which are used in these electrolysers and are a major contributor to the cost of the electrolyser stack. Further specific KPIs relating to the footprint of the stack and hot/cold start times are included.

Finally, Solid Oxide Electrolysers (or steam electrolysers), which operate at temperatures of 500-850°C, are at a much earlier stage of development. In principle, SOELs utilise the reverse process observed in a Solid Oxide Fuel Cell (SOFC) hence the KPIs include the reversible efficiency and reversible capacity, although not all

systems are designed or optimised for use in reversible mode. In general, SOEL have the advantages of high efficiency and fuel flexibility. The KPI targets provided by the FCH 2 JU reflect the stage of development of the technology and its strengths and weaknesses. Considerable reductions in cost (in terms of CAPEX and O&M costs) are required, whilst the efficiency of the technology is already very high. Material issues at high operating temperatures lead to degradation in performance (defined as production loss in %/1000 hrs) and issues with availability. Furthermore, the high temperature operation means that start up times are particularly long.

The three different sets of KPIs reflect the different advantages and specific challenges of the three technologies. In general, however, the common KPIs that provide an overview of the technologies are:

- Electricity consumption @nominal capacity kWh/kg⁸
- Capital cost (€/kW)

It should be noted, however, that the different applications for which the technologies will be suited means that they are not necessarily in direct competition with each other.

One further technology, the Proton Ceramic Electrolyser is being funded to a lesser degree, however this technology is at a lower TRL level and therefore KPIs have not been fixed by the FCH 2 JU at this stage. Two funded projects regarding this technology will be discussed later in this chapter.

Table 3: State-of-the-art and future targets for hydrogen production from renewable electricity for energy storage and grid balancing using alkaline electrolyzers.

No.	Parameter	Unit	State of the art		FCH 2 JU target		
			2012	2017	2020	2024	2030
Generic system*							
1	Electricity consumption @nominal capacity	kWh/kg	57	51	50	49	48
2	Capital cost	€/(kg/d) (€/kW)	8,000 (~3,000)	1,600 (750)	1,250 (600)	1,000 (480)	800 (400)
3	O&M cost	€/(kg/d)/yr	160	32	26	20	16
Stack							
4	Degradation	%/1000hrs	-	0.13	0.12	0.11	0.10
5	Current density	A/cm ²	0.3	0.5	0.7	0.7	0.8
6	Use of critical raw materials as catalysts	mg/W	8.9	7.3	3.4	2.1	0.7

Notes:

*Standard boundary conditions that apply to all system KPIs: input of 6kV AC power and tap water; output of hydrogen meeting ISO 14687-2 at a pressure of 30 bar. Correction factors may be applied if actual boundary conditions are different.

2) Capital cost are based on 100MW production volume for a single company and on a 10-year system lifetime running in steady state operation, whereby end of life is defined as 10% increase in energy required for production of hydrogen. Stack replacements are not included in capital cost. Cost are for installation on a pre-prepared site (fundament/building and necessary connections are available). Transformers and rectifiers are to be included in the capital cost.

3) Operation and maintenance cost averaged over the first 10 years of the system. Potential stack replacements are included in O&M cost. Electricity cost is not included in O&M cost.

⁸ This is an equivalent value to the efficiency of the electrolyser system. The Rated System Efficiency (HHV, AC) is often given as an alternative. As the theoretical minimum electrical energy input required to produce 1kg of hydrogen is 39.4 kWh/kg H₂ (assuming HHV of hydrogen) then: System efficiency = (39.4/[actual kWh/kg required])*100 Example: An electrolyser with a rated system efficiency of 78.8% (HHV, AC) corresponds to 50 kWh/kg.

- 4) Stack degradation defined as percentage efficiency loss when run at nominal capacity. For example, 0.125%/1000h results in 10% increase in energy consumption over a 10 year lifespan with 8000 operating hours per year
 6) The critical raw material considered here is cobalt. Other materials can be used as the anode or cathode catalysts for alkaline electrolyzers. 7.3 mg/W derives from a cell potential of 1.7 V and a current density of 0.5 A/cm², equivalent to 6.2 mg/cm².

Source: reproduced from [14]

Table 4: State-of-the-art and future targets for hydrogen production from renewable electricity for energy storage and grid balancing using PEM electrolyzers.

No.	Parameter	Unit	State of the art		FCH 2 JU target		
			2012	2017	2020	2024	2030
Generic system							
1	Electricity consumption @nominal capacity	kWh/kg	60	58	55	52	50
2	Capital cost	€/(kg/d) (€/kW)	8,000 (~3,000)	2,900 (1,200)	2,000 (900)	1,500 (700)	1,000 (500)
3	O&M cost	€/(kg/d)/yr	160	58	41	30	21
Specific system							
4	Hot idle ramp time ⁽²⁾	s	60	10	2	1	1
5	Cold start ramp time	s	300	120	30	10	10
6	Footprint	m ² /MW	-	120	100	80	45
Stack							
7	Degradation	%/1000hrs	0.375	0.250	0.190	0.125	0.12
8	Current density PEMEL	A/cm ²	1.7	2.0	2.2	2.4	2.5
9	Use of critical raw materials as catalysts	mg/W	-	5.0	2.7	1.25	0.4
10	Use of critical raw materials as catalysts Pt	mg/W	-	1.0	0.7	0.4	0.1

Notes:

Availability is fixed at 98% (value from the electrolysis study).

1) to 3) and 7) similar conditions as for alkaline technology (previous table)

2) The time from hot idle to nominal power production, whereby hot idle means readiness of the system for immediate ramp-up. Power consumption at hot idle as percentage of nominal power, measured at 15°C outside temperature.

3) The time from cold start from -20°C to nominal power

9) This is mainly including ruthenium and iridium as the anode catalyst and platinum as the cathode catalyst (2.0 mg/cm² at the anode and 0.5 mg/cm² at the cathode). The reduction of critical raw materials content is reported feasible reducing the catalysts at a nano-scale.

Source: reproduced from [14]

Table 5: State-of-the-art and future targets for Hydrogen production from renewable electricity for energy storage and grid balancing using high-temperature SOEL.

No.	Parameter	Unit	State of the art		FCH 2 JU target		
			2012	2017	2020	2024	2030
Generic system*							
1	Electricity consumption @rated capacity	kWh/kg	na	41	40	39	37
2	Availability	%	na	na	95%	98%	99%
3	Capital cost	€/(kg/d)	na	12,000	4,500	2,400	1,500
4	O&M cost	€/(kg/d)/yr	na	600	225	120	75
Specific system							
5	Reversible efficiency	%	na	50%	54%	57%	60%
6	Reversible capacity	%	na	20%	25%	30%	40%
Stack							
7	Production loss	%/1000hrs	na	2.8	1.9	1.2	0.5

Notes:

*Standard boundary conditions that apply to all system KPIs: input of AC power and tap water; output of hydrogen meeting ISO 14687-2 at atmospheric pressure. Correction factors may be applied if actual boundary conditions are different.

From 3) and 4) please refer to Table 3 (similar conditions as for alkaline technology)

5) Reversible efficiency is defined as the electricity generated in reversible mode of the electrolyser, divided by the lower heating value of hydrogen consumed.

6) Reversible capacity is defined as a percentage of the electric capacity in fuel cell mode in relation to the electrolyser mode

7) Degradation at thermo-neutral conditions in percent loss of production-rate (hydrogen power output) at constant efficiency. Note this is a different definition as for low temperature electrolysis, reflecting the difference in technology.

Source: reproduced from [14]

3.1.2 Electrolysis state-of-the-art

As mentioned, the three electrolyser technologies under consideration (alkaline, PEMEL, SOEL) are at different stages of their development and deployment. Commercial products are widely available for alkaline and PEMEL technologies, whilst SOEL is at a much earlier stage of development.

3.1.2.1 State of the art – alkaline electrolysers

The alkaline electrolyser is a well-established technology for hydrogen production with systems produced in the megawatt range. Advantages of the alkaline electrolyser are that it does not use noble metal catalysts and is stable over a very long lifetime (greater than 100000 hours) [15]. One significant disadvantage is a low current density caused by ohmic losses across the electrolyte and diaphragm.

A further issue is that historically the systems have shown poor dynamic behaviour, with limited load flexibility. This is because the diaphragms are not very effective at preventing cross-diffusion of gases. Oxygen crossing to the cathode leads to a lowering in efficiency (as it can be converted back to water) and safety issues, which occur to the greatest degree under low loads. These are challenges which need to be overcome for the use of alkaline electrolysers with Renewable Energy Sources (RES) such as wind or solar which has been a major focus of the relevant projects with the FCH 2 JU programme since its inception.

The electrodes of the alkaline electrolyser are immersed in an electrolyte of 25-30 wt.% KOH, in a cell typically operating at 40-90°C. They are separated by a diaphragm which allows transfer of hydroxide ions but prevents mixing of gases. The electrodes used in alkaline electrolyzers are typically highly conductive porous metal frameworks (e.g. mesh, foam etc) coated with high area catalysts [16]. These frameworks allow penetration of the liquid electrolyte to the surface of the electrocatalyst and for the gases, created at this interface with the liquid electrolyte and solid electrocatalyst (i.e. at the triple phase boundary), to be transferred from the electrode to the surroundings.

The cathode catalyst (hydrogen formation) in alkaline electrolyzers is typically a high-area nickel foam or nickel supported on stainless steel. A possible alternative is Ni-Mo on a ZrO_2 - TiO_2 support [17]. The anode catalyst (oxygen formation) is usually Ni_2CoO_4 , $La-Sr-CoO_3$ or Co_3O_4 . Current distributors are typically nickel (the electrodes are directly pressed or welded onto the bipolar plates [16]) and the main containment material is steel coated with nickel.

3.1.2.2 State of the art – PEM electrolyzers

Proton Exchange Membrane electrolyzers contain a proton-conducting but electrically insulating membrane as the electrolyte. At the anode, water is split to form oxygen and protons. These protons pass through the membrane and recombine at the cathode to form hydrogen. The catalysts used in a PEMEL are typically platinum for the cathode (hydrogen production) and an iridium/ruthenium oxide at the anode (oxygen production), both supported on carbon. The typical proton conducting membrane used is Nafion (a fluorinated polymer with sulfonic acid functional groups). The nature of these membranes, which need to be hydrated to maintain conductivity, limits the operation of the electrolyzers to a maximum temperature of typically 90°C.

The main advantages of PEMEL include the high current density that can be produced (compared to the other electrolyser technologies), high voltage efficiencies, good dynamic operation, ability to work under partial load and fast response. These factors make it the best suited technology for coupling with RES. The main drawbacks are durability (related to catalyst loss and membrane lifetime) and cost, partly due to the PGM catalysts.

The FP7 MEGASTACK project investigated the environmental impact of PEM electrolyzers. It was found that their design caused less impacts than the current 1 MW electrolyser technology, for all investigated impact categories, i.e. for global warming, abiotic depletion, acidification and eutrophication. The reduced environmental impacts could be linked to the new design that allowed for a reduction in the number of cell and stack components. However, the use of electricity during the stack operation represents the largest source of emissions leading to global warming. The project found that recycling is essential, and that the use of platinum and iridium in the catalyst layer is the main cause of the stack impacts on abiotic depletion, acidification and eutrophication.

It is not clear whether electrolyser manufacturers are sufficiently considering the environmental impact at stack design phase. In general the recyclability and reduction of the use of PGM definitely needs further efforts to improve the sustainability of electrolytic hydrogen production.

3.1.2.3 State of the art - SO electrolyzers

In the SOEL, steam is reduced to hydrogen and oxide ions at the cathode/electrolyte interface [18]. Oxide ions pass through the conducting solid electrolyte to the anode where they are oxidised to oxygen gas. SOELs have the potential to be used to produce syngas as, at these high temperatures, an SOEL fed with steam and CO_2 can produce both H_2 and CO in the cathode reaction (co-electrolysis). In general, the high temperature operation allows for increased fuel flexibility and SOEL are less susceptible to fuel impurities than low temperature electrolyzers.

SOEL materials have to be tolerant of the high temperatures required for operation. The cathode must have a porous structure, high catalytic activity, high electrical and ionic conductivities, and be compatible with the electrolyte (including similar thermal expansion). Typically a composite of Ni and yttria-stabilised zirconia (YSZ) is used. The nickel acts both as an electrocatalyst and provides electrical conductivity whilst YSZ provides ionic conductivity. Zirconia is chosen for its mechanical strength, corrosion resistance and ability to withstand high temperatures, however it can undergo phase transformation (monoclinic to tetragonal at 1373K) hence alkaline earth or rare earth metal oxides such as yttria (Y_2O_3) [19] or scandia (Sc_2O_3) are added

to provide stability. The cathode is often used as the support for a thin electrolyte layer, hence mechanical strength is important. The main alternatives to Ni-YSZ are lanthanum strontium manganese oxides (LSM) which have a perovskite structure, along with doped versions of this material. The electrolyte must have high ionic conductivity, a dense structure to prevent gas diffusion, be electrically insulating and have high mechanical strength. YSZ is also typically used as the electrolyte in SOEL [e.g. [19, 20]. Alternatives are scandia-stabilised zirconia (ScSZ) (e.g. [21, 22]), doped lanthanum gallates (LaGaO_3) (e.g. [23]) or ceria-based materials (e.g. [24, 25]). The anode (typically LSM) must show similar properties to the cathode, along with high catalytic activity for oxygen evolution. There are issues with delamination during high temperature operation, which have been attributed to differences in ionic conductivity at the interface leading to a build-up in oxygen pressure.

SOEC have the advantage that they operate at extremely high efficiency, as part of the energy requirement for splitting water can be provided by heat, reducing the required potential. They would therefore be particularly useful in industrial applications where waste heat can be used by the electrolyser stacks. Furthermore, as previously mentioned, solid oxide electrolyzers have the potential to be used for the production of syngas from steam and CO_2 . This is a possible route of utilisation of CO_2 via creation of a useful industry precursor (see section 3.3.2.4.2). Therefore, SOEC could be utilised in both fuel and chemical production. Furthermore, the H2020 project HELMETH has investigated the integration of high temperature electrolysis with methanation to demonstrate a power-to-methane route.

The potential for use in a reversible manner would also suggest an application in energy storage and grid-balancing in connection with Renewable Energy Sources (RES), however, the major drawback of SOEC is that the high temperature operation leads to long start-up times and slow response. Furthermore, whilst they are reversible in principle, and considerable research is ongoing in this area, the specific materials issues involved in the operation in SOEC or SOFC mode, means that systems are often optimised for one application or the other.

3.1.2.4 Commercial electrolyzers

In order to assess the commercial state of the art, data has been collected for a range of commercially available PEM and alkaline electrolyser systems and displayed in Figure 5. The efficiency of the system expressed as the **energy consumption** (in kWh) required to produce a kilogram of hydrogen is shown versus the size of the electrolyser system (in terms of system power).

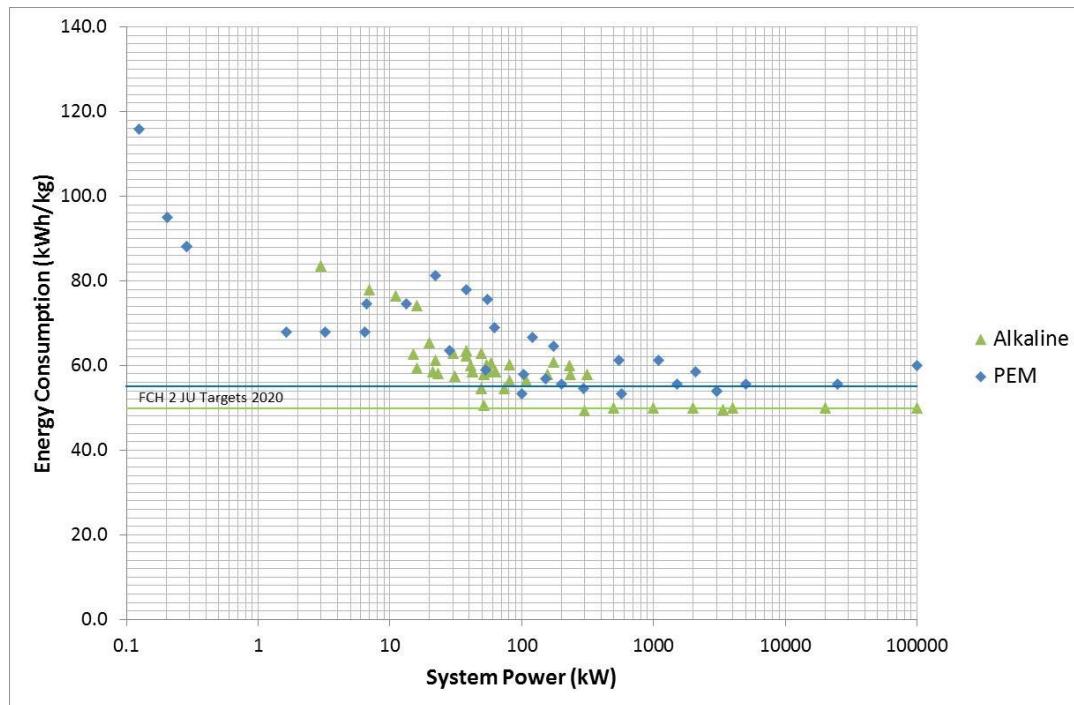
Electrolyzers are included from the following companies:

- PEMEL: Proton (Nel), ITM, Hydrogenics, Areva
- Alkaline: Pure Energy, McPhy, Hydrogenics, IHT.

In order to compare directly to the FCH 2 JU targets, it is necessary that the same boundary conditions have been applied. This is not always the case, though the larger electrolyzers on the market do produce hydrogen at approx. 30 bar pressure, which is one of the main stipulations. Smaller electrolyzers tend to operate at lower pressure.

Efficiency gains appear to be limited beyond a system size of approximately 100-300 kW. This is most likely due to the modularity of systems above a certain scale. Currently, the SoA performance by alkaline electrolyzers is ~50 kWh/kg compared to ~55 kWh/kg for PEMEL. These values correspond almost exactly to the FCH 2 JU target for 2020.

Figure 5 Energy Consumption versus System Power for a range of commercially available electrolysers



Source: JRC, 2020, compiled using publicly available data.

Information regarding **CAPEX** is more difficult to ascertain. In general, companies do not provide this information publicly or alongside product specifications.

However, one producer, Nel, state that the cost for alkaline electrolysers can currently vary from 1150 – 650 €/kW depending on plant size [26, 27]. This is fairly consistent with the SoA value provided for 2017 by the FCH 2 JU of 750 €/kW assuming a 100 MW production capacity. A thorough literature study by Proost et al [28] of future estimations of the costs of these technologies, gives an expectation for the cost per kW of 700-1000 €₂₀₁₇/kW_{HHV-Output} for alkaline electrolysers and 400-1000 €₂₀₁₇/kW_{HHV-Output} for PEM electrolysers by 2030. The fact that little improvement to the cost of alkaline electrolysers is expected is attributed to the maturity of this technology.

Solid Oxide Electrolysers are generally at the Research and Innovation stage as there are still significant materials challenges to be overcome, although there are a number of demonstration projects underway. Only a handful of companies advertise solid oxide electrolyser products for sale e.g. Sunfire (Germany) [29]; mPower (Germany) [30]; OxEon Energy (US) [31]. With the possible exception of Sunfire, it would appear these are at a relatively early commercial stage in comparison to PEM and alkaline electrolysers. Whilst the other companies focus on SOFC units, and only advertise bespoke SOEL systems to order, Sunfire have specialised in the electrolysers and provide fixed-sized units ("hydrogen generators") as products, in an analogous way to the companies that produce alkaline and PEM electrolysers. The Sunfire Hylink unit [32] is a modular unit with a rated AC power of 150 kW. It produces 40 Nm³/hr of hydrogen at a system energy consumption of 41.2 kWh/kg at nominal rated power.

3.1.3 Horizon 2020 Electrolyser Projects

A number of projects have been funded under Horizon 2020 regarding research, development and deployment of electrolyser technologies. The majority of these projects fall under the auspices of the FCH 2 JU, although there are a number of notable relevant projects funded under other calls and topics. The main electrolyser Horizon 2020 research projects are summarised in Table 6 and the funding distribution is depicted in Figure 6.

Table 6: Summary of Horizon 2020 Electrolyser Projects by technology (non-FCH 2 JU projects are shown in italics)

Technology	Acronym	Programme	Topics	Title	Period	EU Funding (€)
Alkaline	ELYNTEGRATION	H2020-EU.3.3.8.3	FCH-02.8-2014	Grid Integrated Multi Megawatt High Pressure Alkaline Electrolysers for Energy Applications	2015-2018	1.9m
	DEMO4GRID	H2020-EU.3.3.8.3	FCH-02-7-2016	Demonstration of 4MW Pressurized Alkaline Electrolyser for Grid Balancing Services	2017-2022	2.9m
	ELECTROCAT	H2020-EU.1.1	ERC-PoC-2016	<i>Novel water splitting catalysts for efficient alkaline electrolyzers</i>	2017-2018	150k
	MEMBRASENZ	<i>H2020-EU.2.1.5</i> <i>H2020-EU.2.1.3</i> <i>H2020-EU.2.3.1</i> <i>H2020-EU.2.1.2</i>	SMEInst-02-2016-2017	<i>Breakthrough of Hydrogen Energy and Hydrogen Mobility by Utilisation of MEMBRASENZ Membranes</i>	2018	50k
Alkaline / PEMEL	QUALYGRIDS	H2020-EU.3.3.8.3	FCH-02-1-2016	Standardized Qualifying tests of electrolyzers for grid services	2017-2020	2.0m
PEMEL	HYBALANCE	H2020-EU.3.3.8.3	FCH-02.10-2014	HyBalance	2015-2020	8.0m
	HPEM2GAS	H2020-EU.3.3.8.2	FCH-02.2-2015	High Performance PEM Electrolyser for Cost-effective Grid Balancing Applications	2016-2019	2.5m
	BIG HIT	H2020-EU.3.3.3.2	FCH-03.2-2015	Building Innovative Green Hydrogen systems in an Isolated Territory: a pilot for Europe	2016-2021	5.0m
	ELY4OFF	H2020-EU.3.3.8.2	FCH-02.1-2015	PEM ElectroLYsers FOR operation with OFFgrid renewable installations	2016-2019	2.3m
	H2FUTURE	H2020-EU.3.3.8.3	FCH-02-7-2016	Hydrogen meeting future needs of low carbon manufacturing value chains	2017-2021	12.0m
	HAEOLUS	H2020-EU.3.3.8.2 H2020-EU.3.3.8.3	FCH-02-4-2017	Hydrogen-aeolic energy with optimised electrolyzers upstream of substation	2018-2021	5.0m
	PRETZEL	H2020-EU.3.3.8.2 H2020-EU.3.3.8.1	FCH-02-1-2017	Novel modular stack design for high pressure PEM water electrolyzer technology with wide operation range and reduced cost	2018-2020	2.0m
	NEPTUNE	H2020-EU.3.3.8.2 H2020-EU.3.3.8.1	FCH-02-1-2017	Next Generation PEM Electrolyser under New Extremes	2018-2021	1.9m
	REFHYNE	H2020-EU.3.3.8.2 H2020-EU.3.3.8.3	FCH-02-5-2017	Clean Refinery Hydrogen for Europe	2018-2022	10.0m
	CRITCAT	H2020-EU.2.1.3	NMP-23-2015	<i>Towards Replacement of Critical Catalyst Materials by Improved Nanoparticle Control and Rational Design</i>	2016-2019	4.4m
	CREATE	H2020-EU.2.1.3	NMBP-03-2016	<i>Critical Raw materials Elimination by a top-down Approach To hydrogen and Electricity generation</i>	2017-2020	4.3m
SOEL	HYLYZER	<i>H2020-EU.3</i> <i>H2020-EU.2.3</i> <i>H2020-EU.2.1</i>	<i>EIC-SMEInst-2018-2020</i>	<i>Industrial electrolyser for large-scale on-site renewable hydrogen production for manufacturing industry</i>	2018	50k
	THIN CATALYZER	H2020-EU.1.3.2	MSCA-IF-2018	<i>Nanostructured anode catalyst layer for oxygen evolution reaction based on a novel thin-film architecture</i>	2020-2022	150k
	SELYSOS	H2020-EU.3.3.8.2	FCH-02.1-2014	Development of new electrode materials and understanding of degradation mechanisms on Solid Oxide High Temperature Electrolysis Cells.	2015-2019	2.9m
	ECO	H2020-EU.3.3.8.2	FCH-02.3-2015	Efficient Co-Electrolyser for Efficient Renewable Energy Storage - ECo	2016-2019	2.5m

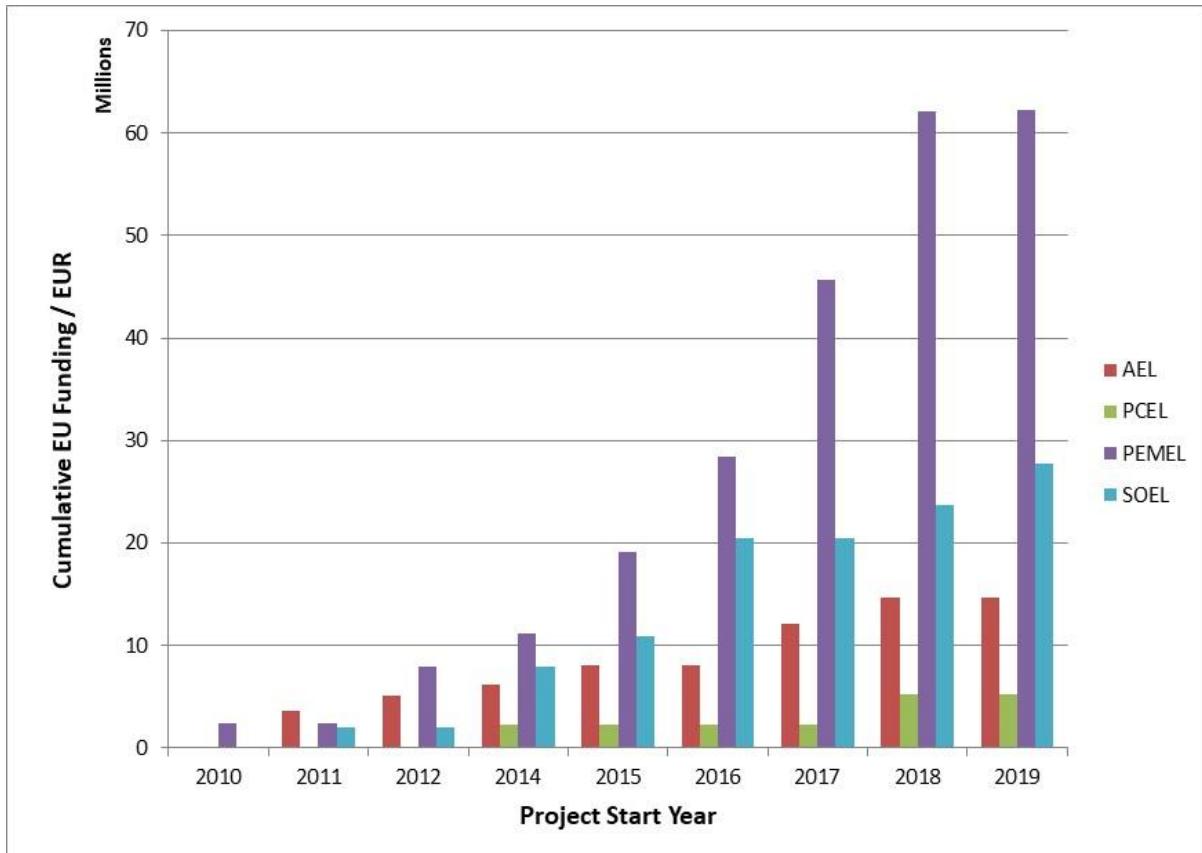
Technology	Acronym	Programme	Topics	Title	Period	EU Funding (€)
	GRINHY	H2020-EU.3.3.8.2	FCH-02.4-2015	Green Industrial Hydrogen via Reversible High-Temperature Electrolysis	2016-2019	4.5m
	REFLEX	H2020-EU.3.3.8.2 H2020-EU.3.3.8.1	FCH-02-3-2017	Reversible solid oxide Electrolyzer and Fuel cell for optimized Local Energy miX	2018-2020	3.0m
	GRINHY 2.0	H2020-EU.3.3.8.2	FCH-02-2-2018	Green Industrial Hydrogen via steam electrolysis	2019-2022	4.0m
	AD ASTRA	H2020-EU.3.3.8.1	FCH-04-3-2018	HAremessing Degradation mechanisms to prescribe Accelerated Stress Tests for the Realization of SOC lifetime prediction Algorithms	2019-2021	3.0m
	BALANCE	H2020-EU.3.3.5 H2020-EU.3.3.2 H2020-EU.3.3.3 H2020-EU.3.3.4	LCE-33-2016	<i>Increasing penetration of renewable power, alternative fuels and grid flexibility by cross-vector electrochemical processes</i>	2016-2019	2.5m
	DOLORES	H2020-EU.1.3.2	MSCA-IF-2015-EF	<i>Degradation of Lifetime of fuel cell Resistance by Electrochemical impedance Spectroscopy</i>	2016-2018	183k
	3D-POWER	H2020-EU.1.3.2	MSCA-IF-2016	<i>Three-Dimensional Perovskite Oxides as Working ElectRochemical devices</i>	2017-2019	195k
	SEARCH	H2020-MSCA-IF-2017	MSCA-IF-2017	<i>SurfaCE structure-Activity-Relationship in atomically-defined, ultrathin film perovskite Catalysts</i>	2018-2020	214k
Other	GAMER	H2020-EU.3.3.8.2	FCH-02-2-2017	Game changer in high temperature steam electrolyzers with novel tubular cells and stacks geometry for pressurized hydrogen production	2018-2020	3.0m
	HYMEFC ECS	H2020-EU.1.1	ERC-PoC-2016	<i>Hydrogen production by membrane free chemical - electrochemical systems</i>	2017-2018	150k

Source: JRC, 2020, compiled using publicly available data.

FCH 2 JU has distributed EU funds for projects related to fuel cells and hydrogen, first under Framework Program 7 (FP7) from 2008-2013 and under the Horizon 2020 Program (H2020) from 2014 onwards.

Within the FCH 2 JU, projects are classified under Energy, Transport and Cross-cutting pillars. The majority of projects relating to electrolyzers are classified under the Energy pillar, which includes hydrogen production. Additionally, a number of demonstration projects utilising commercial electrolyzers at Hydrogen Refueling Stations are present in the Transport pillar, however these will not be discussed here as they are not seeking to advance the SoA, but to deploy existing technology. In Figure 6 the cumulative level of EU funding contributed towards projects related to the different electrolyser technologies is shown, specifically for those projects developing electrolyser technologies (this includes all projects listed in Table 6, not just the FCH 2 JU projects). It can be seen that the most funding has been applied to PEM electrolyzers whilst lower rates of funding have been directed at alkaline and solid oxide electrolyzers. A smaller amount of funding has also been provided for two projects regarding Proton Ceramic Electrolyzers (PCEL), a novel high temperature electrolyser for which KPIs have not yet been fixed.

Figure 6: Cumulative level of EU contribution versus project start year for different electrolyser technologies



Source: JRC, compiled using publicly available data

Below is a short discussion of the projects per technology, showing how the Horizon 2020 programme is addressing the KPIs outlined in Section 3.1.1. Some earlier projects from FP7 are also mentioned in the case of the FCH 2 JU as many of the Horizon 2020 FCH 2 JU projects have built on expertise developed in these earlier projects. This is therefore useful in showing how the programme has progressed from Research and Development projects to more large-scale demonstration and deployment.

The specific performances achieved by the projects are often confidential for commercial reasons, but where public statements have been made on the achievements, specific mention will be given. In particular, the most recent public report of the FCH 2 JU Programme Review (2017) [33] published in November 2018 will be used to provide relevant numbers for the projects funded under that programme, although ongoing projects may have progressed beyond the levels provided.

3.1.3.1 Alkaline electrolyser projects

For this technology, the main focus of the FCH 2 JU has been to develop alkaline electrolyzers for the production of hydrogen from renewable electricity, for energy storage and grid balancing activities. This addresses the limitations of the earlier commercial technologies stated above. Over time, a clear transition from research to demonstration projects has been observed [33].

The FP7 projects RESELYSER and ELYGRID focussed on developing more efficient, lower-cost, high pressure alkaline electrolyzers. RESELYSER involved the development of novel separators and catalyst materials, whilst ELYGRID focussed on cell improvements, power electronics and balance of plant.

Following directly on from ELYGRID, the Horizon 2020 ELYNTEGRATION project targeted the design and engineering of a robust, flexible, efficient and cost-competitive, multi-MW system, capable of dealing with dynamic electric supplies from high renewable share sources. This concluded with the demonstration of a high

pressure electrolyser for grid integration at the scale of 250 kW. ELYNTEGRATION is currently being followed up by the DEMO4GRID project which aims to realise the commercial setup and demonstration of a 4 MW electrolyser system in Austria with a targeted system efficiency of 52 kWh/kg H₂, for grid balancing from renewable energy sources.

A further FCH 2 JU project is providing more general support for the development of both alkaline and PEM technologies. QUALYGRIDS (currently still ongoing) is developing standardised tests for both alkaline and PEM electrolysers integrated into the grid.

According to the publicly reported figures in the FCH 2 JU Programme Review of 2017, the alkaline research projects have shown progress in addressing the minimum operating load capabilities through the use of innovative materials. It also states that ELYNTEGRATION aims to significantly improve CAPEX to 1300 €/(kg/d) (at the time of the 2017 report, CAPEX was stated as 2200 €/(kg/d)) and electricity consumption was at 48 kWh/kg; this compares to the 2020 targets of 1250 €/(kg/d) for CAPEX and 50 kWh/kg electricity consumption for the system).

Two non-FCH 2 JU projects have been identified in the area of alkaline electrolysers. MEMBRASENZ is an SME Phase 1 project which is performing the assessment of an advanced separator material for alkaline electrolysers. The prototype membrane (at TRL7) surpasses the performance of the state of the art membranes on the market and could therefore lead to increased electrolyser efficiency and a reduction in H₂ price. It has higher ionic conductivity, mechanical and thermal resistivity. This project has received €50k of funding to perform an assessment of the scale-up of the membrane in industrial conditions, a market and IP strategy and a wider business plan.

ELECTROCAT developed novel water splitting catalysts for alkaline electrolysers, with the aim to develop several categories of electrocatalysts with higher energy efficiencies and greater stability than the incumbent technology, at a similar cost.

3.1.3.2 PEM electrolyser projects

As for alkaline electrolysers, early FCH 2 JU projects under FP7 largely focussed on improvements in PEM electrolyser KPIs at the level of the stack. PRIMOLYZER targeted the efficiency, current density, durability and cost of the electrolyser stack through the development of novel catalyst and membrane materials and through operation at higher pressures (100 bar). NEXPEL also looked at catalysts and membranes in order to replace the most expensive materials, whilst targeting a stack efficiency in excess of 75% (LHV). NEXPEL was built on in the follow-up project NOVEL where a 1 kW laboratory-scale system was built using the materials previously developed, with a target of 70% system efficiency (LHV). Again, the major focus was on the reduction in cost of key components (catalysts, bipolar plates) and an increase in durability. A further early project, ELECTROHYPEM, had a similar focus, performing research into novel catalyst/support combinations, alternative membranes and ultimately incorporating them into a prototype stack capable of operation over a wide pressure and temperature range. In more recent projects, the focus has changed from low TRL research and innovation to applications of PEM electrolyser technologies at a larger scale. The first of these, MEGASTACK, which was still funded under FP7, focussed on the design of a large capacity electrolyser (3-4 MW), in order to provide sufficient capacity for HRS, Power-to-Hydrogen and grid-balancing applications.

Under Horizon 2020, HPEM2GAS has been developing a low cost PEM electrolyser for grid management on the scale of 180-300 kW, including balance of plant and an improved stack design. The project targeted a 3-fold increase in current density whilst maintaining competitive efficiency and seeking to minimise costs. HYBALANCE has been set up in Denmark to demonstrate the feasibility of central large-scale electrolysers to provide grid services, coupled with hydrogen supply for mobility and industry. Similarly, BIG HIT will utilise a 1.5 MW PEM electrolyser as part of a hydrogen territory in Scotland, utilising energy from wind and tidal turbines to produce hydrogen to heat local schools, power a local harbour and supply an HRS for fuel cell vehicles. The HAEOLUS project will install a 2 MW electrolyser at a remote wind farm in Norway which will be operated under energy storage mini-grid and fuel production configurations and designed for flexibility and remote operation. The H2FUTURE project will perform a 26 month demonstration of a 6MW PEM electrolysis plant in Austria to provide grid-balancing services under quasi-commercial operation. The REFHYNE project will install a 10 MW PEM electrolyser to supply hydrogen to the hydrogen pipeline system at a German refinery. The electrolyser will need to be highly responsive to follow the demands of the plant. It will be the largest PEM electrolyser in the world and will be designed as a building block for 100 MW electrolysers.

An additional project, ELY4OFF, is developing an autonomous off-grid electrolysis system linked to RES. This will include the communication and control system for optimising efficiency when integrated in a real installation.

Whilst these recent projects will go a long way to demonstrating PEM electrolyzers in a range of real-world scenarios at high TRL levels, a recent FCH 2 JU call has asked for more fundamental research and innovation on "game-changer" electrolyzers. This would suggest that the large facilities being developed are still having issues achieving the KPIs of cost, efficiency, lifetime and operability. With this in mind, the project PRETZEL will develop a 25 kW electrolyser, based on a patented technology which will allow it to operate at a pressure difference of 100 bar, and which should lead to current densities of 4-6 A cm⁻² (considerably in excess of the KPI target for the FCH 2 JU in 2030) and an overall system efficiency of 70% (HHV). Costs are also targeted by the use of non-precious metal cell coatings and novel catalyst supports. A second new project, NEPTUNE, will also seek to reduce costs at the cell, stack and system level. The project will also target the current density KPI with a value of 4 A cm⁻², while maintaining the nominal energy consumption.

According to the publicly reported figures in the Programme Review Report 2017, these projects have reported costs from 4000 €/(kg/d) (HYBALANCE, 500 kg/day). The project ELY4OFF aims to achieve 6000 €/(kg/d) (24 kg/d). HYBALANCE has also shown that for systems greater than 3 MW (> 1200 kg/d), a CAPEX of 2300 €/(kg/d) is achievable. When looking specifically at MW-sized stacks, the FP7 project MEGASTACK shows that a CAPEX of 1200 €/(kg/d) can be reached. This would improve on the 2020 target for PEM electrolyzers of 2000 €/(kg/d) provided in the MAWP. Recently, the ELY4OFF project significantly reduced their estimate to 800 €/(kg/d) for a 100 MW annual production scale [34].

The electrolyzers in HYBALANCE and ELY4OFF are expected to reach an energy consumption of 54 and 50 kWh/kg respectively. MEGASTACK has achieved 50 kWh/kg at stack level with a current density of 0.7 A/cm² and a degradation rate of 0.12% / 1000h [34]. HPEM2GAS aims to achieve 48 kWh/kg at system level (and has achieved this at cell and short stack level [34]). For comparison the 2020 target is 55 kWh/kg at system level, suggesting good progress towards this KPI.

One further achievement against the MAWP targets is that H2FUTURE has achieved a footprint of 10 m²/MW [34] which is an order of magnitude better than the target for 2020 and also better than the 2030 target. Furthermore, HYBALANCE has achieved a footprint of 45 m²/MW [34].

Several non-FCH 2 JU projects are also contributing in this technology area. HYLYZER was an SME Phase 1 Feasibility Study performed by Hydrogenics. They have developed HyLYZER [35], a PEM electrolyser technology for producing on-site high purity hydrogen with zero-emissions from renewable energy sources at an average stack efficiency of 85% (HHV). The feasibility study was performed to plan the commercial strategy and industrial scale-up of the product from a demo plant to a viable commercial product. The market analysis demonstrated that the market size and growth of the green hydrogen industry justified the planned investment. The patent study concluded that the product was well protected whilst sales of 622.3 M€ were predicted from 2021-2025, with a payoff period of only 2 years.

CREATE (funded under H2020-EU.2.1.3. - INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies - Advanced materials) is a research and innovation action receiving more than €4.3m aiming to develop innovative MEAs for low temperature PEMFC and PEMEL with reduced costs due to elimination of critical raw materials (platinum group metals). The approach of the research is to move towards anion conducting polymer electrolytes and bipolar membrane electrolytes which allow for adapting the pH at each electrode and providing opportunity for the use of non-PGM catalysts (or catalysts with a considerable reduction in PGM content). PEMFC and PEMEL produced using these materials will be evaluated for targeted applications, i.e. photovoltaic electricity storage, off-grid back-up power and hydrogen production. The target is to reduce, by a factor of 5, the amount of PGM being used versus the state of the art, which would achieve the 2024 target of the FCH 2 JU. This project is still ongoing and will conclude in June 2020.

Two additional projects, CRITCAT (funded under H2020-EU.2.1.3. - INDUSTRIAL LEADERSHIP - Leadership in enabling and industrial technologies - Advanced materials) and THIN CATALYZER (funded under H2020-EU.1.3.2. - Nurturing excellence by means of cross-border and cross-sector mobility), have both been funded to address the issue of expensive PGMs. CRITCAT was funded to look at the properties of ultra-small transition metal nanoparticles for a number of industrially relevant processes, including energy conversion technologies. THIN CATALYZER is a recently funded project that will look specifically at materials for the anode reaction of PEM electrolyzers (oxygen evolution reaction) produced via pulsed laser deposition (PLD) in order to form an ultra-thin catalyst layer.

3.1.3.3 SO electrolyser projects

For Solid Oxide Electrolyzers (SOEL), where the technology is at an earlier stage of development, the projects funded by the FCH 2 JU have on the whole been at a lower TRL level than those projects funded for alkaline and PEM electrolyzers.

Under FP7, The project ADEL aimed to optimise the electrolyser lifetime by operating at lower temperatures. It also targeted high energy efficiency at the level of the complete system including the heat and power source and the electrolyser unit. In a press release by SOLIDPower as a follow-up to the project [36], it was stated that the SOEL had been operated for over 6000 hours at 700°C and a current density of 0.5 A/cm² with no significant degradation. The project SOPHIA was set up to design a 3 kW pressurised system coupled to a solar energy source. The concept of co-electrolysis (of steam and CO₂) was also addressed along with LCA and a techno-economic assessment to investigate different PtX scenarios. HELMETH aimed to integrate high temperature electrolysis with methanation to demonstrate a route with synthetic methane as the energy storage medium (see also Section 4.3).

Of the currently ongoing Horizon 2020 projects, SELYSOS and ECO are focussed on the degradation issues which limit the lifetime of the SOEL and aim at reducing the temperature of operation, specifically through developing and testing novel electrode and electrolyte materials. SELYSOS is mainly focussed on steam electrolysis whilst ECO is mainly directed at co-electrolysis.

More recent projects are attempting to develop the scale of the technology for demonstration purposes. GRINHY has been working on developing a 120 kW stack with a lifetime of 10000 hours and a production loss of <1% which would achieve the FCH 2 JU target for 2024. They are also looking to achieve efficiency in excess of 80% (LHV) and aim to provide hydrogen at the purity required for annealing processes in the steel industry, for more than 7000 hours of operation. A follow-up project, GRINHY 2.0, will integrate a 720 kW SOEL into an iron and steel works, whilst achieving an improved efficiency of up to 84% (LHV) and aims to operate for 13000 hours with an availability of 95% (achieving the FCH 2 JU 2020 target).

A further project in this area, which has recently begun, is REFLEX, which is aiming to develop a smart energy hub based on reversible solid oxide technology, including a field demonstration involving linking with solar and mini-hydro renewable energy sources.

Finally, the recently funded AD ASTRA project will define accelerated stress testing (AST) protocols through a systematic understanding of degradation mechanisms of aged components in solid oxide cells (relevant to both fuel cell and electrolyser modes) building on information obtained from a number of previous FCH 2 JU projects. AST protocols will be defined and validated, making the link between accelerated testing and real world scenarios.

The PRD Report 2017 refers to the progress being made with regards to degradation rates. For SOELs this is defined as production loss, and a target of 1.9%/1000 hrs is given for 2020 in the MAWP. The achievements stated range from 0.43%/1000h (HELMETH, steam electrolysis, short stack, 320 hour test) to 4.5%/1000h (SOPHIA, co-electrolysis, short stack, > 1500 hour test). The GRINHY project aims at a 1%/1000h degradation rate (and in a recent update has stated that they have achieved 0.8%/1000 hours at constant temperature in electrolysis mode at 0.5 A/cm² compared to thermo-neutral voltage [34]). The PRD report 2017 states that, in general, long term testing at system level and under realistic operating conditions is still required to confirm the lifetime targets. It also states that degradation rates should be observed in combination with the operating current density, whereas milder operating current densities are generally selected as nominal operating current density or as current density in long-term tests. It was, however, also recently reported that the ECO project had demonstrated an electrolyser stack with an electrical efficiency degradation rate of only 0.05%/1000 hrs [34].

At PRD 2018, the GRINHY project also made a cost projection of 1500 €/(kg/d) for production on the 100 MW scale and furthermore reported that a consumption of 42.7 kWh/kg has been achieved (against the 2020 target of 40 kWh/kg). HELMETH has demonstrated a stack electricity consumption of 35.5 kWh/kg.

Several additional non-FCH 2 JU projects relevant to this field have been funded under Horizon 2020. DOLORES was a Marie Curie Fellowship at the University of Sheffield focussing on the degradation rate of Solid Oxide Cells (SOC) primarily for application in SOFC but with additional relevance to SOEL. The high rate of degradation (1.5–2%/1000 hours) hinders the take-up of the technology hence this project investigated the processes occurring at the interface between the yttria-stabilised zirconia (YSZ) electrolyte and the lanthanum

strontium manganite cathode as a new degradation mechanism was recently identified at the host institution. The main technique applied in this project was Impedance Spectroscopy to investigate the electronic and ionic conductivity of the materials. This has identified entirely new short-range dielectric processes occurring in YSZ under an applied DC voltage [37].

BALANCE is a Research and Innovation Action (RIA) funded, under multiple programmes, in excess of €2.5m that began in December 2016 and will run until November 2019. Its aim is to gather leading SOEL and SOFC research centres in Europe into a collaboration for the acceleration of the development of reversible solid oxide cell technologies (ReSOC). The first step is to identify, quantify and analyse national research activities into ReSOC and then to develop an integrated research agenda. From the technical side, the project aims to develop the next generation of ReSOC cells, integrate them in stack assemblies and determine the constraints of using reversible operation at system level and on integrating the technology with the grid. Research into manufacturability, modelling at multiple levels and techno-economic assessments are also included. The aim is to achieve 50% efficiency in fuel cell mode and 90% efficiency in electrolyser mode, and to demonstrate the technology at system level including all relevant Balance of Plant (BoP). Although the project is not complete, the production loss value reported in an early project deliverable for the SOEL single cell was 3.5-7%/1000hrs which is still considerably higher than the 2020 target of 1.9%/1000hrs [38].

The project 3D-POWER (funded under the programme H2020-EU.1.3.2. - Nurturing excellence by means of cross-border and cross-sector mobility) focuses on material properties of perovskite oxides combined with functional metallic materials to develop 3D structures for a range of electrochemical devices, including electrolyzers.

Finally, in the project SEARCH (also funded under the programme H2020-EU.1.3.2. - Nurturing excellence by means of cross-border and cross-sector mobility), epitaxial, atomically defined Ni-Fe-based perovskite thin film catalysts will be investigated with advanced operando characterization tools, to develop and exploit these materials. The overall aim of the project is to aid the market penetration of commercial electrolyzers by developing high-activity, stable, inexpensive and earth-abundant catalytic materials.

3.1.3.4 Other projects

As previously mentioned, two projects have been funded in the course of the FCH 2 JU regarding proton ceramic electrolyzers (PCEL). PCELs potentially have the advantage of being able to produce pure dry pressurised hydrogen at the maximum pressure of the electrolyser, unlike other electrolyser technologies.

ELECTRA was a FP7 project which developed tubular PCEL cells and a kW-size multi-tubular module operating at 700°C for production of hydrogen from steam at up to 20 bar pressure. Tubular designs can handle pressure, sealing and lifetime issues better than planar cells. The ongoing Horizon 2020 project GAMER is continuing this work. The PCEL stack will be integrated in a steam electrolyser system thermally coupled to renewable or waste heat sources in industrial plants. The project aims to establish high volume production of the tubular cells and incorporate them in a 10kW system delivering pure, dry hydrogen at 30 bar pressure, progressing the technology from TRL 3 to TRL 5.

One final project, which does not really fall under any other class is HYMEFCECS. This is a project looking at a novel way to produce hydrogen via a European Research Council Proof of Concept grant of €150k. The project has developed a method to produce hydrogen from water without electrochemical oxygen production, and without a membrane, in two phases (i) electrochemical hydrogen production (ii) spontaneous chemical oxygen production. They claim that this leads to a higher efficiency. The fact that there is no risk of mixing hydrogen and oxygen removes the need for a membrane allowing higher pressure use and improving system reliability. The project's aim is to further develop their laboratory prototype for applications in (i) power to hydrogen storage of renewable energy (ii) on-site hydrogen production for HRS; plus to develop a business plan for implementation.

3.1.4 Connecting Europe Facility Power to Hydrogen project

Sector coupling/sectoral integration, along with smart grids, is intended to contribute to the creation of a fully integrated internal market. Therefore, the European Commission launched for the first time in 2016 the

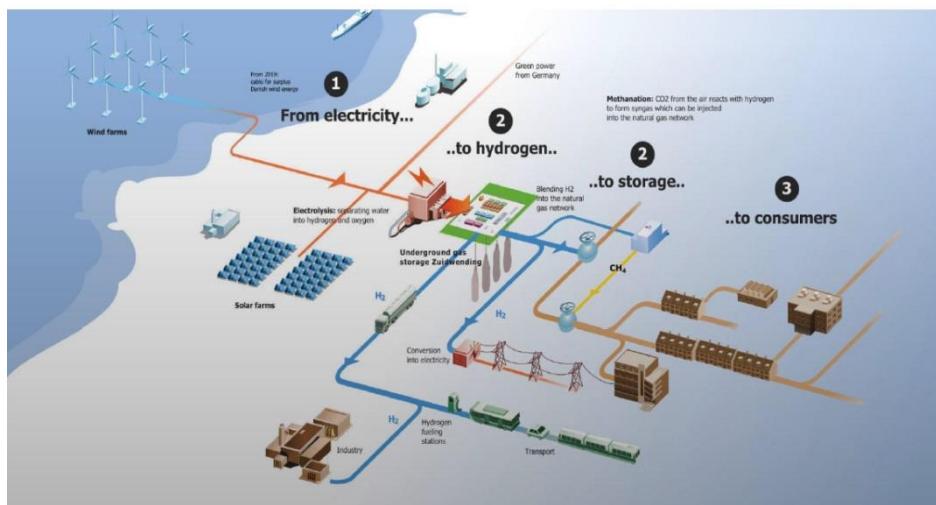
Connecting Europe Facility (CEF) Synergy call for proposals [39] in the transport and energy sectors, with enabling and strengthening the synergies between the three CEF sectors among its key priorities. CEF Synergy calls for proposal are meant to support these synergies, in particular in areas such as smart energy grids, electric mobility, intelligent and sustainable transport systems and joint rights of way of infrastructure coupling.

Within the projects selected from the first call of 2016, one falls within the scope of this report. TSO 2020: Electric "Transmission and Storage Options" along TEN-E and TEN-T corridors for 2020 has a total budget of €11,772,833 with an EU contribution of €7,063,700 (60 %) [40]. This Action contributes to the implementation of the TEN-E Project of Common Interest (PCI) 1.5 Interconnection between Endrup (DK) and Eemshaven (NL) (known as COBRA cable) and of the TEN-T core networks on the North Sea-Baltic and Rhine-Alpine corridors.

The main objective of the project (see Figure 7) is to demonstrate the technical and commercial viability of power to hydrogen solutions in the context of the Groningen region (NL), and second, to assess the replicability of the solutions to other regions. These solutions are intended to simultaneously balance the intermittent power input from the COBRA cable and to develop the use of hydrogen for transport applications along the TEN-T corridors.

Figure 7: CEF Synergy: TSO 2020

● CEF Synergy :TSO2020 – A milestone for European deployment of innovation (2)



Source: [40]

Upon completion of the Action, the deployment of grid management solutions to facilitate the implementation of the COBRA cable is planned, together with establishing a hydrogen production and distribution network in Groningen and neighbouring regions connected to the TEN-T network.

3.2 Hydrogen Distribution and Storage

Hydrogen distribution and storage technologies have been the focus of only a few H2020 projects, therefore the SoA and KPI assessment is kept brief. The topics covered in this section are hydrogen admixture with natural gas, hydrogen separation, hydrogen grid distribution, large scale hydrogen storage and hydrogen carriers.

Hydrogen admixture into the natural gas grid belongs to the power-to-gas (PtG) concept [41] and is addressed in Section 3.2.1. The main issues concerning downstream separation of hydrogen from a mixture with natural gas (H2NG) are described in Section 3.2.2.

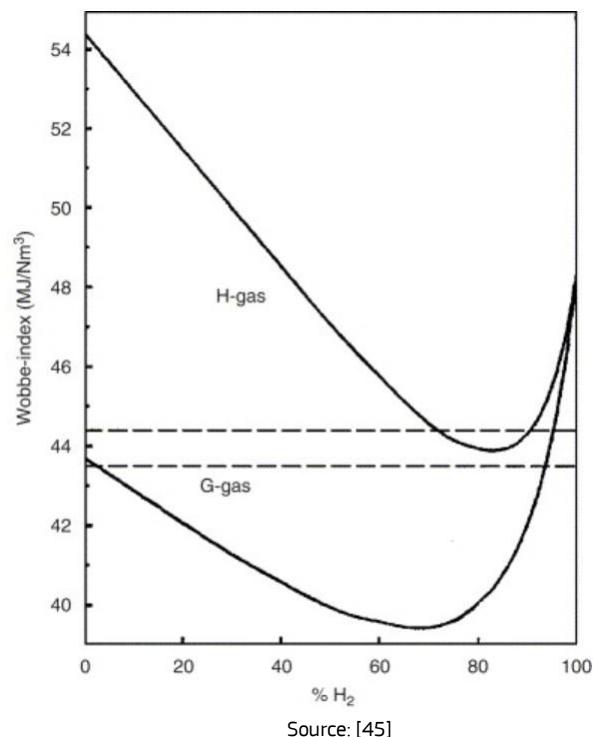
The hydrogen grid distribution and large scale storage are addressed respectively in Section 3.2.3 and 3.2.4. Finally the topic of Liquid Organic Hydrogen Carriers (LOHC) is described in Section 3.2.5 Hydrogen carriers.

3.2.1 Hydrogen admixture into natural gas grids

Hydrogen and methane (produced via the methanation process) admixture into the natural gas grid is commonly considered as part of the power-to-gas (PtG) concept, potentially enabling the coupling of the electricity and gas sectors through the conversion of electricity to another energy carrier [41]. Hydrogen produced using an electrolyser can be introduced into the natural gas grid and then used as a blend or re-separated for further use. For the downstream separation of hydrogen please see Section 3.2.2.

The concept of hydrogen admixture is argued to enable CO₂ emissions reduction for the gas sector and to utilize the storage capacity of the existing gas infrastructure. Estimates indicate almost 3 million kilometres (km) of natural gas transmission pipelines around the world and almost 400 billion cubic meters (bcm) of underground gas storage capacity [42]. In Europe, in December 2018, there were about 225,000 km of transmission pipelines and 235⁹ underground gas storage sites with 187¹⁰ bcm of capacity [43, 44].

Figure 8 The impact of the addition of hydrogen to H-gas and G-gas¹¹ on the Wobbe index. Dotted lines represent the Wobbe index range of G-gas, which has been adopted for gas appliances on the Dutch market.



It should be noted that hydrogen changes the properties of the natural gas, for example as shown in Figure 8, and based on EASEE-gas Common Business Practice 2005-001/01¹² it is treated as an impurity. With increasing hydrogen concentrations the methane number, the Wobbe index and the ignition delay are all reduced, while the gross calorific value (GCV) is changed¹³ and the flame propagation speed is increased. As GCV and Wobbe index are at the base of current billing practices, the admixture of hydrogen influences the price of the natural gas. Generally, the metering devices commonly used are not affected by hydrogen concentrations below 10 vol% [46].

⁹ 205 belonging to EU28 and 30 non-EU28 (where EU28 means Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and UK, status December 2018)

¹⁰ 134 bcm for EU28 and 54 bcm non-EU28 (status December 2018)

¹¹ H- and G- gas refer to high calorific and low-calorific (Groningen) natural gas qualities, respectively, according to EN 437.

¹² Common Business Practices (CBPs) are standards, procedures and/or protocols commonly used throughout the gas industry in Europe and which are recommended by EASEE-gas for adoption by all relevant industry players to simplify and streamline business processes across the whole of Europe.

¹³ The calorific value of hydrogen per mass unit is higher than of natural gas, and lower per unit of volume. In addition, the lower viscosity and density causes a slower flow of fuel into the combustion chamber than in the case of natural gas. As a result, modifications of the fuel delivery systems to the combustion chamber may be required to maintain the desired combustion conditions.

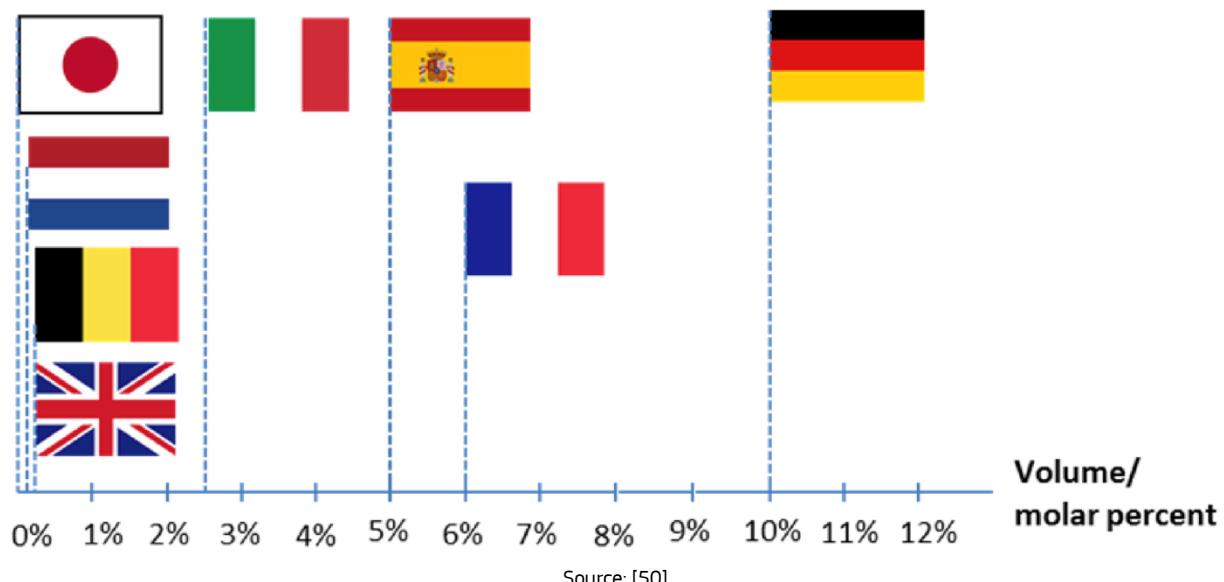
Hydrogen leak detection is an issue to consider when using natural gas infrastructure for hydrogen blended with natural gas. Most gas detectors are configured to detect the presence of methane in the air. The addition of hydrogen to natural gas may cause inaccurate device operation (i.e. no reaction after exceeding the gas concentration limit in the air). With up to 10 vol% admixture of hydrogen, the effect on the functionality of the detectors is, however, marginal and can be compensated by the recalibration of devices [47].

The effects of hydrogen admixture on the components of the gas grid and on end-users are outside the scope of this report, but it is worth mentioning that its impact encompasses the following three areas: existing gas infrastructure (transmission and distribution grids, compressor stations etc.), underground gas storage and end-use applications [48]. In the context of standardisation it seems difficult to specify a generic technical limit for admixture of hydrogen which would be valid across the whole value chain and across Europe, since any limit would have to be defined by the most sensitive end use application [49]. There are also difficulties in determining the costs of increasing hydrogen concentration in the EU gas grid, which are different for transmission and distribution grids, underground storage facilities, as well as for end-user appliances. Therefore issues to be taken into account while determining the potential of natural gas infrastructure use for energy storage vary across the value chain, because of technical differences of the infrastructure and appliances involved.

Within the broader context of CEST, the capacity of the transmission grid and underground gas storages could be considered as a means for large scale bulk energy storage.

The legal limits for hydrogen concentration in natural gas for some countries are presented in Figure 9.

Figure 9 Legal limits to admixture



The German centre for technical and scientific know-how in the gas and water sectors (DVGW) has a goal to adjust the German standards to 20 vol.% hydrogen admixture in the gas network [51], and in Britain there are health and safety rules for blending of up to 20% hydrogen, as will be investigated within the HYDEPLOY project.

The natural gas pipelines constructed with support of the structural funds along the TEN-E corridors under the 2014-2020 Multiannual Financial Framework have to comply with the TEN-E Regulation¹⁴. In principal this infrastructure has to present at least one of the qualities of the smart gas infrastructure¹⁵. The documents do

¹⁴ Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for trans-European energy infrastructure and repealing Decision No 1364/2006/EC and amending Regulations (EC) No 713/2009, (EC) No 714/2009 and (EC) No 715/2009. See also Guidance on Ex-ante Conditionalities, section A.7.4 Smart energy distribution, storage and transmission systems.

¹⁵ Characteristics such as supporting integration of generation from non-conventional sources (RES), integration of gas power plants in the electrical grids, or enhancing the flexibility of the gas networks.

not mention hydrogen explicitly, but references to hydrogen-readiness of pipelines were referred in justifications, as recommended by EU Commission Task Force for Smart Grids¹⁶.

It should be noted that, according to Directive 2009/73/EC of the European Parliament and of the Council concerning common rules for the internal market in natural gas, a Transmission System Operator must ensure non-discriminatory access to the transmission network for all market participants, which also includes the acceptance of non-conventional gases such as hydrogen, within the currently available standardised gas quality parameters.

3.2.1.1 Hydrogen admixture KPIs

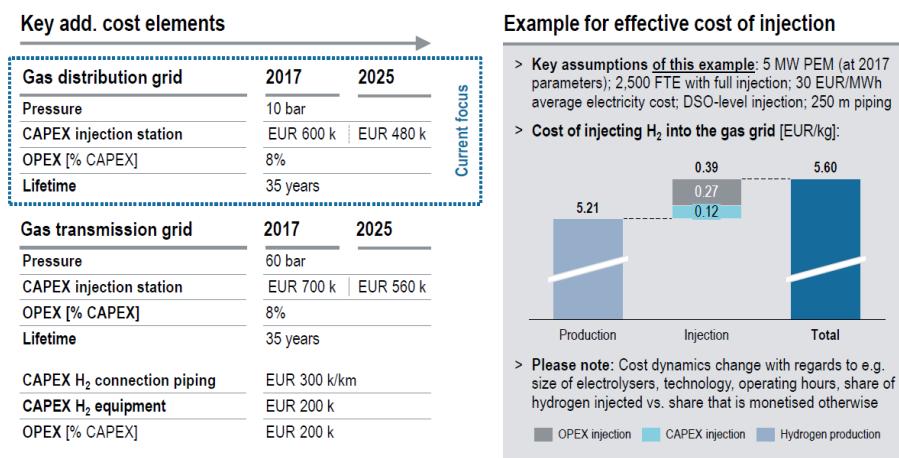
A hydrogen injection or admixture installation, (another often used name is PtG installation) consists of several separate components, typically an electrolyser, a gas mixing station/ hydrogen injection station, hydrogen tank, compressor, as well as control and measurement apparatus. The hydrogen admixture KPIs can be related to the main technology, the **electrolyser** (see Section 3.1.1). The energy efficiency of the whole installation should also be considered, as all the components will have an energy demand.

FCH 2 JU does not provide tabularised state-of-the art and future targets for hydrogen admixture into the natural gas grid. In any case, the process of admixture does not require development of any novel components or technologies. All necessary components are commercially available and might at most require some adjustments. Those adjustments consist of checking the tightness of seals and valves for hydrogen, as well as material durability issues.

3.2.1.2 Hydrogen admixture SoA

The technical specifications of the admixture installation can vary, depending on the amount of electricity to be stored, the regime of electrolyser operation and the connection to the transmission or distribution grids. These variations determine the chosen electrolyser technology and capacity, the required buffer storage and/or additional compression needs of the produced hydrogen. The hydrogen admixture installation must be prepared for the provision of hydrogen with the pressure compatible with that prevailing in the gas network used. The indicative costs of the components of the hydrogen injection interface are given in Figure 10.

Figure 10: Key cost elements and example for effective cost of injection



Source: [52]

A pre-mixing of the gas in a gas mixing station might be necessary to allow to stabilise hydrogen content during hydrogen injection into the gas grid and to account for changes of the gas flows rates¹⁷. The standard layout of the gas mixing station is similar to well-established nitrogen mixing stations and consists of separators, control valves, static and dynamic mixers, as well as feedforward loops and locking traps to allow

¹⁶ EG4/SEC0060/DOC; EU Commission Task Force for Smart Grids, Expert Group 4, Smart Grid aspects related to Gas

¹⁷ Typically the natural gas grids experience the seasonal, daily or even hourly flow rate changes of the gas flow rates.

quality shutdown. For low hydrogen concentrations, pre-mixing might not be necessary. Compared to the cost of the electrolyser, the cost of the hydrogen injection station is not considered to be a major contributor [53]. In case the hydrogen concentration in the gas grid is to be kept within a certain range, buffer hydrogen storage tanks may also be needed, to compensate the variability in hydrogen production.

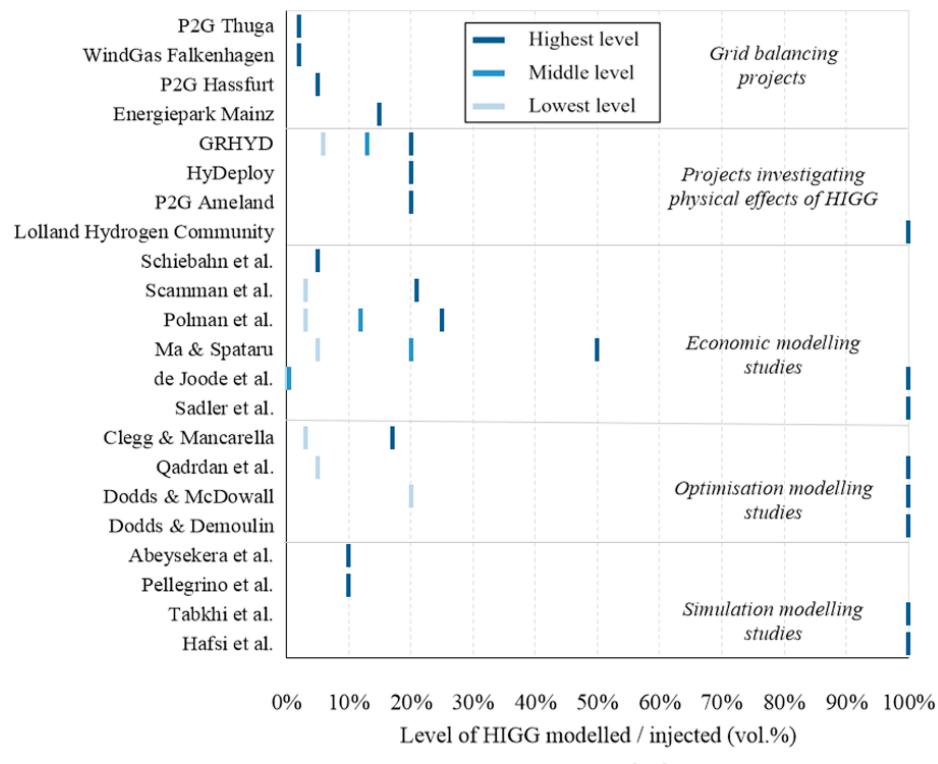
Current discussions on hydrogen admixture are related to the business case and the possible issues on the end-user side, which are addressed in many reports (e.g. [49]). In addition, gas operators see barriers to investment at policy level, due to unbundling rules which do not allow for them to deploy an admixture installation. However, in their opinion these installations and their direct control could play an important role for network operation.

3.2.1.3 Hydrogen admixture projects and national strategies

No H2020 projects have been identified which specifically address admixture. This does not mean, however, that this concept is not interesting for stakeholders, as there are around 40 projects identified in Europe which are examining hydrogen admixture [42, 54]. In the recently published FCH 2 JU AWP 2019 [55] there is a call topic (FCH-02-5-2019) regarding the systematic validation of the ability to inject hydrogen at various admixture levels into high-pressure gas networks under operational conditions.

The issues concerning hydrogen admixture are addressed in detail in a review of Quarton and Samsatli, as this application has specific economic, technical and modelling opportunities and challenges [53]. Figure 11 presents the overview of the hydrogen admixture limits taken into account in selected projects and studies.

Figure 11 Maximum levels of hydrogen injection into the gas grid (HIGG) used in real-life projects and assumed in modelling studies.



As already mentioned, there are multiple initiatives on admixture at national and international levels.

Germany leads in the area of P2G project deployment. PtG systems injecting admixtures of up to 2% and 10% of hydrogen have been widely demonstrated in the past. The projects map recently presented by DVGW consists of 62 projects representing a total capacity of 308 MW [56].

"Transformation paths of gas infrastructure towards GHG neutrality" [57] is a recently finalised German project which examines the cost-optimal transformation pathways to greenhouse gas neutrality of gas networks and gas storage. It consists of the determination of cost-optimal transformation paths, including additional costs, for the transformation of gas grids and gas storage to GHG neutrality within the technology pathways involving admixture of renewable power-to-gas hydrogen (RE-PtG-H₂) and renewable methane (RE-PtG-CH₄). It addresses questions regarding how much hydrogen can be added into the natural gas system and whether existing infrastructure can be used for this purpose.

France is working on the GRHYD [58] project (€15 million, 2013-2020) that is supported by the French Government and is a part of the Strategy of the Hauts-de-France region's 3rd industrial evolution. The GRHYD project is a five-year demonstration of hydrogen injection into the natural gas distribution network with a blend of up to 20%. A recent study "Gas Independence in France in 2050" [59], aiming for a 100% renewable gas mix in France by 2050, is focussed on natural gas, which is the second, after electricity, most consumed grid energy in France. Admixture is one of the solutions analysed.

The United Kingdom engagement in admixture projects indicates an interest in hydrogen concentrations as of 20%, as well as the use of pure hydrogen (see Chapter 4.2.3). The HYDEPLOY project (€7.6 million, 2016-2023) is a demonstration of the use of blended hydrogen in the UK gas grid. Up to 20% of H₂ injection into the closed¹⁸ gas network within HYDEPLOY (installation 2019, trials 2020) and two trials on the open network (2021-2023) are planned. The HYDEPLOY project is now in Phase II and has been granted an approval from the UK Health & Safety Executive to run a 12 month live trial of blended hydrogen and natural gas beginning in summer 2019. The hydrogen delivery to heat homes will be up to 20 %. Recently, information about the Centurion Project [60] has been released. This project is investigating the installation of a 100 MW PEM electrolyser at the INOVYN Runcorn Site, which already produces hydrogen (used mainly on-site) as a co-product of the chlor-alkali process. The project is a feasibility study. It explores the electrolytic production, pipeline transmission, salt cavern storage and gas grid injection of hydrogen at an industrial scale. The study will explore the system design and costs and will assess the business case for deployment. The transport of hydrogen by pipeline to salt caverns near Lostock, where it can be stored pure or blended with natural gas, will be explored, along with the feasibility of injection into the local gas network. Project Centurion plans to build upon the work performed in HYDEPLOY and the proposed HYDEPLOY 2, which, if funded, will develop the evidence base for transporting blended hydrogen through trials within two public gas networks in the North West and North East of England. The project will also develop a full deployment plan for hydrogen blending within the gas network.

At the international level the HYREADY project should be mentioned. It is a joint international project involving partners from the Canada, Ireland, Poland, France, Spain, USA, Netherlands and Germany. New partners can still join. It started in 2017 and is planning to produce a set of generic engineering guidelines on how to identify and quantify the effects of hydrogen addition to natural gas in a specific network and to propose feasible mitigating measures in case the assessed consequences are not acceptable. These guidelines should distinguish between the consequences at grid level (i.e. pipeline materials), component level (i.e. tightness of the particular components) and location level (i.e. safety zones).

The GERG (GERG is the European Gas Research Group) Hydrogen in Pipeline Systems (HIPS) project had looked into the impact of hydrogen on the gas grid and issued a number of recommendations [61]. Following up on the results of the HIPS project, the HIPS-NET network was launched, see Section 4.4.9.

3.2.2 Hydrogen separation

If hydrogen is mixed with natural gas, it may later need to be recovered from the gas mixture if it is necessary to use pure hydrogen, or to protect hydrogen sensitive end-use appliances. Separation of hydrogen from natural gas can be carried out via the following methods:

- Pressure Swing Adsorption (PSA)
- Membrane separation
- Cryogenic separation/partial condensation

¹⁸ Closed gas network means a gas network (closed, separated gas system) operating independently from the national grid.

- Electrochemical separation
- Hybrid solutions

Absorption and gas centrifuges, as well as Temperature Swing Adsorption (TSA), which are methods with relatively high cost, low efficiency and low relevance to the issue of separating hydrogen from H2NG blends, have been excluded from this review. The term “separation” is commonly used for a process increasing the concentration of hydrogen, and the term “purification” is used for a step upgrading the hydrogen quality to the desired degree.

3.2.2.1 Hydrogen separation KPIs

As for other technologies, the main KPIs for hydrogen separation are **CAPEX** and **OPEX**. These are affected by technical parameters such as power, capacity/size of the unit, chemical composition of the gas (i.e. hydrogen concentration in the H2NG, presence of impurities, etc.), and inlet/outlet pressures, all of which determine **cost of separation**. Other additional KPIs can be defined, such as **hydrogen recovery factor**, **energy efficiency of extraction** and **hydrogen purity**. Depending on the separation technology, these factors can be influenced by the specific materials chosen and geometries (for example the membrane area and shapes) employed. As there are many technological solutions for separation, the individual approach for the particular applications should be taken into account. This creates a situation where giving fully comparable technical KPIs is not always feasible across all of the analysed solutions. KPIs and future targets have been provided by the FCH 2 JU for hydrogen separation technologies in the AIP 2010 and AWPs 2015 and 2016. One of the targets are further **cost reductions**, which should be possible due to manufacturing process optimisation and increasing production capacities (50,000 systems/year in 2020). The **hydrogen recovery factor** (also often referred to as recovery rate) for the improved system component production steps should be >95 %. Those targets should be achieved at the scale of 25 kg H₂/d or higher, while separating hydrogen from mixtures containing less than 10% of hydrogen in H2NG. Under these conditions the **cost of hydrogen separation** should be less than 1.5 €/kg and the **energy effectiveness of extraction** of hydrogen from hydrogen concentration streams of <10% should be below 5 kWh/kg.

3.2.2.2 Hydrogen separation SoA

Gas separation technologies are commercially available [62]. This section gives an overview of the state-of-the-art of the main separation technologies, namely pressure swing adsorption, membrane separation, cryogenic distillation and electrochemical separation. These different technologies are often used in hybrid solutions where each of the separation processes is operating in its optimum domain. The basic advantages and disadvantages of a single separation technology versus a hybrid process vary and depend on the quality and quantity of the gas processed, and on the desired hydrogen purity.

Pressure Swing Adsorption (PSA) is a standard industrial method to separate a particular gas species from a mixture of gases [63]. The separation process is based on the property of gases to be adsorbed under pressure according to their affinity to an adsorbent material. The differences in gas adsorption rates of the adsorbent material can be used to capture specific gases. Porous media with adsorption properties suitable to the gas mixture are chosen based on this selectivity. This process is energy intensive as the gases have to be compressed.

The PSA method works most efficiently for gases with high hydrogen concentrations (over 75 %). Using PSA, it is possible to obtain hydrogen purity up to 99.9999 % and hydrogen recovery factors between 75 and 92 % [64]. About 85% of the hydrogen produced globally is purified by PSA [65], and this method can efficiently purify large amounts of hydrogen. PSA units are installed in Steam Methane Reformer (SMR) plants, which are designed to produce up to 100,000 Nm³/h of high purity H₂.

The estimated cost of using the PSA method for H2NG from a gas pipeline with a working pressure of 20 bar, assuming a 10% hydrogen concentration in the gas and a hydrogen recovery rate of 80%, can range between 3.3-8.3 USD/kg H₂. For a 20% hydrogen concentration, costs drop to 2.0-7.4 USD/kg H₂ [66].

Following the separation of hydrogen, if the natural gas has to be reinjected into the gas grid, it has to be re-pressurised as the output pressure of a PSA is around 2 bar¹⁹. As this may involve large volumes of natural

¹⁹ The natural gas transmission system operate at pressure levels of typically 40-80 bar.

gas, compression could be a considerable cost factor, due to the size of the compressors needed. In addition there would also be a high energy demand. The separation of hydrogen at natural gas pressure reduction stations, for example where transmission lines feed into the distribution lines, would have the advantage of eliminating the need to recompress the natural gas, which would significantly reduce the costs of hydrogen separation.

Similarly to the PSA method, membrane technologies work best at separating hydrogen from a gas with high hydrogen content. This separation technology is based on the differences in gas permeability through various membrane materials. Membranes require a pressure gradient since the driving force for the separation, as the rate of permeation is linked to the pressure differential [67]. The purity of the hydrogen obtained is inversely proportional to the degree of hydrogen recovery from the gas. The membrane surface area necessary for the separation of hydrogen is inversely proportional to the pressure difference between the sides of the membrane. The higher the gas pressure introduced into the separator, the smaller the membrane surface area achieving the desired hydrogen flow can be. Membrane technology is very energy efficient and cost efficient for small units, simple in operation and compact [68]. On the other hand, considering the possibility of membrane failure, it is necessary to design and develop replacement circuits for safety reasons. This means that all of the separation lines need to be doubled, so that in the event of membrane failure the flow can be redirected, and the end user device is not damaged by unfiltered gas feed, which leads to a cost increase. Using membranes does not significantly reduce the inlet gas pressure, which means that it is not necessary to recompress the carrier gas before using it further [69]. The response time of membrane systems is considered as instantaneous, which allows for immediate results of corrective actions for end use appliance protection [70].

The most developed membrane separation methods are those based on polymeric and dense metal membrane systems, which can reach a moderate hydrogen purity of 90–98% and moderate recovery rates of 85–95% [64, 71]. Recently, even 99.999 vol% has been demonstrated at elevated temperatures, using dense metallic membranes (Pd and its alloys) [47]. The recovery factor strongly depends on the hydrogen concentration in the blend, pressure differential and the type of membrane. Currently there are four different types of membranes commercially available: polymeric membranes, porous (ceramic, carbon, metal) membranes, dense metal membranes, and ion-conductive membranes [69].

Cryogenic separation, known also as cryogenic distillation, or partial condensation, is a process based on differences in the condensing temperatures of gases in the gas mixture. This method had been typically used at large scales in the past for the purification of off-gases for the petro-chemical industry, but seems less common today, possibly due to the high costs and energy intensity of this process. By lowering the temperature below the point of liquefaction of natural gas, but where hydrogen remains in the gas phase, it is possible to separate hydrogen from H₂NG. Hydrogen has a boiling point of minus 252.9 °C, which is lower than that of nearly all other substances. Disadvantages of the cryogenic separation are high costs because of the high energy consumption of cooling [72], several hours of start-up time [70], pre-treatment of the feed gas to remove components that might freeze (H₂O<1 ppmv; CO₂<100 ppmv [70]). In comparison to PSA or membranes, the lack of flexibility and decreased reliability of the process is notable. Recovery factors of 95% are typical [73]. An advantage of cryogenic separation over other methods is that it has excellent economies of scale and is therefore interesting for large industries [74]. Hydrogen purity up to 99% is possible [74], but usually moderate purities (95% or less) are achieved [75]. At smaller scales, cryogenic hydrogen purifiers are commercially available, which offer hydrogen outlet purities of 99.999%+ (e.g. [76]).

The electrochemical separation method (using electrochemical membranes) consists of removing a specific component (hydrogen) from the gas mixture by a selective chemical reaction in which only the component to be separated from the mixture is involved. This method is suitable for small scale purification devices and in principle would be also scalable for larger demands, but it still needs to be demonstrated. Furthermore, because it requires a relatively small amount of space, it can be integrated into existing processes more easily than other methods. Electrochemical membranes can also be used for hydrogen compression (already realised for up to 54 bar [77]) and simultaneous enrichment of hydrogen [78]. Hydrogen with a purity of 97.9797% was reported with a recovery rate of nearly 100% [79–81]. In the case of separation of hydrogen from a hydrogen/methane mixture (8–100%) with a proton exchange membrane (PEM) fuel cell²⁰, pure hydrogen was obtained for a recovery rate less than 80% [80]. Sulphur is poisonous for electrochemical

²⁰ This work describes hydrogen separation using PEM fuel cell technology. In electrochemical separation, the hydrogen in the gas mixture is oxidized at the anode and hydrogen is evolved at the cathode. Experiments were performed using a single proton exchange membrane (PEM) fuel cell (25cm² active area MEA), fed with pure hydrogen as well as various hydrogen–methane mixtures and hydrogen–argon mixtures.

membranes and it has to be removed down to ppb concentrations. Simulations show that beside harmful gas species, humidity and temperature influence the performance of electrochemical membranes [82].

This technology seems to be proven and commercially available for the separation of a number of gases, but apparently not yet in the field of hydrogen separation from natural gas. Under H2020 one project is oriented at investigating the electrochemical separation of hydrogen from H2NG (MEMPHYS, see below). It should be noted that electrochemical membranes are being extensively investigated for electrolyser and fuel cell components development.

3.2.2.3 H2020 Hydrogen separation projects

Two projects have been identified which tackle the separation of hydrogen from a H2NG blend, as given in Table 7.

Table 7: Summary of Horizon 2020 Separation Projects by technology

Technology	Acronym	Programme	Topics	Title	Period	EU Funding (€)
Electrochemical separation	MEMPHYS	H2020-EU.3.3.8.3.	FCH-03-1-2016	Membrane based Purification of HYdrogen System	2017-2019	2m
Membrane based hybrid technology	HYGRID	H2020-EU.3.3.8.3.	FCH-02.5-2015	Flexible Hybrid separation system for H2 recovery from NG Grids	2016-2020	2.5m

Source: JRC, Source: JRC 2020, based on publically available data.

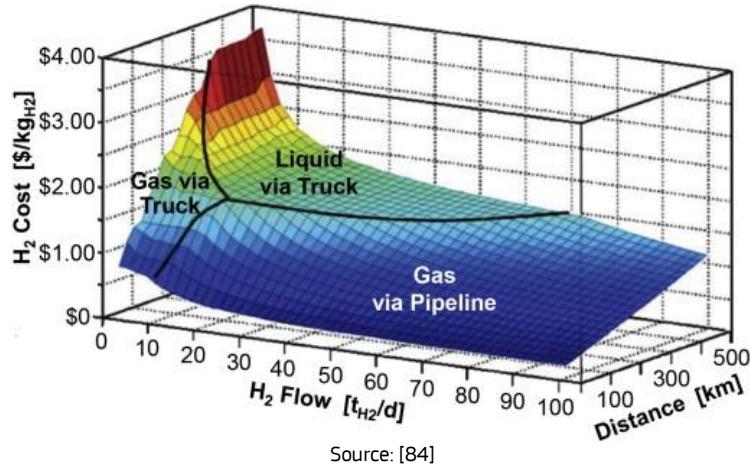
Electrochemical separation is being developed within the MEMPHYS project. Of the relevant KPIs, the target set for energy consumption (3 kWh/kg H₂) has been achieved. The targets set for the recovery rate (>90%) has not been achieved yet. In order to provide improvements versus the state of the art, MEMPHYS focuses on alternative catalysts to improve tolerance against toxins. Additionally, EIS diagnostics are used to understand the water management in the cell and can help to analyse when and why a cell is failing. This project is due to finish soon, however the membrane is reported as in preparation, and under laboratory testing.

Membrane based hybrid technology, which in this particular case means a combination of membrane separation, electrochemical separation and temperature swing adsorption, to decrease the total cost of hydrogen recovery, are being developed within the HYGRID project. It aims to prepare a novel hybrid system integrating these three technologies for hydrogen purification: Membrane separation technology for removing H₂ from the “low H₂ content” (e.g. 2-10%), followed by electrochemical hydrogen separation (EHP) optimal for the “very low H₂ content” (e.g. <2%) and finally temperature swing adsorption (TSA) technology to remove humidity produced in both systems upstream.

3.2.3 Distribution of hydrogen through dedicated pipelines

The distribution of hydrogen through dedicated pipelines is a cost effective option for larger quantities of hydrogen and moderate distances. A recent report by the IEA [49] finds that for distances below 1500 km, dedicated pipelines are likely to be the cheapest option. Other studies see pipelines as the most cost effective even for shorter distances (see Figure 12), which is probably explained by the different underlying assumptions. For long distance transport of hydrogen, hydrogen carriers or liquefaction have been proposed for transport by ship or trucks (see Section 4.2.5). Truck distribution would be most suitable for lower quantities of hydrogen and shorter distances. Hydrogen pipelines are currently used to supply hydrogen to industrial areas and can be considered an established technology with no further research needs. Currently, around 4500km of hydrogen pipelines have been installed worldwide, of which 1600 km are in Europe [83].

Figure 12: Minimum hydrogen transmission costs as a function of H₂ flow and transport distance.



To supply hydrogen, a cheaper alternative to constructing a new hydrogen pipeline would be to convert an existing natural gas line. This concept is explored in the UK by projects such as Aberdeen [85] and H21 Leeds City Gate [86]. The H21 Leeds City Gate project aims to convert the existing natural gas network in Leeds, one of the largest UK cities, to 100% hydrogen. This conversion targets the distribution network in the first phase of the project. The project aims to deliver heat to customers in the greater Leeds area for a total of around 17% UK domestic meter connections, at the same cost as for natural gas. A 12.5 GW hydrogen production facility, with 8 TWh inter-seasonal hydrogen storage and carbon capture and storage, with capacity to sequester up to 20 million tonnes of CO₂ per annum by 2035, is to be developed. These initiatives are developed under the UK Government's Industrial Strategy [87].

The Netherlands is also active in investigating 100%²¹ hydrogen distribution through parts of the existing gas grid. Concepts are being developed to connect Dutch industrial clusters to a supply of hydrogen by 2030. Funding of the ambitious plans for the Hydrogen Valley still need to be arranged [88], but there is already an ongoing project, Green Village, where hydrogen is supplied to a residential area through the distribution grid [89]. As part of the Smart Delta Resources Platform, the project Waterstof Symbiose Delta Regio will convert natural gas pipelines to transport excess hydrogen from one industrial partner to two companies using hydrogen [90]. There will be financial support from the region, and from the ministry of economy regarding regulatory aspects.

There are no projects funded under H2020, but this distribution option is expected to gain relevance in the future.

3.2.4 Large scale hydrogen storage

Hydrogen can be stored in many different ways, e.g. as compressed gas (at different pressures), liquefied, in metal hydrides or in carriers as ammonia or liquid organic (LOHC, see Section 4.2.5). Considering large scale storage as involving more than 10 tonnes of hydrogen, as defined in the MAWP of the FCH 2 JU, only two hydrogen storage technologies seem to be currently suitable, from a techno-economic point of view, to store that amount of hydrogen: liquefied hydrogen and geological underground compressed hydrogen. There are other hydrogen storage technologies such as buried pipes or tanks (as compressed gas) or aboveground storage tanks (also as compressed gas), but the investment cost per kg of hydrogen stored is at least one order of magnitude higher compared to geological underground compressed hydrogen storage [91].

In the case of liquefied hydrogen, hydrogen is cooled down in liquefaction plants below its boiling point (20.3 K) and stored in cryogenic tanks, at pressures no higher than 5 bar, which should be well insulated to reduce to a minimum the boil-off of the stored hydrogen. Liquid hydrogen has the advantage of having the lowest possible volumetric density for hydrogen in its molecular form. For underground compressed hydrogen

²¹ Although stakeholders often refer to 100% hydrogen in the CEST context, the hydrogen produced and distributed will obviously contain impurities.

storage, hydrogen is compressed and stored in geological formations, which in principle could be depleted gas reservoirs, natural aquifer formations, abandoned mines or man-made salt caverns. Salt caverns appear to be the most suitable choice for seasonal hydrogen storage, because of their storage capacity and operating conditions (i.e. high injection rates) [91].

3.2.4.1 Hydrogen storage KPIs

Large scale hydrogen storage, as defined in the MAWP of the FCH 2 JU [14], refers to more than 10 tonnes of pure hydrogen stored for at least 48h. The MAWP provides a set of KPIs to define the performance of large scale hydrogen storage, not indicating any specific technology. For each of these KPIs the State of the Art and targets for 2020, 2024 and 2030 are given (see Table 8).

These targets assume that the hydrogen is retrieved clean (purity not stated) and at a pressure of 30 bar from the storage system. It can be assumed that **chain efficiency** and **release energy use** are related to the performance of the hydrogen storage system from the energy point of view, but unfortunately there is no definition of what these KPIs refer to, and/or the boundaries of the system(s) under analysis. To solve this issue of lack of definition, the authors of the present report have defined a KPI addressing the energy performance of the storage system. It is named **storage efficiency** and is calculated as shown in the formula below, where $E_{H_2,in}$ is the energy needed to store one kg of hydrogen in the storage system, $E_{H_2,out}$ the energy needed to retrieve one kg of hydrogen from the storage system, $H_{2,loss}$ are the energy losses related to the hydrogen that leaks from the storage system during its storage or that cannot be retrieved, per kg of hydrogen stored. Finally, $H_{2,in}$ is the amount of energy per kg of hydrogen stored (e.g. LHV or HHV). Logically, for the estimation of $H_{2,loss}$ it is necessary to define a timeframe.

$$\text{Storage efficiency} = 100 * \left[1 - \left(\frac{E_{H_2,in} + E_{H_2,out} + H_{2,loss}}{H_{2,in}} \right) \right]$$

Table 8 Key performance indicators for large scale hydrogen storage

KPI	Unit	State of Art		FCH 2 JU target		
		2012	2017	2020	2024	2030
Chain efficiency	%	-	60	67	70	72
Release energy use	kWh/kg	-	13.3	11	10	9.3
System capital cost	€/kg	1.2	1.1	1.0	0.8	0.6

Source: [14]

3.2.4.2 Hydrogen storage SoA

3.2.4.2.1 Liquefied hydrogen

When analysing liquefied hydrogen technology, two systems should be considered: liquefaction plants and liquid hydrogen storage tanks.

There are currently more than 13 hydrogen liquefaction plants in North America with production capacities of 5–34 tonnes/day (TPD), 4 plants in Europe with capacities of 5–10 TPD, and 11 plants in Asia with capacities of 0.3–11.3 TPD. The main consumer of this liquefied hydrogen is the oil industry, followed by aerospace agencies [92].

Nowadays, hydrogen liquefaction plants that produce more than 5 tonnes/day of hydrogen are considered as large-scale. The energy requirement of these plants is in the order of 10–12 kWh/kg H₂. The liquefaction is usually performed by means of the hydrogen Claude cycle (using liquid nitrogen for precooling). The liquefaction plants require levels of hydrogen purity in the range of 10–100 ppm (depending on the contaminant) but they provide hydrogen of extremely high purity (<1 ppm) [93]. CAPEX is around \$5 million per H₂ tonne/day. In terms of OPEX, hydrogen liquefaction costs are mostly related to the cost of liquid nitrogen for pre-cooling and the electrical energy required for compression [94].

It is expected that with larger scale plants (>50 tonnes/day), the power requirements could be reduced by up to 50% (5-6 kWh/kg H₂). The same applies to cost, where a reduction of 50% of the costs (including CAPEX and OPEX) is also expected [93]. An alternative liquefaction technology, magnetocaloric hydrogen liquefaction, promises cost-effective and efficient hydrogen liquefaction because it eliminates gas compressors, the largest source of inefficiency in the traditional Claude cycle liquefiers, and the use of liquid nitrogen to precool the hydrogen. However, this technology is still at an early stage of development.

Hydrogen should remain below -253°C to remain in the liquid state. For this reason, liquefied hydrogen tanks have to be well insulated to reduce heat losses to the minimum. They are double-hulled, with a vacuum created between the inner and outer walls. This vacuum is then filled with a thermally insulating material (e.g. perlite). The internal wall of the tank is made of austenitic stainless steel. The design of the support structure between the outer and the inner wall is critical to reduce heat ingress. Despite the thermal insulation, a small amount of hydrogen evaporates due to heat ingress, therefore liquefied hydrogen tanks have to incorporate a system to release the boil-off gas in order to avoid the build-up of internal tank pressure.

Historically, liquefied hydrogen has been related to aerospace applications. This is one of the reasons why the largest liquefied storage tanks worldwide are found in the facilities of aerospace agencies such as NASA and JAXA (270 tonnes for NASA and 38 tonnes for JAXA, (see Figure 13). In the frame of the Hydrogen Energy Supply Chain (HESC) project, a world-first pilot project to safely and efficiently produce and transport clean hydrogen from Victoria's Latrobe Valley (Australia) to Japan [95], Kawasaki Heavy Industries Ltd. is building two tanks able to store 87.5 tonnes of hydrogen each. It intends to implement them in a ship tanker for the transport of liquefied hydrogen from Australia to Japan. They have achieved a thermal insulation of 0.01 W/mK. In the case of the NASA tanks, evaporation rates are of the order of 0.05 % of the total volume of the tank, per day [96]. Linde reports higher evaporation rate in their tanks (<0.1-0.3% / day), however, these tanks have smaller capacity (20-145 tonnes of LH₂) [97] than the ones installed by NASA. The evaporation rate also depends on the geometrical shape of the container. Spherical shapes have a lower evaporation rate, due to the more favorable volume-surface ratio.

In a scenario with high demand for hydrogen, it is expected that a single liquefied storage tank will have to contain of the order of 3000 tonnes of hydrogen [93].

Combining the liquefaction of the hydrogen plus its storage it is possible to establish the State of the Art values of the **storage efficiency** and its medium-term target. As explained above, a timeframe should be considered when calculating this KPI. We have used 48 hours (minimum duration for large scale hydrogen storage, as defined in the MAWP), in this way the value obtained will represent the maximum value for this KPI. Values can be found in **Table 9** below (considering LHV) and have been calculated using information from references [93] and [96].

Table 9 Storage efficiency for liquefied hydrogen

KPI	State of Art	Expected development ²²
Storage efficiency (%)	66.6	83

Source: calculated from [93] and [96]

²² This value is linked to the deployment of large scale hydrogen liquefaction plants.

Figure 13 Liquid hydrogen storage tanks.



Source: [93]

Liquid hydrogen has also been proposed for the distribution of hydrogen, see for example the transport of hydrogen from Australia to Japan, as described in section 4.2.4. The FP7 FCH JU project IDEALHY analysed the effect on the environmental impact of the aggregate state in which the hydrogen is distributed. It used two different methodologies based on LCA and on the Renewable Energy Directive (RED). In both methodologies distribution of hydrogen in liquefied form presented a better performance than for compressed hydrogen in terms of primary energy demand and GHG emissions, considering a 100-150 km round trip distance by road [98].

3.2.4.2.2 Underground compressed gas storage

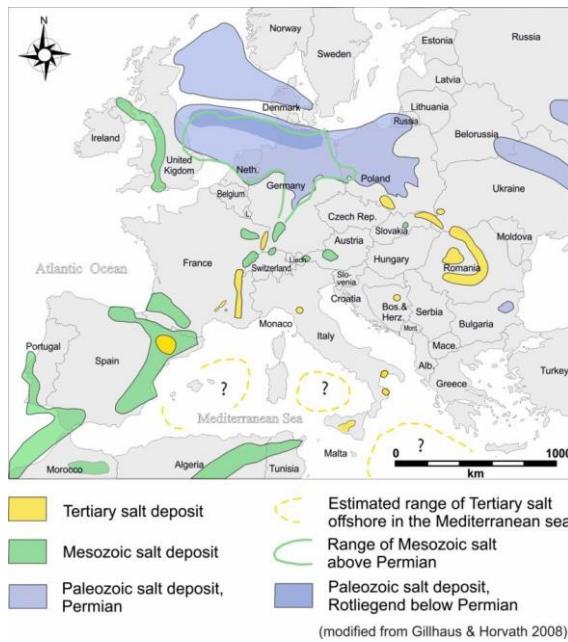
Currently, large scale underground hydrogen storage can only be found associated with refineries, used to ensure a continuous supply of hydrogen. According to the HyUNDER report "*Overview on all Known Underground Storage Technologies for Hydrogen*" [99] there are only three sites worldwide with underground hydrogen storage, all of which are using salt caverns (there are additional sites where town gas - a gas mixture of natural gas, hydrogen, carbon-dioxide, other gases and gas impurities - has been stored in the subsurface). Two of these caverns are located in Texas (Clemens and Moss Bluff) and the third is in Teesside (UK). The Clemens and Moss Bluff caverns can store more than 2500 and 3700 tonnes of hydrogen respectively, whilst the Teesside cavern is suitable for the storage of more than 750 tonnes of hydrogen.

The H21 project will repurpose already existing caverns in Teesside for intraday storage, which together with SMR and inter-seasonal storage, will supply a maximum 1 in 20 peak hour demand of 3,180 MW_{HHV}. Inter-seasonal storage of 702,720 MWh_{HHV} (calculated as 40 days of maximum average daily demand-coldest year, equivalent to the energy content of 209 million Sm³ hydrogen) will be enabled by salt cavern storage located on the East Humber coast [86].

Salt caverns appear to be the most suitable geological formation for underground hydrogen storage. They are extremely tight to gases, due to the visco-plastic nature of salt. They can withstand high pressures (up to 20 MPa) and allow flexible operation, with high injection and withdrawal rates (both up to 1MPa/day), ideal for the storage of renewable energy. In addition, there are no hydrogen losses due to hydrogen reaction with the rock and no microbiological activity that could transform the hydrogen [91].

The main disadvantage of hydrogen storage in salt caverns is that this geological formation is not present everywhere. In the case of Europe, the distribution of salt deposits can be seen in Figure 14.

Figure 14 Salt deposits in Europe



Source: [99]

The construction of a salt cavern requires a significant upfront investment. However, this makes a relatively small contribution to the total specific hydrogen costs (a few percent) and that ratio does not vary substantially with the electricity price [100]. The salt cavern is built by means of a leaching process where rock salt is dissolved with injected water and the brine generated is withdrawn. This brine has to be disposed of in an environmentally friendly manner. Once the cavern is built, the gas is injected through a piping system supported by a compressor installed on the surface of the well. A safety valve and a rubber-based packer (to ensure tightness between the pipe and the casing) are also part of the equipment. In addition, a gas drying system is needed to remove the moisture coming from the remaining brine located at the bottom of the cavern. The cavern is filled with hydrogen but some part of this hydrogen should remain in the cavern to ensure its mechanical stability (cushion gas). The amount of cushion gas will depend on the geometry of the cavern, but it is of the order of one third of the total amount of gas stored. In some cases this cushion gas could be reduced to zero when the cavern is operated at constant pressure.

A summary of the current SoA of relevant parameters for underground hydrogen storage is found in Table 10.

Table 10 Underground hydrogen storage parameters

Parameter	Unit	State-of-Art
Geology		Rock salt
Reference depth	m	380-930
Volume	m ³	210000-580000
Maximum pressure	bar	46-152
Minimum pressure	bar	55-70
Cushion gas	Mio kg	0-34
Working gas	Mio kg	8.5-55.2

Source: [99]

Storage efficiency is calculated considering the compressor work to inject and retrieve the hydrogen in the reservoir, the energy necessary for the conditioning of the hydrogen (gas drying system), the hydrogen leaks from compressor and reservoir and the remaining cushion gas, which will not be available. Ideally, the cushion gas could be recovered at the end of the lifetime of the reservoir and, in the case of salt caverns, leakage rates are very small, so, for the sake of simplicity, both these factors can be discarded in the calculations. Compression work is directly related to the pressure difference between the compressor inlet and outlet. Unfortunately, there is not much literature regarding compressor and hydrogen drying system performance

at the large scale. A rough estimation from the few values found in literature [101], [102] indicates that the SoA of the **storage efficiency** for underground hydrogen storage in salt caverns is around 95%.

3.2.4.3 H2020 Hydrogen storage projects

Two projects within the CEST Report H2020 projects screening have been identified which address the storage of hydrogen; HYUNDER for underground storage and PRESLHY for liquefied hydrogen. A further project, IDEALHY which took place earlier under FP7 also considered liquefaction. HYUNDER performed a study on the potential of underground hydrogen storage in Europe, including benchmarking with competing storage technologies, and identification and evaluation of application areas, stakeholders, safety, regulatory framework and public acceptance. Results from this project have been used as a reference in Section 4.2.4.4. The PRESLHY project is focused on safety aspects associated with liquefied hydrogen. Previous efforts have been made regarding liquefied hydrogen; in the IDEALHY project (FP7) a concept to reduce the energy demand of the liquefaction process was developed.

3.2.5 Hydrogen carriers

In this section, we will only consider the conversion of hydrogen into other molecules for the purpose of storage and transport of hydrogen. The chemical compounds obtained by reacting hydrogen with other molecules, and able to release it under specific conditions, will be defined here as hydrogen carriers. A distinction within the general class of hydrogen carriers²³ can be made between molecules which emit CO₂ when hydrogen is released (e.g. methanol) and those which do not, such as Liquid Organic Hydrogen Carriers (LOHC) and ammonia.

Several different hydrogen carrier systems have been proposed and the distinction between carrier and fuel is not clear cut. In this report, we will consider a molecule as a fuel if it is employed directly (e.g. burned in a combustion engine) for power generation, and as hydrogen carrier if the molecule is used to decouple the hydrogen production and use sites, and hydrogen obtained from the carrier molecule is used to produce power. A carrier molecule is therefore used for storing hydrogen and releasing it at a different time and possibly a different place.

The concept of hydrogen carriers is gaining increasing importance considering the potential role of hydrogen in the energy transition. If hydrogen is to be distributed and stored in large amounts and distributed over long distances, carriers may have advantages over other options such as hydrogen transport through pipelines (especially for intercontinental transport), or shipping in liquefied or gaseous form. They could take advantage of already available infrastructure used for fossil fuels, or for chemical commodities such as ammonia, and potentially require smaller economic investments and energy consumption under specific conditions.

For the purpose of this report, hydrogen carriers are defined as hydrogen-containing liquid or gaseous compounds from which hydrogen can be liberated on-demand, enabling the safe, efficient and economically appealing distribution and/or storage of hydrogen (intended as an energy vector). The process required to hydrogenate/dehydrogenate the compound should use as little energy as possible, be reversible under practical conditions, and be economically feasible. The compound used as the hydrogen carrier should be a gaseous or liquid molecule under standard conditions of pressure and temperature; we therefore disregard hydrides in this discussion.

For the sake of clarity, the concept of reversibility needs to be clearly defined. Available literature often distinguishes between 'reversible' and 'irreversible' hydrogen carriers [103]. Here we will define as a 'reversible hydrogen carrier' a compound whose hydrogenated form can be regenerated by using only gaseous hydrogen as reactant (such as for LOHC). An 'irreversible hydrogen carrier' is a carrier compound whose hydrogenated form can be obtained by reacting hydrogen with other gaseous molecules (e.g. CO₂ for methanol, or nitrogen for ammonia). Despite being, in principle, reversible, molecules such as methanol and ammonia should, in general, be labelled as 'irreversible' hydrogen carriers, since after hydrogen is obtained, they release other gaseous products such as CO₂ or nitrogen into the atmosphere. This is not the case for 'reversible' hydrogen carriers. Hydrogen storage cycles based on irreversible carriers should include in their energy and economic cost estimates also the capture of the 'spent' gaseous carrier (CO₂ and N₂) from the atmosphere, whereas cycles based on reversible carriers should take into account the production and replacement (due to carrier loss) of the carrier molecule.

²³ We will consider only molecules which are in a gaseous or liquid form at room temperature and atmospheric pressure. Solids, such as metal hydrides will not be part of our discussion.

3.2.5.1 Hydrogen carriers KPIs

KPIs for hydrogen carriers should include **storage** and **transport efficiency**. **Transport efficiency** is highest for compounds with a high storage density and little or no need for cooling and compression. **Storage efficiency** is high if there is a low dehydrogenation energy demand and little need for purification [104]. See also Figure 15, and Table 10, which provides some data on typical transport and storage efficiencies of various LOHC systems.

Storage efficiency is the ratio of the energy of the produced hydrogen to the energy content of the hydrogen input plus any energy demand for both the hydrogenation and dehydrogenation reaction processes (see Figure 15). **Transport efficiency** can be defined as the ratio between the energy content of the transported hydrogen minus the energy required for the transport and the energy content of the transported hydrogen [104] (see Figure 15). In general, transport efficiency diminishes progressively with distance and it is therefore important that transport efficiencies are compared against each other over the same distances and modes of transport (overland, sea).

In the FCH 2 JU AWP 2017 a call topic provided a target for **chain efficiency**, however a definition was not provided. It is likely only intended to relate to the efficiency of the storage, since a target of >70% was provided. In the same call topic, a target for energy use for releasing hydrogen is set at <10 kWh/kg H₂ (around 25% of the energy content of hydrogen, based on its HHV).

Another important KPI mentioned in the FCH 2 JU call is **CAPEX**, which, in the absence of a better definition, can be defined as the cost needed to store 1 kg of hydrogen. Whenever possible, the distinction between storage and transport CAPEX should be given. **Storage CAPEX** is defined as the capital investment needed for storing 1kg of hydrogen over a well-defined time interval and **transport CAPEX** is defined as the capital investment needed for moving 1kg of hydrogen over a well-defined distance. In the case of storage **CAPEX**, the purity and the pressure of the product hydrogen should also be provided.

3.2.5.2 Hydrogen carriers SoA

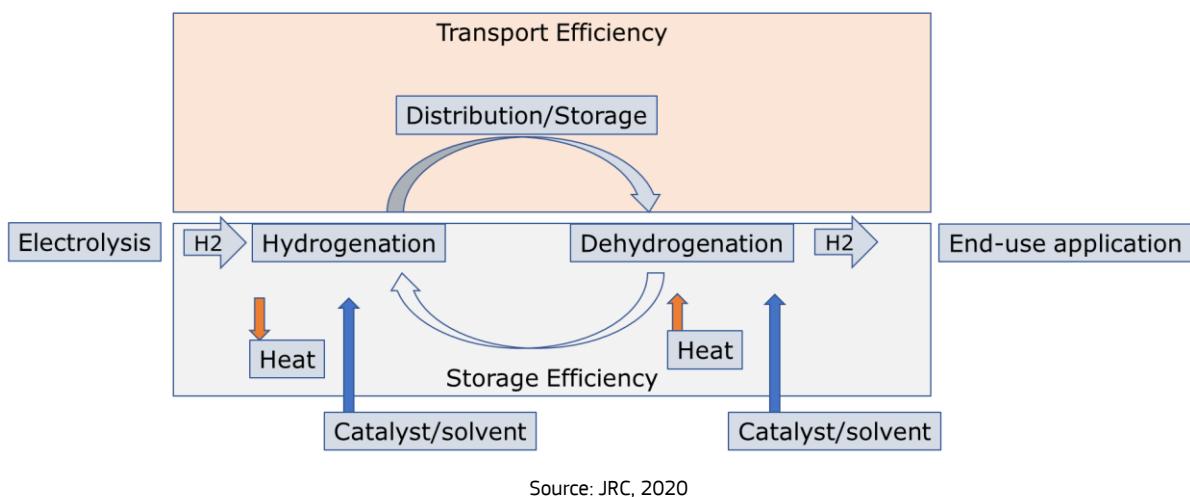
3.2.5.2.1 Liquid Organic Hydrogen Carriers (LOHC)

Liquid Organic Hydrogen Carriers (LOHC) consist of molecules able to release or accept hydrogen under specific temperature and pressure conditions. They have a hydrogen-poor and hydrogen-rich form (e.g. benzene/cyclohexane), are liquid at room temperature and atmospheric pressure, and can be charged and discharged several times by means of catalytic hydrogenation and dehydrogenation cycles. They can be considered as reversible hydrogen carriers. LOHC have a high volumetric energy density, can be stored and transported at ambient conditions for long periods without significant losses and can be handled in infrastructure already employed for liquid fossil fuels (e.g. ship tankers).

The LOHC concept was first proposed by Japanese researchers for the benzene/cyclohexane system [104] and many possible LOHC compounds have been investigated (see Table 11), although some have limited promise due to drawbacks such as high cost, energy demand or toxicity. The Japanese company Chiyoda is developing large-scale hydrogen transport via ships based on methylcyclohexane (and toluene for the dehydrogenated form).

Even if not directly consumed when hydrogen is released, LOHC will likely experience a decline in storage efficiency due to degradation associated with cycling.. In the literature [104], an estimation of 0.1 wt% loss per cycle can be found. In terms of transport efficiency, it should also be noted that if LOHC are rehydrogenated in a different location than where dehydrogenation occurred, the energy needed to transport the hydrogen-poor form of the LOHC should be accounted for in the transport efficiency, or in the full power-to-chemical/chemical-to-power cycle performance. An overview of storage and transport efficiencies for different types of LOHC compounds is provided in Table 11. It should be noted that storage efficiencies can be higher if hydrogenation heat can be fully utilized.

Figure 15 Hydrogen carrier systems schematic overview.



Source: JRC, 2020

Table 11: Efficiencies (%) of LOHC and hydrogen carriers with internal heat recovery and CGH₂ (200 bar, pipeline) as a reference. Transport takes place by ship over a distance of 5000 km. NEC: N-ethylcarbazole, DBT: dibenzyltoluene, AB: 1,2-dihydro-1,2-azaborine, FA: formic acid, MET methanol, NAP: naphthalene, TOL: toluene.

	NEC	DBT	AB	FA	MET	NAP	TOL	CGH ₂
Storage efficiency	62.6	60.8	73.9	11.0 ^a	71.5	54.1	53.8	97.3
Transport efficiency	90.3	90.3	83.1	90.3	95.2	95.5	90.3	(79.2) ^b

^a This value includes the distillation process.

^b This value is taken directly from the article cited, but we believe that it is not appropriate in this context to compare compressed hydrogen transport through pipelines with transport of other hydrogen carriers via ship.

Source: adapted from [104]

3.2.5.2.2 Other hydrogen carriers

Ammonia, methanol and formic acid have all been proposed as hydrogen carriers [103, 105-108]. Their production will be discussed in Section 3.3 and a comparison between some of their performances and that of some LOHC is presented in Table 11.

Table 11 does not contain information on ammonia, since it was not part of the study. Unfortunately, a straightforward comparison with other hydrogen carriers according to the methodology developed by Niermann et al. is not feasible here. Several studies are nevertheless available [109] and suggest that ammonia is more economically attractive and efficient as an energy carrier than toluene, methanol, and synthetic diesel fuels [42, 110, 111]. A report by Bartels and Pate [112] provides techno-economic information on the storage and distribution of ammonia. According to the authors the transport efficiency of ammonia is higher than that of transporting compressed hydrogen through pipelines for a distance of 1500km. However, the storage efficiency for ammonia used as hydrogen carrier is slightly less efficient than transporting hydrogen directly (due to the energy cost of reconversion to hydrogen).

A study by Grinberg Dana et al. [113] compared carbon- and nitrogen-based compounds using a purposely developed 'power-to-fuel-to-power' (PFP) index, able to highlight the energetic efficiency of a synthetic process: the higher the index, the more efficient the produced fuel. Among all the chemical compounds considered, even including those for which the carbon source is CO₂ from flue gases, ammonia has the highest PFP index. This highlights the highly efficient process which separates nitrogen from the atmosphere and the relatively low amount of energy required for ammonia synthesis. Although the production of ammonia is well established, the release of hydrogen from ammonia is estimated to require 1.41 MWh/tNH₃, due to the high temperature required for thermal cracking (starting from around 400°C, and with full

conversion achievable around 650°C) and the losses of hydrogen during the purification process [109]. This would imply a process efficiency of around 76%. Ammonia cracking also requires expensive metal catalysts such as ruthenium if performed at lower temperature. Using cheaper metals such as nickel is also possible, but this requires temperatures around 900°C. Recently, promising research has shown potential for the use of cheap alkali and alkaline earth imides as catalysts for ammonia cracking, with performances close to those of ruthenium [105]. It is already possible to find assessments in scientific literature on the potential advantage of coupling wind power generation with ammonia generation [114-117], [105].

Ammonia is the most advantageous carrier only if the starting point for its production is renewable energy, and fossil fuels are avoided. Where the feedstock used for hydrogen carrier synthesis is a fossil fuel, then methanol becomes the most economic and efficient hydrogen carrier alternative, achieving a better economic performance (about 25% cheaper) than ammonia [118]. Methanol process efficiency is also higher than that of the ammonia pathway, but only in case the capture, storage and transport of capture, storage and transport of CO₂ for methanol synthesis are not accounted for.

Another review comparing several carriers provides estimates for the total heat required for releasing a kg of hydrogen from the hydrogen carriers [119]. The data of Table 12 complement those of Table 11, and give an idea of the relative efficiencies for storage options. Steam reforming²⁴ of methanol offers the advantage of producing higher amounts of hydrogen than thermolysis²⁵ and partial oxidation²⁶ processes, and is considered the method of choice for recovering hydrogen from methanol. Formic acid has advantageous decomposition thermodynamics, but is hindered by the necessity of energy-demanding distillation steps since it is produced and handled in diluted form.

Table 12: Enthalpies of dehydration and temperatures required for several hydrogen carriers.

	Enthalpy of dehydrogenation [kWh/kg H ₂]	Typical temperatures for hydrogen release [°C]	Enthalpy of evaporation (if gas phase during dehydrogenation) [kWh/kg H ₂]	Total heat which must be provided [kWh/kg H ₂]
Methanol	2.3	250	4.4*	6.7
Ammonia	4.2	>425	2.1	6.3
Formic Acid	4.3	<100	-	4.3
Toluene	9.7	350	1.5	11.2
Dodecahydro-N-ethylcarbazole (DNEC)	7.6	220	-	7.6
Perhydro-dibenzyltoluene (PDBT)	9	300	-	9

*For steam reforming of methanol, one must evaporate both methanol and water. In a real case, a stoichiometric excess of water of approximately 50% is typically used; this excess ratio is used to generate the value above.

Source: adapted from [119]

From the information in Table 12 and Table 11, methanol and ammonia show good potential for long distance hydrogen transport.

Ammonia, in particular, is receiving a great deal of interest in both Japan and the US for its possible role in energy applications. Japan, as part of its hydrogen strategy, seeks to import hydrogen from locations with

²⁴ CH₃OH + H₂O → 3 H₂ + CO₂

²⁵ CH₃OH → 2 H₂ + CO

²⁶ CH₃OH + 0.5 O₂ → 2 H₂ + CO₂

abundant renewable power. Australia sees potential for ammonia to be used to ship hydrogen to Japan, and Japan is investing in research on the decomposition of ammonia. Similar planning does not seem to be ongoing at a European level.

2019 estimates from the IEA suggest lower costs for transporting hydrogen as ammonia over long distances. It is claimed that transport via inland pipeline is cheaper through compressed hydrogen for distances less than 1500km. Above this distance, shipping hydrogen in the form of ammonia or LOHC (methylcyclohexane/toluene) becomes less expensive, with ammonia having a marginally lower cost, and ammonia also being cheaper than compressed hydrogen for transmission in pipelines at distances over 3500km [42].

In spite of the many positive features of ammonia as an energy carrier, the widespread use of nitrogen based compounds may not necessarily be the best choice for reducing GHG emissions in the long term. N₂O emissions along any technological chain based on nitrogen-containing chemicals should be carefully accounted for, since this GHG has a factor of 298 for equivalence with CO₂ (in terms of greenhouse gas activity). Methanol produces CO₂ when used as a hydrogen carrier or directly as a fuel (see also Section 3.3.2.2).

In summary, the synthesis of hydrogen carriers is based on well-established processes, but several challenges still need to be addressed if these are to be used on a large scale. Research on catalysts to improve storage efficiency and dehydrogenation at moderate temperatures seems the most critical issue. Any future research activities should be focused on carrier compounds that are environmentally benign, and infrastructure designs able to transport large amounts of hydrogen efficiently and at a low cost.

3.2.5.3 H2020 Hydrogen carrier projects

The HYDROGENLOGISTICS project has the goal to develop a hydrogen release system and to reduce cost and complexity, based on the use of the compound dibenzyltoluene (DBT). DBT has the advantage of safe handling and low toxicity. The storage density of hydrogen in the hydrogenated compound is 57 kg/m³ LOHC [120] at ambient conditions. The German SME Hydrogenious is the sole beneficiary of this project, and a key partner in the FCH 2 JU HYSTOC project. The project has performed an assessment of the environmental impact, and found that the main source of impacts is the dehydrogenation process due to the high energy demand (ca. 14.4 kWh / kg H₂ released) of this process [121]. To minimize the energy demand of the dehydrogenation process, the integration of the process with a SOFC has been suggested. Waste heat from SOFCs would be available if a power-to-power concept is the aim [104].

A French company (Hysilab), active within the cluster of Capenergies, is aiming at commercialising a liquid hydrogen carrier based on a liquid silicon hydride derivative (Hydrosil). In 2017, Hysilab was the only beneficiary of the H2020 project DELIVERS. HRS in the long term, and industrial customers in the short term, were identified as the main potential beneficiaries for the developed technology.

No H2020 projects on ammonia as hydrogen carrier were identified. Somewhat related to the scope, under FP7 the FCH JU supported projects with the aim to use ammonia to provide power to telecommunication towers, a concept which is also pursued by the H2020 RENGEN project.

3.3 Hydrogen-to-X (hydrogen-to-chemicals/hydrogen-to-fuels)

Applications labelled as 'hydrogen-to-X', where X is either a chemical or a fuel, can be defined in different ways. In the context of this report, the concept of power-to-X is considered as the combination of an initial power-to-hydrogen step followed by a hydrogen-to-X one. Power-to-hydrogen applications have been extensively described in Section 3.1. This section will refer to the possible chemical conversion paths using hydrogen produced through electrolysis.

In some cases, hydrogen obtained through electrolysis can be directly introduced in a synthetic chemical process without modifying a well-established design (such as is the case for ammonia synthesis), while in other situations (such as for methanol), a new process has to be devised and hydrogen has to be combined directly with carbon dioxide.

It has been suggested that there will be a renewable energy generation surplus, and to exploit the currently available infrastructure and expertise to absorb this by storing green electricity by producing commonly traded chemicals (e.g. [106]).

In this document the label 'hydrogen-to-X' will be used to refer to both 'hydrogen-to-chemicals' and 'hydrogen-to-fuels' options. In both cases, hydrogen is first produced using electricity²⁷ (power-to-hydrogen), and then further reacted in order to produce other chemical compounds (hydrogen-to-chemicals/hydrogen-to-fuels). The only difference between the two expressions is given by the final use of the produced molecule. In the case of 'hydrogen-to-fuels' (often referred to as e-fuels) the aim is to obtain an energy carrier which can be used to replace a conventional fossil fuel. 'Hydrogen-to-chemicals' instead defines the conversion path achieving a specific chemical product. The obtained chemical can also be used as a hydrogen vector and converted back to power ('chemical-to-power'). For a graphical summary of the possible conversion steps see Figure 4.

Any hydrogen-to-fuel conversion process further drives down the efficiency of the overall power-to-fuel-to-power conversion chain, and it should be carefully assessed on a case by case basis, in order to determine whether it makes sense to incur extra conversion losses, and it would be more sensible to use the produced molecule not as an energy carrier, but as a chemical commodity in itself (see also Section 3.2.5.1).

Another concept which is often closely associated with hydrogen-to-X is 'hydrogen (or power)-to-industry'. Hydrogen-to-industry not clearly defined, and in general is outside the scope of this report. We suggest it should refer only to the use of green hydrogen in the refining and steelmaking industries [122], and for producing high grade heat in industrial applications.

Ammonia and methanol are already produced in large quantities and are the two largest (in terms of amount produced) chemicals in the chemical industry. They are transported in large amounts and are traded globally.

Over the years, several large scale production pathways of chemicals with green hydrogen have been suggested. Among these, the most relevant are those related to an ammonia economy [107] and a methanol economy [106, 123]. Other organic molecules have also been considered, for instance formic acid [124].

Methane can also be considered part of the products obtained through a hydrogen-to-X conversion chain, but due to its importance, its already well-established role as a fuel and chemical feedstock, and its current dedicated large infrastructure, it will be treated separately in Section 3.3.4.1.

3.3.1 Hydrogen-to-chemicals KPIs

Obtaining clear and simple KPIs for describing a Hydrogen-to-X conversion process is not straightforward. The conversion of hydrogen into chemicals can be broken down into several conversion steps, each defined by specific parameters. A common trait of all pathways is the starting electrolysis step (power-to-hydrogen), whether this is electrolytic water splitting, a direct electrolytic step (for instance direct electrolytic ammonia synthesis), or a co-electrolysis process. This is followed by the further reaction of the reagents produced (hydrogen in the case of water electrolysis, syngas in the case of co-electrolysis) with other molecules in order to obtain the desired chemical products (hydrogen-to-X). This synthetic step is then followed by the possible transport, storage, and use steps for the chemical produced by the first synthetic step.

The KPIs we propose relate to the synthesis process where hydrogen is combined with other molecules, and is used to obtain ammonia, methanol, formic acid, or other hydrocarbons (electrofuels, e-fuels). However the steps before and after synthesis cannot be completely ignored in the following discussion (Section 3.3.2.6). Usually, the available literature on power-to-X and hydrogen-to-X applications does not neatly separate the different conversion steps, but typically describes the process of converting electricity into chemicals and chemicals back to electricity (power-to-chemicals-to-power) as a continuum. The focus of any analysis will therefore change according to the specific final scope of the analysis itself. The concept of process conversion efficiency should generally take into account the energy required for producing hydrogen.

The energy efficiency of synthetic processes involving hydrogen combination with other molecules, in order to obtain other chemicals, is usually the most relevant specific parameter to be considered when assessing the overall hydrogen-to-X path.

The starting step of electrolytic conversion of water into hydrogen can be easily captured by the KPIs described in Section 3.1.1 and can be considered the same, irrespective of the chemical produced. The

²⁷ For simplicity we are not mentioning co-electrolysis or direct electrolysis options in this introduction, but conceptually electrolysis could be replaced by a co-electrolytic step, or by the direct electrolytic synthesis of the final product.

potential reconversion of the chemical back into power has to be assessed for each specific application, or business case and is out of scope for this report. The supply of reagents other than hydrogen can be considered either as a self-standing process, or incorporated in the synthetic process of the desired chemical. In some cases, such as for the synthesis of ammonia, nitrogen separation from air is usually already included as part of the traditional boundaries of a standard well-established chemical process. For new processes based on carbon capture and use (CCU), such as power-to-methanol pathways, the required CO₂ could be either considered a commodity externally brought into the process (in a similar way to the role of fossil fuels in current chemical processes), or a reagent obtained and integrated in the chemical design itself. Some further considerations on CCU can be found in Section 3.3.2.5.

It is obvious that new synthetic routes have the potential to reduce the carbon emissions of specific products and can have a significant impact in greening the chemical industry. Some possibilities will be summarised below, but it should be emphasised that every organic synthesis, even the most complex, requires a source of carbon and hydrogen [125, 126].

In general, the utilisation of CO₂ as a precursor has the potential to improve the impact of a process, not simply by sequestering, at least temporarily, potential green-house gas emissions in a chemical product, but also by offering alternative synthetic routes which can fall under the aims of green chemistry. For instance, obtaining a product through a synthesis which reduces the use of solvents, or decreasing the number of synthetic steps, will have an added value which is not simply associated to the recycled CO₂ emissions. This is particularly true for homogeneous catalytic processes.

In seeking to define KPIs it should be borne in mind that, especially for the synthetic step following electrolysis, a KPI can refer to a technical dimension which is not necessarily equivalent across several potential hydrogen-to-X paths. This is because the distinctive chemical identity of one molecule cannot be directly compared to that of another if it defines a specific use (e.g. use of ammonia as fertiliser), but only if the molecule can be considered as an intermediate step towards the same end product (e.g. hydrogen or electricity). Moreover, the design of a specific synthetic process should be considered in its context. A specific design could prioritise one aspect against another (e.g. time yield against efficiency), without having to be necessarily considered as lower-performing. Finally, in the absence of precise and specific field data, the analysis of any complex synthetic process requires the use of chemical engineering software modelling to obtain meaningful results.

In spite of all these caveats, it is possible to define some general KPIs for hydrogen-to-X applications. Two straightforward technical KPIs are the process conversion energy efficiency and the space time yield.

The **process conversion energy efficiency** can be defined as the ratio between the energy contained (HHV or LHV) in a tonne of product and the energy required (electrical, thermal and chemical) for obtaining that tonne of product. Since hydrogen production is a fundamental part of the synthetic process itself, it should be accounted for. In any process including a hydrogen-to-X conversion process, the process conversion energy efficiency will be substantially affected by the use of electricity within the electrolytic process producing hydrogen.

Process conversion energy efficiency is not necessarily the only parameter which has to be considered, since a chemical process also has to be efficient in terms of time use. Another possible KPI to be used in assessing the performance of a synthetic step in a hydrogen-to-X application is **space time yield**, which can be defined as the amount of product synthesized in a reactor with a definite volume for a defined time unit, under specific pressure, temperature and flow conditions. This quantity allows direct comparison of different reactor designs operated under similar conditions.

Another important parameter which should be considered for optimisation if a synthetic chemical process is directly supplied with renewable energy from intermittent sources are the **ramp up** and **ramp down** rates of the synthesis process itself. Due to the intermittent nature of some renewable energy sources, solutions to overcome a non-steady electricity supply have to be devised. This is an issue, since chemical synthesis is optimised under stable conditions. Solutions such as hydrogen buffering and designs with high turn-down ratios could be practicable, but at the moment, information in this respect is not available and buffering seems to be the easiest design option available [122].

Economic KPIs can also be used for assessing different process designs. **CAPEX** and **OPEX**²⁸ can be defined with respect to the production capacity of the plant considered. They are heavily impacted by the electrolyser

²⁸ OPEX here includes also the O&M costs as defined in Section 4.1, but includes also electricity costs.

costs and the cost of electricity used by the electrolyser, respectively. The KPIs defined in Section 3.1 will, therefore, significantly affect the CAPEX and OPEX for power-to-X conversion process.

The **levelised cost per unit of chemical product** can be defined as a parameter to capture the net value of a unit of product over the lifetime of a generating asset and can be used to compare the economic potential of different designs for production processes.

3.3.2 Hydrogen-to-X SoA

3.3.2.1 Ammonia

Ammonia is one of the most important synthetic commodity chemicals. Its largest consumer is the fertiliser industry. Ammonia has also been proposed as a fuel [107, 127] and as a hydrogen carrier (see Section 3.2.5) [108]. Currently, the most widespread production method is the Haber-Bosch process. This synthetic method is based on hydrogen and nitrogen reacting at 300–550°C and 100–300 bar over an iron catalyst. The most common source of hydrogen used in industrial plants, at least in Western Europe, is methane steam reforming [128]. Nitrogen is usually obtained through an air separation unit, and once a stoichiometric 3:1 hydrogen mixture is obtained it has to be compressed to the required pressure before the ammonia synthesis process can start.

Steam reforming requires removal of sulphur and carbon monoxide before the hydrogen enters the ammonia production reactor, since both compounds are pollutants for the ammonia synthesis catalysts. Hydrogen purity is therefore an important parameter, and electrolysis can guarantee hydrogen production attaining the required purity without significant purification steps. The main drawback for the use of hydrogen produced by electrolyzers is electricity costs [129, 130]. The technology has however already been proven. In the past, there have been examples of hydrogen production through electrolysis in ammonia plants, but generally only countries with high availability of cheap hydropower have employed this method. Since the eighties, hydrogen production has rarely been performed via electrolysis, due to the generally high cost of electrical power.

Several sources estimate the energy required for ammonia production through the use of hydrogen coming from water electrolysis to be around 9–12 MWh/tNH₃ [122, 131]. Based on ammonia's HHV this would imply a process conversion efficiency between 52 and 70%. Using a conventional process with natural gas as feedstock, this efficiency is estimated to range between 62 and 78%.

A recent study [132] claims that the use of an alternative ammonia synthesis process based on electrolytic hydrogen production has the potential to compete economically with a fossil fuel-based Haber-Bosch synthetic process. A 2017 report from DECHEMA [131] estimates the cost of ammonia production using electrolytic hydrogen to range from a minimum of 255–380€/tNH₃ (with electricity at 10€/MWh) to a maximum of 735–800€/tNH₃ (with electricity at 50€/MWh). In the same report, the production cost of natural gas based ammonia in Europe is estimated to be 350€/tNH₃. Recent reports estimate the levelised cost of ammonia produced by electrolysis to be up to 2–3 times more than that of a standard fossil fuel based production method [42, 122]. A 2019 IEA report estimates a competitive levelised cost for ammonia produced using electrolysis if the available electricity has a price of around 10–40\$/MWh and gas prices are around 3–10\$/MBtu (~10.2–34.1\$/MWh) [42]²⁹.

The direct electrochemical production of ammonia has also been proposed and is a subject of academic research [133, 134]; this production method is, however, still far away from practical demonstration.

3.3.2.2 Methanol

Methanol is a commodity chemical, which is claimed to also have the potential to play a role across different sectors. It is used as a fundamental chemical precursor in many industrial syntheses (e.g. formaldehyde, methyl tert-butyl ether (an antiknock agent) and acetic acid) and can be blended with petrol as a fuel additive.

In particular, its use as an energy carrier has been the main pillar of a proposed “methanol economy” [106]. Methanol can be used as a fuel in the transport sector, even in higher percentages than those currently allowed. Methanol is the precursor for DME (dimethyl ether), which can be used in the chemical industry, or can potentially be employed as a fuel for diesel engines. Methanol can also be used as a precursor for olefin

²⁹ Natural gas coupled with carbon capture is expected to shift the competitive electricity price range up by 5–10 \$/MWh.

synthesis (such as propylene and ethylene), thus having an additional potential role as precursor for petrol and diesel synthesis [135].

The standard industrial process for producing methanol uses syngas (a mixture of carbon monoxide and hydrogen) as precursor and a zinc/copper catalyst. It requires high pressures (50-250 bar) and moderate temperatures (200-350°C) [136].

As for most other chemicals considered in this report, methanol production can have an impact on decarbonisation if both precursor carbon sources (CO_2 , CO) and hydrogen sources (H_2) are not directly linked to fossil fuel sources. Carbon has to be derived from alternative sources (such as biomass, or geothermal emissions), or obtained by CO_2 sequestration.

The direct synthesis of methanol from CO_2 and hydrogen is a well-studied exothermic process and there are at least two plants using this process successfully: the George Olah-Carbon Recycling International (CRI) Plant in Iceland [137] and the Mitsui Chemical plant in Japan [138]. The direct use of CO_2 has the drawback of producing significant amounts of water and has equilibrium yields which are not as favourable as those of CO, but it should have the advantage of facilitating the overall reaction kinetics, since it is believed that CO_2 and not CO is the species reacting with hydrogen and producing methanol [135, 139]. Despite this benefit, the presence of high amounts of pure CO_2 seems to have a detrimental effect on the reaction [136]. The catalyst usually employed in the process is based on $\text{Cu/ZnO/Al}_2\text{O}_3$ (the same as for the current fossil fuel-based reaction); because of the moderate cost of these materials, the catalyst does not seem to have a significant impact on the overall process cost [140].

Several sources estimate the energy required for methanol production through the use of hydrogen from water electrolysis to be around 11-12 MWh/tMeOH [131, 140, 141]. Based on methanol's HHV this would imply a process conversion efficiency of around 52-57%. Using a conventional process with natural gas as feedstock, this efficiency is estimated to be around 60-62%. Where direct air capture is used for obtaining CO_2 , the conversion efficiency is expected to drop by a further 5% [42].

There seems to be a consensus that the biggest contributor to the price of direct methanol production from CO_2 and hydrogen is the cost of hydrogen produced through electrolysis. Even when accounting for the savings in capital costs offered by avoiding the construction and installation of a reformer in a conventional methanol plant, low-carbon hydrogen production has to be cheaper than current state of the art to be competitive under current market prices [135, 140]. Electrolysis is expected to account for about 75% of CAPEX for a plant producing methanol with green hydrogen [131].

A 2017 report from DECHEMA [131], despite acknowledging difficulties linked with high market volatility and uncertainties in projecting costs, states that methanol produced by reacting CO_2 and green hydrogen does not offer a sufficiently profitable business case without subsidies. In a best case scenario, at an electrolyser operating time of 7000 h/year, methanol production costs would be 670 €/t for 50 €/MWh power cost and 290 €/t for 10 €/MWh power cost.

In Europe, production costs for conventional methanol production process based on petrochemicals are estimated to be 400 €/t methanol [142]. Other sources quantify the span of worldwide production costs of methanol based on fossil feedstocks at between 60 and 260 €/t methanol [143]. In general, market prices for methanol seem to be rather volatile.

Potentially methanol can also be obtained by reacting a syngas mixture produced by co-electrolysis, even if current price estimates are not favourable and further developments in SOEL technology are required for driving costs down [144].

A recent report from the IEA estimates the levelised cost of methanol produced by electrolysis to be up to 3 times that of a standard fossil fuel based production method [42]. The same report estimates that a competitive levelised cost for methanol produced using electrolysis could be achieved if the available electricity has a price around 5-50\$/MWh and gas prices are approximately 3-10\$/MBtu [42]³⁰.

CRI, the operator of the Icelandic plant, is active in at least two H2020 projects and is developing the technique, expanding also towards Asian markets.

³⁰ Natural gas coupled with carbon capture is expected to shift the competitive electricity price range up by 5-15 \$/MWh.

3.3.2.3 Formic Acid

Formic acid (HCOOH) is a chemical which already has a significant role as an organic precursor in the chemical industry [145]. It is mainly used as a preservative, silage aid and antibacterial agent in livestock feed [146] and has recently been proposed as a hydrogen carrier, in particular for the automotive sector [124, 147]. Formic acid is usually synthetized by reacting methanol with carbon monoxide (CO) and hydrolysing the produced methyl formate.

A direct industrial homogeneous or electro-catalytic synthesis of formic acid from CO_2 and H_2 , is possible, but the process is deemed not to have reached beyond a TRL of 3-5 [141, 148].

It is possible to overcome the entropic penalty associated with the reaction of gaseous CO_2 and H_2 forming liquid formic acid, by exploiting strong bases and solvation effects [136]. The implementation of these processes is, however, difficult and presents practical challenges. Despite these difficulties, different multiphasic cycles for the synthesis of formic acid have been demonstrated [136].

The modelling of a plant based on one of the above mentioned processes (patented by BASF) by Pérez-Fortes et al. [141, 148] quantified how the profitability and the competitiveness of direct synthesis of formic acid vary based on reagent and product prices. Despite a significant decarbonisation potential identified by Otto et al. [126] and Sternberg et al. [149], the overall profitability of direct CO_2 and H_2 conversion in comparison with the methyl formate hydrolysis route, which is currently the most widespread synthetic route in Europe, is strongly dependent on the price of the final product (formic acid) and not likely to be economically advantageous without subsidy [148].

It should also be noted that the techno-economic data available are not based on actual pilot plants, and significant contributions in cutting costs might be made by finding cheaper solvents and catalysts.

The energy required for formic acid production through the use of hydrogen from water electrolysis is around 4 MWh/tFA [141, 148]. Based on formic acid's HHV this would imply a process conversion efficiency of approximately 38%.

An overview of possible catalysts used in hydrogenation to, and dehydrogenation of, formic acid is given by Singh et al. [150]. We are not aware of general guidelines for identifying the most appropriate catalyst for formic acid synthesis. However, a proposal for trying to detect suitable cheap and efficient catalyst options for the direct conversion of formic acid to CO_2 and H_2 was compiled by Eppinger and Huang [124]. A promising possibility was identified by the authors, but the intrinsic uncertainties associated with the comparability of data in scientific literature reviews do not allow a definitive verdict.

Another uncertainty regarding the future of formic acid is linked to its potential role as hydrogen carrier in automotive applications. Despite the considerable efforts undertaken, to the best of our knowledge, no automaker, or big player in the field of hydrogen transport and distribution is considering formic acid as an option for replacing compressed gaseous or liquid hydrogen. A group of students at Eindhoven TU are working on a formic acid fuelled bus [68].

3.3.2.4 Syngas

One of the most ubiquitous precursors in the modern petrochemical industry is syngas, which is a mixture of CO and H_2 [151]. Among the possibilities not yet explored in the sections above, the Fischer-Tropsch process is definitely worth mentioning. Through this process the synthesis of olefins can be achieved [152].

3.3.2.4.1 Reverse water gas shift

The synthetic possibilities offered by syngas production should not be underestimated. By varying the ratio between CO and H_2 through the Water Gas Shift (WGS) and the Reverse Water Gas Shift (rWGS) reactions, different products can be achieved by using CO_2 and H_2 as reagents (from methane, to mixtures of higher alkanes, equivalent to diesel).

Dry reforming³¹ is another option for obtaining syngas [153].

³¹ The dry reforming reaction involves CO_2 and CH_4 as reagents, and produces a mixture of H_2 and CO .

3.3.2.4.2 Co-electrolysis

Achieving the direct production of syngas through co-electrolysis (power-to-syngas) of H₂O and CO₂ is currently receiving attention, despite the difficulties in developing this technology at an industrial level [151, 154, 155]. Co-electrolysis relies on the same technology as high temperature water electrolysis and is therefore based on a solid oxide electrocatalytic process occurring at temperatures around 700–900°C. The extent of the actual electrocatalytic direct production of CO and the potential simultaneous role played by rWGS after hydrogen is produced through electrolysis is debated, but it seems that experimental design and conditions influence the actual reaction mechanism co-electrolysis follows for the production of a syngas mixture [156, 157].

Furthermore, although typically not directly targeting methanation, the process of co-electrolysis of CO₂ and H₂O by solid oxide electrolyzers can be regarded as a possible methanation route. The direct synthesis of CH₄ has also been achieved, but seems to be at an earlier research stage [158]. The use of water in co-electrolysis has the advantage, over direct CO₂ electrolysis, of using steam which reduces soot formation [159].

3.3.2.5 CO₂ sources capture and use

In addition to hydrogen, any organic chemical product such as methanol, formic acid, methane or any other hydrocarbon, needs to have a carbon dioxide or carbon monoxide source available if achieved through a HtX rather than a fossil fuel based path. The process of capturing CO₂ directly from air, or from an emission point, and subsequently using it in a chemical process, is defined as carbon capture and utilisation (CCU).

Since a separation process becomes more energy intensive and therefore expensive the higher the dilution of the species of interest is, highly concentrated CO₂ sources will be cheaper, and any CCU based synthetic process will try to exploit concentrated sources in its proximity first [160]. Transport of CO₂ to the utilization site also impacts the cost and the feasibility of a CCU path.

Several general reviews summarising the possible use of CO₂ as a precursor in the chemical industry are available [161–163]. Unfortunately, the potential sinks of the available point CO₂ sources for CCU synthetic pathways are often overestimated in their actual decarbonisation potential [164]. As an example urea, which is often cited as a possible CO₂ sink, does not have much actual potential, since it is already produced by using available CO₂ industrial emissions [165].

Direct capture of CO₂ from the atmosphere (Direct Air Capture, DAC) has the advantage of decoupling CO₂ capture from a conventional source (geothermal, fossil or biological). Its main drawback is the high dilution of about 400 ppm of CO₂ in the atmosphere. The thermodynamic minimum energy needed for direct air separation is around 20 kJ/mol CO₂ [166]. The levelised cost of direct air capture based on field and laboratory scale tests is estimated to be between 94 and 232 USD/t CO₂ and requires either 8.81 GJ of natural gas, or 5.25 GJ of natural gas (which is used for process heat) and 366 kWhr of electricity, per ton of CO₂ captured [167]. According to the authors, their estimates are conservative and margins for improvement and optimisation are significant, and will strongly depend on technological maturity. The authors also challenged earlier estimates which were more pessimistic on the economic potential of direct air capture [168].

3.3.2.6 Electrofuels

The idea of producing electrofuels (also called synthetic fuels or e-fuels) from "environmentally friendly" precursors such as hydrogen and captured carbon dioxide has the advantage of exploiting parts of the well-established fossil fuel infrastructure currently available. It has been advocated as a first step towards transport decarbonisation, in particular for transport segments which cannot be easily electrified, such as aviation.

Since the term electrofuel is used frequently, and sometimes with different definitions, we will refer to the definition given by Brynolf and others [169]³². Since the use of electrofuels is associated with carbon dioxide release, a caveat should be always given when a carbon-containing chemical is recommended as a fuel. Whereas it is true that the production of the chemical could be made overall "greener" by utilising captured CO₂ (CCU), if the sequestered carbon is not stored for significantly long periods, the emissions associated with the electrofuel use are not necessarily decreasing [170]. Any energy cycle where a proposed energy carrier (such as formic acid or methanol) is producing CO₂ (either by direct combustion, or as hydrogen carrier), is

³² "Electrofuels are carbon-based fuels produced from carbon dioxide (CO₂) and water, with electricity as the primary source of energy. Electrofuels are also known as power-to-gas/liquids/fuels, e-fuels, or synthetic fuels. They are potentially of interest for all transport modes; some can be used directly in combustion engines and may not require significant investments in new infrastructure."

only shifting carbon emissions from the production to the consumption step, unless the emitted CO₂ can somehow be captured after use.

In the case of any hydrogen carrier (see Section 3.2.5), but especially for electrofuels, the whole power-to-x-to-power cycle should be accurately assessed since only then, the potential advantages can be evaluated. The use of LCA (Life Cycle Analysis) has been already explored for quantifying the environmental impact of captured carbon emission in different contexts [170, 171].

3.3.3 Horizon 2020 Hydrogen-to-X projects

The conversion of hydrogen into chemicals is a relatively recent focus for large European projects. The EU's R&D programmes have only been supporting projects touching upon these topics with significant resources since 2014 (see Table 13).

Table 13: Summary of Horizon 2020 Hydrogen-to-X Projects by technology (non-FCH 2 JU projects are shown in italics)

Technology	Acronym	Programme	Topics	Title	Period	Overall budget	EU contribution
FT and co-electrolysis	KEROGREEN	H2020-EU.3.3.5.	LCE-06-2017 - New knowledge and technologies	<i>Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO₂, syngas formation and Fischer-Tropsch synthesis</i>	2018-2022	€4 951 958,75	€4 951 958,75
		H2020-EU.3.3.2.					
	Eco	H2020-EU.3.3.8.2	FCH-02-3-2015	Efficient Co-Electrolyser for Efficient Renewable Energy Storage	2016-2019	€3 239 138,75	€2 500 513,75
	CELBICON	H2020-EU.3.2.	<i>ISIB-06-2015 - Converting CO₂ into chemicals</i>	<i>Cost-effective CO₂ conversion into chemicals via combination of Capture, ELectrochemical and BI-chemical CONversion technologies</i>	2016-2019	€6 211 040,25	€5 429 201,50
Methanol	eCOCO ₂	H2020-EU.3.3.2.	<i>CE-SC3-NZE-2-2018 - Conversion of captured CO₂</i>	<i>Direct electrocatalytic conversion of CO₂ into chemical energy carriers in a co-ionic membrane reactor</i>	2019-2023	€4 447 978,75	€3 949 978,75
	MefCO ₂	H2020-EU.2.1.5.3.	H2020-SPIRE-2014	<i>Synthesis of methanol from captured carbon dioxide using surplus electricity</i>	2014-2019	€11 068 323,75	€8 622 292,60
	CIRCLENERGY	H2020-EU.3.3.	<i>SMEInst-09-2016-2017 - Stimulating the innovation potential of SMEs for a low carbon and efficient energy system</i>	<i>Production of renewable methanol from captured emissions and renewable energy sources, for its utilisation for clean fuel production and green consumer goods</i>	2017-2018	€71 429	€50 000
	FReSMe	H2020-EU.3.3.2.	<i>LCE-25-2016 - Utilisation of captured CO₂ as feedstock for the process industry</i>	<i>From residual steel gasses to methanol</i>	2016-2020	€11 406 725	€11 406 725

Technology	Acronym	Programme	Topics	Title	Period	Overall budget	EU contribution
	LOTER.CO2M	H2020-EU.2.1.3. H2020-EU.2.1.2.	NMBP-19-2017 - Cost-effective materials for "power-to-chemical" technologies	CRM-free Low Temperature Electrochemical Reduction of CO ₂ to Methanol	2018-2020	€4 264 452,50	€4 264 452,50
Methanol derivates	CASCADE-X	H2020-EU.1.3.2.	MSCA-IF-2017 Individual Fellowships	CO ₂ to light olefins conversion by cascade reactions over bifunctional nanocatalysts: an 'all X-ray' approach	2018-2020	€196 400,40	€196 400,40
	CO2Fokus	H2020-EU.3.3.2.	CE-SC3-NZE-2-2018 - Conversion of captured CO ₂	CO ₂ utilisation focused on market relevant dimethyl ether production, via 3D printed reactor- and solid oxide cell based technologies	2019-2022	€3 994 950	€3 994 950
	COZMOS	H2020-EU.3.3.2.	CE-SC3-NZE-2-2018	Efficient CO ₂ conversion over multisite Zeolite-Metal nanocatalysts to fuels and OlefinS	2019-2023	€4 752 386,25	€3 997 163,75
Formic Acid/Methanol derivates	C2FUEL	H2020-EU.3.3.2.	CE-SC3-NZE-2-2018	Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem	2019-2023	€4 130 291,25	€3 999 840
Formic acid	CO2COFS	H2020-EU.1.3.2	MSCA-IF-2018 Individual Fellowships	New Heterogeneous Catalyst Materials for Hydrogenation of CO ₂ to Formic Acid: Metallocphthalocyanine-Based 2D- and 3D Covalent Organic Frameworks	2019-2022	€239 722,56	€239 722,56
Roadmaps/Resources Assessment	ENERGY-X	H2020-EU.1.2.3	FETFLAG-01-2018 - Preparatory Actions for new FET Flagships	ENERGY-X: Transformative chemistry for a sustainable energy future	2019-2020	€976 115	€976 115
	STRATEGY CCUS	H2020-EU.3.3.2	LC-SC3-NZE-3-2018 - Strategic planning for CCUS development	Strategic planning of regions and territories in Europe for low-carbon energy and industry through CCUS	2019-2022	€3 069 473,75	€2 959 533,75

Source: JRC, Source: JRC 2020, based on publicly available data.

Two main types of projects can be distinguished: the first group is trying to develop or characterise catalytic processes for power-to-chemicals applications (low TRL), while the second is performing field tests or demonstrations for power-to-hydrogen/hydrogen-to-chemicals applications (medium TRL). While the first class of projects (e.g. CASCADE-X, or CO2COFS) is dominated by academic players, the second sees the participation of industrial partners which are interested in developing power-to-hydrogen/hydrogen-to-chemicals conversion technologies in industrial settings.

Drawing conclusions from the projects listed in Table 13 is difficult for two reasons. The first reason is the recent starting date of most of the projects. With the exception of MEFCO2, CELBICON and ECO all the projects are still running, or had not even started at the cut-off date of this report. The second reason is the lack of access to detailed project reports and deliverables. Many projects do not have a dedicated webpage containing technical information.

All the projects aiming at power-to-fuels applications are developing co-electrolysis solutions for producing electrofuels. For most of these projects, co-electrolysis is the only option considered. Two projects (KEROGREEN and ECOCO2) have the goal to develop substitute fuels for aviation. With the exception of CELBICON these projects do not seem to focus on also developing carbon capture. The steel industry seems to be particularly interested in developing CCU solutions which can valorise steelmaking emissions by converting them into methanol (C2FUEL, ECOCO2, FRESME and COZMOS).

Several projects are investigating power-to-methanol conversion pathways. With the exception of LOTER.CO2M, which is pursuing a new direct co-electrolytic methanol synthesis, all the projects are aiming at methanol production through heterogeneous catalysis. Two (CASCADE-X and COZMOS) are explicitly planning to exploit the production of olefins by developing innovative methanol to olefins processes.

The only project specifically targeting formic acid production is CO2COFS. C2FUEL has formic acid as one of the expected target products.

Two projects (ENERGY-X and STRATEGY CCUS) are developing roadmaps and performing mapping exercises for the development of power-to-X applications across Europe. This also includes CCU.

No hydrogen-to-ammonia demonstration or field test seems to be currently running in Europe under H2020.

As the table shows, Europe is ramping up investments for hydrogen-to-X under H2020 with projects totalling about €63.3 million in contributions from public funds. For most of the projects considered, European funds are covering the majority of the project costs, with around 90% percent of projects costs supported by public funds. Hydrogen-to-methanol applications received the largest fraction of financial support (around 56%), followed by applications aiming at fuel or fuel precursor (such as syngas) development (around 30% of public funds). Many projects are nevertheless developing olefin production routes via methanol synthesis. These projects were considered together with power-to-methanol applications. Roadmap and planning activities secure about 6% of the total European funding in this field.

In the following sections, a more detailed description of the projects of Table 13 will be provided; this description is based on the CORDIS project abstracts and whenever possible, contains information on expected TRL levels, KPIs, and technical objectives.

3.3.3.1 Fischer Tropsch and co-electrolysis

- KEROGREEN offers a novel conversion route to sustainable aviation fuel synthesised from H₂O and CO₂ powered by renewable electricity. The conversion is based on plasma driven CO₂ dissociation, solid oxide membranes and Fischer-Tropsch (F-T) synthesis of kerosene. In this project the technology readiness level is raised from TRL 3 to 4 by novel system integration into a container sized unit producing 1kg/hr kerosene. The projected cost at this stage of development is estimated a +50% of fossil kerosene.
- The overall goal of ECO (see also Section 3.1 – this is the only power-to-X project financed by the FCH 2 JU) is to develop and validate a highly efficient co-electrolysis process for conversion of excess renewable electricity into distributable and storable hydrocarbons via simultaneous electrolysis of steam and CO₂ through SOEC (Solid Oxide Electrolysis Cells) thus moving the technology from technology readiness level (TRL) 3 to 5.
- CELBICON aims at the development, from TRL3 to TRL5, of new CO₂-to-chemicals technologies for small-scale, decentralized market penetration. These technologies will bridge cost-effective CO₂ capture and purification from the atmosphere through sorbents, with electrochemical conversion of CO₂, followed by bioreactors carrying out the fermentation of the CO₂-reduction intermediates (syngas, C1 water-soluble molecules) to form valuable products (bioplastics such as polyhydroxyalkanoates (PHA), isoprene, lactic acid, methane, etc.) as well as effective routes for their recovery from the process outlet streams. Over the project duration, the two process lines described will undergo a thorough component development R&D programme so as to be able to assemble three optimised TRL5 integrated test-rigs (one per TP). A life cycle assessment with CO₂ from different sources (cement industry or biogas) and electricity from preferably renewable sources to prove the recycling potential of the concept is performed.
- The project ECOCO2 aims to set up a CO₂ conversion process using renewable electricity and steam to directly produce synthetic jet fuels with balanced hydrocarbon distribution (paraffin, olefins and aromatics) to meet the stringent specifications in aviation. The CO₂ converter consists of a tailor-

made multifunctional catalyst integrated in a co-ionic electrochemical cell that enables in situ electrolysis and water removal from hydrocarbon synthesis reactions. This intensified process can lead to breakthrough product yield and efficiency for chemical energy storage, specifically CO₂ per-pass conversion > 85%, energy efficiency > 85% and net specific demand < 6 MWh/t CO₂. ECOCO₂ aims to demonstrate the technology (TRL5) by producing > 250 g of jet fuel per day in an existing modular prototype rig that integrates 18 tubular intensified electrochemical reactors.

3.3.3.2 Methanol

- The project MEFCO₂ is to encompass flexible (in operation and feed) methanol synthesis with high carbon dioxide concentration-streams as an input, the latter originating from thermal power stations using fossil fuels. The other synthesis reactant, hydrogen, is to originate from water electrolysis using surplus energy, which would be conversely difficult to return to the grid. The principal technological challenge to be overcome is anticipated to be the development of a suitable catalyst and process, which would allow for high-CO₂-content feeds, relatively transient operation (save for an upstream buffering technology), and economically viable operating conditions.
- CIRCLENERGY is supporting the company Carbon Recycling International (CRI) to up-scale its current plant scale and offer a standard, modular emissions-to-liquids plant design with nominal 50.000 t/yr methanol production capacity.
- The FRESME project will produce methanol that will be demonstrated in ship transportation. This fuel will be produced from CO₂, recovered from an industrial blast furnace, and hydrogen recovered both from the blast furnace gas itself, as well as hydrogen produced by electrolysis. The project will make use of the existing equipment from two pilot plants, one for the energy efficient separation of hydrogen and CO₂ from blast furnace gas, and one for the production of methanol from a CO₂-H₂ stream. This can be realised with a small amount of extra equipment, including supplemental H₂ production from an electrolyser and a H₂/N₂ separation unit from commercially available equipment. The pilot plant will run for a total of three months divided over three different runs with a nominal production rate of up to 50 kg/hr from an input of 800 m³/hr blast furnace gas. This size is commensurate with operation at TRL6.
- LOTER.CO₂M aims to develop advanced, low-cost electro-catalysts and membranes for the direct electrochemical reduction of CO₂ to methanol by low temperature CO₂-H₂O co-electrolysis. Field testing of the co-electrolysis system in an industrially relevant environment will enable the evaluation of the commercial competitiveness and the development of an exploitation plan. The demonstration of new materials at TRL5, and the potential of this technology for market penetration, will be assessed by achieving a target electrochemical performance > 50 A/g at 1.5 V/cell, a CO₂ conversion rate > 60%, and a selectivity > 90% towards methanol production with an enthalpy efficiency for the process > 86%. A significant increase in durability under intermittent operation in combination with renewable power sources is also targeted in the project through several stabilization strategies to achieve a degradation rate of < 1%/1000 h at stack level. The developed low-temperature CO₂ conversion reactor will offer fast response (frequency > 2-5 Hz) to electrical current fluctuations typical of intermittent power sources and a wide operating range in terms of input power, i.e. from 10% to full power in less than a second. A life cycle assessment, which will compile information at different levels from materials up to the electrolysis system including processing resources, will complete the assessment of this technology for large-scale application.

3.3.3.3 Methanol derivates

- The cascade process proposed by CASCADE-X connects hydrogenation of CO₂ to methanol (MeOH) and conversion of MeOH to olefins, both well-known industrial processes requiring two different reactors operating at widely different temperatures (250 vs 400°C) and pressures (50 vs 1 bar). The targeted bifunctional catalyst will be obtained by integrating, at the molecular scale, an active metal alloy for the CO₂-to-MeOH reaction onto a zeotype catalyst for selective MeOH-to-olefins conversion. The project aims at the rational optimization of bifunctional catalyst and reaction conditions for the cascade process, by gaining fundamental knowledge on properties and performance relationships for the combined system and by interfacing, in a positive feedback loop, characterization, synthesis and catalytic testing tasks.

- The CO2FOKUS project aims to realise the full potential of a number of concrete strategies to exploit the direct use of CO₂ for the production of dimethyl ether (DME) by CO₂ hydrogenation. With CO₂ utilisation at its heart, CO2FOKUS will seek to exploit the inherent advantages of both chemical and electrochemical systems to establish robust, industrially optimal proofs-of-concept, reaching TRL 6 by the end of the project. The project will explore energy-efficient processes for two separate, potentially integrated systems, namely a 3D printed multichannel reactor and a solid oxide fuel cell (for co-electrolysis and electrolysis/reverse operation). Both systems will be evaluated for operational flexibility in an industrial environment with a CO₂ emission point source. H₂, as a renewable energy source, will be supplied via the solid oxide cell operating in electrolysis mode.
- COZMOS will develop an energy-efficient and environmentally and economically viable conversion of CO₂ to fuels and high added value chemicals via an innovative, cost effective catalyst, reactor and process. The concept will combine the sequential reactions of CO₂ hydrogenation to methanol and methanol to C3 hydrocarbons. Complete conversion of CO₂ to an 85 % yield of C3 hydrocarbons will be achieved by using an optimised bifunctional catalyst within a single reactor.

3.3.3.4 Formic Acid/Methanol derivates

- C2FUEL will run a demonstration at Dunkirk between DK6 combined cycle power plant, Arcelor Mittal steel factory and one of the major European harbours, a showcase for future replication. The CO₂ present in the blast furnace gas will be selectively removed and combined with green hydrogen generated by electrolysis fed with renewable electricity to produce two promising energy carriers (DME and FA). It will simultaneously allow for the reuse of CO₂ emissions from the steel-making factory, the use of the electricity surplus in the Dunkirk area and the improvement of the operational and environmental performance of the DK6 combined cycle. C2FUEL key projected targets are an annual production of 2,4 Mt of formic acid, 100 kt of green hydrogen for seasonal storage using 3,6TWh of renewable electricity and 1,2 Mt of DME with 320 kt of green hydrogen using 11TWh of renewable electricity.

3.3.3.5 Formic Acid

- The CO2COFs project will meet the need for new heterogeneous catalyst materials for catalytic CO₂ hydrogenation to formic acid (FA) by developing novel metallophthalocyanine (MPc)-based covalent organic frameworks (COFs) with high crystallinity and large surface area for renewable hydrogen storage in formic acid (FA).

3.3.3.6 Roadmaps/Resources Assessment

- The ENERGY-X project brings together interdisciplinary academic research (chemistry, physics, engineering and economic science) with cross-industrial technological expertise (chemical, engineering, utilities, mobility, agriculture) to provide a platform for future chemical energy conversion technology in Europe. ENERGY-X will also transfer the knowledge into two demonstration projects: manufacturing of carbon-neutral aviation fuels and decentralized production of fertilizers with no CO₂ footprint.
- At present the CCUS clusters being progressed are concentrated in Western Europe around the North Sea. The STRATEGY CCUS project aims to elaborate strategic plans for CCUS development in Southern and Eastern Europe at short term (up to 3 years), medium term (3-10 years) and long term (more than 10 years).

3.3.4 Methanation (Hydrogen-to-Methane)

Methane is already a fundamental commodity, both in the energy and the chemical sector. Methane is nowadays mainly extracted from natural gas, and it can be considered as both a fuel and as a 'raw material' for the chemical industry. It has been argued that it has the prospect to play an increasingly important role in transport³³, but it has also been pointed out that it causes significant greenhouse gas emissions if not made from biomass or sequestered CO₂. The biggest advantage of synthetic methane is that, being virtually the same as methane coming from natural gas, its use, its infrastructure and therefore its acceptance can profit from decades of experience.

Here, we use the term 'methanation' to refer to the key process behind many applications usually labelled as 'power-to-gas' [172]. In this document we will explicitly define production of synthetic methane as exploiting electrolytic processes for a 'hydrogen-to-methane' route. This process can be included in the hydrogen-to-X family of applications.

The production of methane by combining hydrogen with carbon monoxide or carbon dioxide, through catalysis, is a technological option which has been developed since the seventies and eighties. We consider methanation as a 2-step process:

- 1) Hydrogen production.
- 2) Either CO₂³⁴, CO or a mixture of the two is combined with H₂ for CH₄ production.

3.3.4.1 Methanation KPIs

The H2020 programme does not provide the state-of-the art and future targets for methanation.

KPIs can nonetheless be defined:

- **Energy efficiency** of the process, defined as the ratio between the energy contained (HHV or LHV) in a tonne of product and the energy required (electrical, thermal and chemical) for obtaining that tonne of product. The efficiency is affected by whether the waste heat of the exothermic methanation process can be used. The efficiency is around 83%, based on the lower heating value [173].
- **CAPEX** – related to process concept, complexity, volume and scale.
- **OPEX** – apart from the electricity needed for the production of hydrogen, this includes the operation of the plant, replacement of catalysts and handling of the process as well as CO₂ separation costs.

Other parameters have been proposed [174]:

- Achievable **gas quality of the product gas**. The properties of SNG produced in a power-to-methane chain must be similar to the properties of natural gas distributed in the gas grid. Typically, natural gas contains more than 80% CH₄. A >98% CO₂ conversion of is needed to achieve methane content of >90% [174]
- To be suitable for use in a power-to-methane context, based on the use of intermittent sources of renewable energy, **dynamic operation** is a key parameter. Part-load operation in a load range of 20 – 100 % should be possible [175]. In addition, the start/stop and ramping up and down (load change rate) of the process is important in the context of hydrogen-to-X.

As for the other hydrogen-to-X processes described above, the space-time yield is a KPI. In literature, further indicators such as methane production rate are proposed, with often varying definitions [176].

³³ The Directive on the deployment of alternative fuels infrastructure (COM(2013)18) recognizes natural gas as an alternative fuel.

³⁴ The Sabatier process is based on the reaction of CO₂ and H₂ in order to produce methane.

3.3.4.2 Methanation SoA

Synthetic methane is produced from the reaction of hydrogen with carbon oxides, which are typically in the form of either CO or CO₂. Today, methanation technology is not implemented as part of an industrial chemical manufacturing chain, as methane is mainly extracted from natural gas. During the oil crisis in the 1970s and 80s, efforts were made to produce synthetic natural gas (SNG) with CO from coal gasification, but few plants were implemented at a commercial scale [177]. During this period the plants would be operated on an industrial, multi-MW scale and be running continuously.

In the recent past, methanation has seen increased attention as part of the power-to-methane concept, focussing on CO₂ methanation by hydrogen. The main advantage of methanation in this context is the fact that synthetic methane can be used as a storage medium for renewable hydrogen, making use of the current gas infrastructure without further investments. In a future, more decentralised energy system, methanation units at smaller scales could also make sense, and they should be able to be operated dynamically. This has implications for the reactor concepts, which have to fulfil additional requirements, such as scalable reactor designs and load flexibility.

Methanation also plays a role in the production of biomethane³⁵. Biogas is produced through the anaerobic digestion of biomass, which yields a mixture of methane (50–70%), carbon dioxide (30–50%) and other gases [178]. Biogas can be upgraded into biomethane (suitable for injection into the gas grid) by removing the CO₂ through physical or chemical processes, or through methanation. For the latter process, the CO₂ is combined with H₂ from another source and reacted to methane. This additional methanation step can increase the biomethane yield considerably. The integration of Power-to-Gas with biogas production was investigated by DNV GL, with the conclusion that there are challenges related to the matching of the substrate flows. This is due to the fact that there would be a steady supply of CO₂ from biogas production and variable supply of hydrogen in the case of the coupling of the electrolyser to wind/solar energy sources [179].

In this report the key methanation routes considered with regard to power-to-methane applications are chemical and biological processes. Chemical, also referred to as thermochemical, or catalytic methanation, or Sabatier process, is a high temperature process based on metal catalysts. For biological methanation, the reaction is catalysed with microorganisms.

Photocatalytic or direct electrolytic are not part of the scope, since these methods are at much earlier development stages.

3.3.4.2.1 Methanation processes – chemical methanation

Both carbon dioxide and carbon monoxide conversion to methane are exothermic processes. Currently, the main focus of process development is based on carbon dioxide conversion, for which several catalytic methanation concepts exist. There are several types of reactors for chemical methanation processes. These reactors can be classified according to the type of the support for the catalysts (e. g. honeycombs or pellets), the temperature control (e. g. isothermal or adiabatic) or the number of phases involved in the methanation reaction [180]. Reviews by Rönsch et al. [177] and Götz et al. [174] offer a comprehensive overview of the different methanation processes. The efficiency for the whole synthetic methane production chain (from renewable energy generation to methane production) is currently around 55%, on the assumption that no use is made of the heat generated. [174]. The energy efficiency of the catalytic methanation process itself is currently around 70–80%, depending on the reactor type, with energy losses in the form of heat. The high temperature required for chemical methanation (at least 300 °C) provides an opportunity for integrating and using waste heat. In case of a production process in combination with high temperature electrolysis, if the waste heat streams are fully utilized, then the overall efficiency, including electrolysis, could approach 80% [181].

³⁵ According to EN16723-1, biomethane is defined as “gas comprising principally methane, obtained from either upgrading of biogas or methanation of biosyngas.”

Table 14 Methanation processes

Process	Reaction	Enthalpy
CO methanation	$3 \text{ H}_2 + \text{CO} \rightarrow \text{CH}_4 + \text{H}_2\text{O}$ (steam)	$\Delta H_R = -206 \text{ kJ/mol}$
CO₂ methanation	$4 \text{ H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$ (steam)	$\Delta H_R = -165 \text{ kJ/mol}$
(Sabatier reaction)		

Source: adapted from [177]

The highly exothermic reactions imply that the temperature control within a catalytic reactor is a significant challenge. The various reactor concepts that have been developed present different routes for an efficient removal of heat. The most technically advanced processes are fixed-bed reactors and structured reactors. Fixed-bed reactors have been implemented at large scale and are commercially available, but may not be suitable for dynamic operation or smaller plant sizes. In fluidised bed reactors, methanation takes place within a moving bed of catalyst particles. This enables a good mixing of gas and solid catalyst particles and high heat transfer. Another means of heat management is the introduction of highly thermally conducting structures. Methanation reactors are under development where the catalyst material is coated on monolithic metal or ceramic structures, which offer a better transport of heat [182]. Structured reactors have another advantage as they can be both compact and modular [174].

Apart from methanation reactor concepts, the catalyst material has a great influence on the process. The methanation reaction can, in principle, be catalyzed by the metals of groups 8–10 of the periodic table, but due to a selectivity of close to 100%, high activity, sulphur tolerance, and low cost, nickel is commonly used in commercial methanation plants [174]. The catalyst material is often in a supported form on high surface area metal oxides [177].

Although methanation reactors are already commercially available, research is still necessary to understand the actual reaction mechanism, in order to develop new catalysts, to improve current methanation catalysts and to develop reactor designs as well as process models. Process temperature control, enhancements of cost efficiency and flexibility, i.e. dynamic operation behaviour when coupled to intermittent RES, are also in the focus of research [177]. In principle both chemical and biological methanation react well to load changes, with the limiting factor being the process control, rather than the process itself [174]. Minimum loads around 10% should be possible for most methanation concepts, but for adiabatic fixed bed reactors, the reactor design may need to be adapted [174].

The heat from the exothermic methanation process can be used for increasing the efficiency of hydrogen production with SOEC. An integration with co-electrolysis (see Section 3.3.2.4.2) to produce syngas, which in turn is converted to methane is also possible. The efficiency and methane production rate of the two routes are compared in a publication [183], which showed that there is a trade-off between efficiency and methane yield.

Relatively high investment expenditures are incurred for the methanation installation, probably due to the fact that there is a limited market for such plants. The actual investment costs for methanation plants are highly uncertain. The review by Götz et al. [174] found values ranging from 1500 €/kW to 130 €/kW_{SNG} for a 110 MW plant. There is also no agreement on the cost of synthetic methane, which could be anywhere from 10 [184]-640 [185] €/MWh_{fuel}. According to another source synthetic natural gas could cost in the range 100-290 €/MWh in 2030 [169]. In general there does not seem to be a favourable case for methanation from an economic perspective.

3.3.4.2.2 Methanation processes – Biological methanation

Since the late nineties, biological methanation has received an increasing level of attention and there are methanation projects based on this technology. Hydrogen and carbon dioxide are converted into methane, with methanogenic microorganisms acting as biocatalysts. Biological methanation is characterized by a much lower temperature of the process and greater flexibility of production than chemical methanation. The process of biological methanation takes place at ambient pressures and a temperature of 20–40°C for archaeal or mesophilic bacteria and 45–60°C for thermophilic bacteria. The reaction can take place either in biogas digesters (by adding hydrogen) or in dedicated reactors. Both chemical and biological methanation are based on the strongly exothermic Sabatier reaction. As the temperature of the biological process is low, there is not

much opportunity to utilise the waste heat (e.g. for heating the biogas digester). The overall power-to-methane efficiency could be up to 58%, compared to >80% for the chemical route with optimal heat integration [180].

The main advantage of biological methanation is the short response time, which can be only a few seconds from the start of the reaction until reaching full power. Bacteria involved in the process may stay dormant for weeks or months and begin to react when the process is started. A catalyst is also not required, which may reduce installation costs. An additional advantage is the fact that, unlike catalytic methanation, biological methanation can be carried out using unpurified gas, containing a relatively low concentration of pollutants such as H₂S. However, further research is needed on the effect of compounds such as CO or NH₃[179].

Apart from a slow reaction rate, the much larger volume needed for the reactor vessel is among the disadvantages of biological methanation. Biological methanation can be carried out either *in situ*, within a digester of a biogas plant, or in a separate reactor. The addition of hydrogen to the biogas production process leads to a higher conversion of CO₂ compared to conventional biogas upgrading [178]. Biogas contains up to 50% carbon dioxide, however the biological methanation reaction is linked to the availability of CO₂ for the process, as the amount of hydrogen injected has to be permanently adapted to the carbon dioxide production which entails cost intensive gas measurement and automation equipment [186].

A separate methanation reactor can be optimised for the biological process and higher methane formation rates are possible. Investment costs for methanation plants have been reported to range from 400 €/kW for an *in situ* 5 MW SNG plant, to 600 €/kW for the external reactors [180].

For both types of reactors (*in situ* or separate), the rate limiting step is the homogeneous supply of hydrogen to the bacteria. A consequence of this is that, in spite of the low temperature of the biological process, there is a considerable electricity demand for mechanical stirring (0.4 – 0.8 kWh/m³ SNG [180]). This is used in most reactor types to increase the availability of hydrogen for the reaction.

In general, determination of the energy efficiency of biological methanation should take the methane content of the reactant gas into account, which can range from 13–98%, depending on the reactor concept [174].

As already mentioned, the methane formation rate should also be considered, which may be low for *in situ* reactors with a high methane concentration.

In summary, due to lower costs and short response time, biological methanation is an attractive alternative to chemical methanation, in particular for smaller plant sizes. At the moment, however, this technology is still in the research and development phase, with some larger scale pilot projects in operation.

3.3.4.2.3 Methanation demonstration projects

Two recent reviews summarising methanation demo projects are available. The first focuses on a detailed and comprehensive overview of mainly European projects [187]. The second offers a technological overview of methanation processes and a general overview of [n] projects at demonstration and commercial scale [177]. According to these reviews, Germany is leading in terms of efforts regarding methanation technologies.

The AUDI e-gas project has installed 6MW of electrolyser capacity coupled to a wind park combined with a cooled fixed bed methanation unit. The reactor concept, initially developed by ZSW, is based on a multi-tubular fixed bed reactor with small diameter catalyst filled tubes, which are cooled by molten salt or other cooling media [182]. The CO₂ is obtained from a biogas plant. The overall process efficiency is stated to be 54% without using heat, for a planned "e-gas" output of 1000t/a [188].

The FP7 FCH JU HELMETH project aimed at thermally integrating methanation with high temperature electrolysis. The demonstration of the integrated system was not entirely successful, however an efficiency of 76% HHV was achieved [189]. The multi-step methanation module reactor concept was based on boiling water cooling and operated at pressures up to 30 bar.

The Electrochaea concept, based on optimised *Acheaea* organisms, seems to have overcome some of the challenges for biological methanation, as it reports achieving a product purity of 98–99% at an overall energy efficiency of 58% for power-to-methane [190]. The BIOCAT project demonstrated this concept for a plant of 1MW near Copenhagen, injecting the SNG into the distribution grid. The plant uses an *ex situ* reactor, and the total CAPEX for this first-of-a-kind plant was around €3.85 million [178].

3.3.4.3 H2020 Methanation projects

- The ongoing project STORE&GO will demonstrate three different methanation routes at locations in Falkenhagen in Germany, Solothurn in Switzerland and Troia in Italy, based on existing facilities from previous hydrogen admixture projects. Different types of catalytic methanation reactor will be demonstrated in Falkenhagen and Troia, while the Solothurn plant will be based on biological methanation. The synthetic methane will be injected into the transmission grid in Germany, and into the distribution grid at the two other sites [175]. The biological methanation at the Switzerland site is based on the Electrochaea concept and started operation in January 2019. In Falkenhagen, a metallic honeycomb-type catalytic reactor with good radial heat transport will be scaled up to MW-size.
- The Italian company PLC is developing ProGeo, a 500 kW Power-to-Gas modular unit, supported by funding from the SME support programme SIE 2015. There are no details on the methanation technology.
- ELECTHANE OWS, also funded through a SIE call, planned to commercialize a biological process that converts CO₂ and H₂ (after electrolysis of renewable electricity) to CH₄ (main component in natural gas). However, the project concluded that there is currently no positive business case. No further information is available on this project.
- PENTAGON, funded under a 2016 LCE call, investigates the integration of energy conversion technologies into district level energy systems. The key focus areas are PtG for coupling with typical district heating plants and a district energy management platform for the combined monitoring and management of all district energy carriers. This work can support the creation of eco-districts, which aim to integrate objectives of sustainable development within a district area. Among the many options investigated is PtG, which is understood as methanation of renewable hydrogen. The methanation reactor at the laboratory test plant will use a fixed bed methanation reactor, employing commercially available nickel-based catalysts, with the hydrogen being produced through SOEC.
- The ELECTROGAS concept for electrochemical production of SNG will be supported by an SME grant.
- The EIT InnoEnergy supported project CO2-SNG³⁶ is looking into the conversion of carbon dioxide captured from power units into synthetic natural gas. The aim of the pilot plant launched by TAURON at the power station in Łaziska is to supply vehicles. “Excess” electrical energy is used during the project to generate hydrogen; subsequently, hydrogen is, together with carbon dioxide captured from boiler flue gases, used in the methanation reactor for the production of synthetic methane. The carbon dioxide required for the process comes from the pilot plant for capturing CO₂, which is extracted from flue gases from a working power unit.

³⁶ This project is not listed in the overview table in Annex A, as no further information on this project was available.

3.4 Analysis of funding

There are multiple possibilities to obtain funding for R&I and deployment of CEST related technologies. At EU level the main instrument in the time period considered (2014-2020) is the Horizon 2020 (H2020) research and innovation programme [191]. Funding of CEST is also available, among other routes, through the Connecting Europe Facility (CEF) [13] and European Structural and Investment Funds³⁷. The European Investment Bank, through the InnovFin programme, has given loans to projects on related topics, such as the Danish Everfuel project, as mentioned in section 4.1.3, but not to projects fully within the scope of this report. CEF and Structural and Investment Funds are dedicated to the development of European infrastructure and are therefore less relevant to the scope of this work, with the exception of one project funded under CEF, TSO2020 (see section 3.1.4). The European Institute of Innovation & Technology (EIT), under the Knowledge and Innovation Community (KIC) InnoEnergy, is also supporting relevant projects (for example SNG - CO₂, see section 3.3.4.3), although detailed information on these is not available.

As described in Section 2.2, the full list of H2020 projects within the timeframe analysed for this report was screened according to a list of keywords. A total of 55 projects were identified as falling within the scope. The full list of projects can be found in Table 18. The EU contribution to those 55 projects is EUR 180 million, and was awarded to the projects through the H2020 instruments are listed in Table 15. The share of the total EU funding per funding instrument is shown in Figure 16. The key role of the FCH 2 JU as a funding body for CEST projects is evident, as it is providing 47% of the funding, mainly for electrolyser projects.

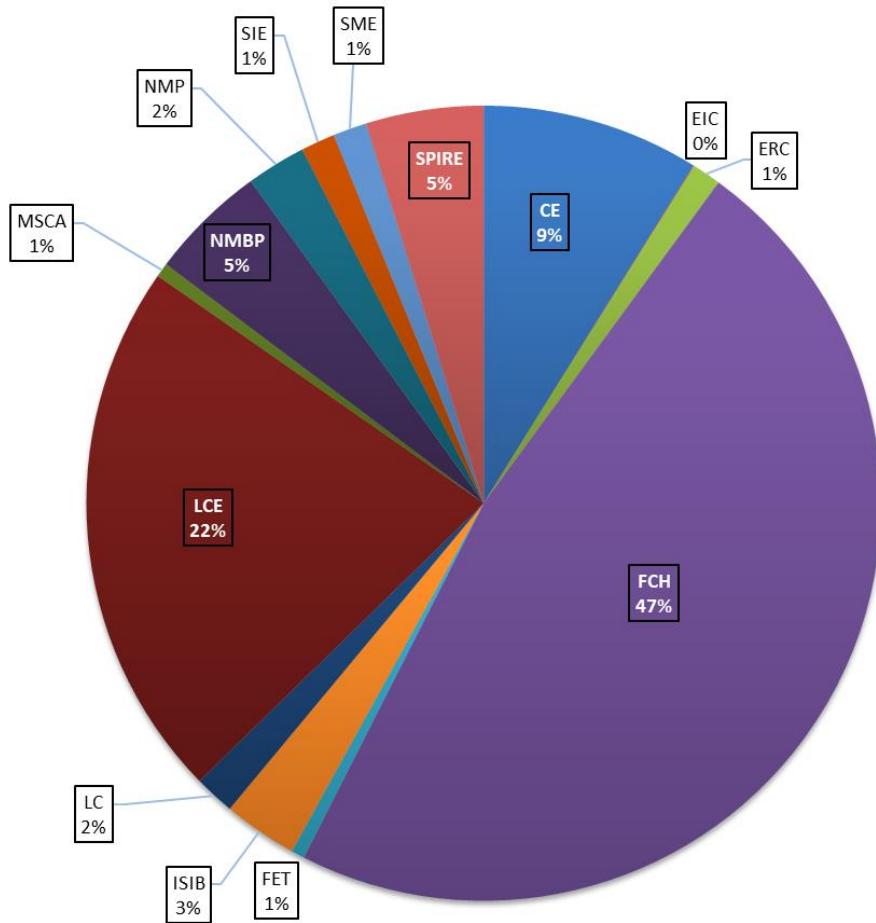
Table 15 H2020 instruments used to fund the identified CEST projects

Topic code	Pillar/Focus area	Field
CE	Connecting economic and environmental gains – the Circular Economy	
EIT	European Institute of Innovations & Technology	InnoEnergy - Pioneering change in sustainable energy
ERC	European Research Council	Applications in any field of research
FCH	Fuel Cells and Hydrogen 2 Joint Undertaking	Research, technological development and demonstration (RTD) activities in fuel cell and hydrogen energy technologies in Europe
FET	ERA-NET Cofund for FET Flagships	
ISIB	Specific Challenge – Innovative, Sustainable and Inclusive Bioeconomy	Research and Innovation Action - Converting CO ₂ into chemicals
LC	Low-cost, low-carbon energy supply (Workprogramme 2018-2020)	Building a low-carbon, climate resilient future: secure, clean and efficient energy
LCE	Secure, Clean and Efficient Energy (Workprogramme 2014-2017)	Competitive low carbon energy
MSCA IF and ITN	Marie Skłodowska-Curie Individual Fellowships (IF-EF) and Innovative Training Networks (ITN-EID)	Global Fellowships or Standard European Fellowships, i.e. Career Restart panel as well as European Training Networks (ETN) - multi-partner research training networks
NMBP and NMP	Nanotechnologies, Advanced Materials, Biotechnology and Advanced Manufacturing and Processing	Transforming European Industry - Innovative and sustainable materials solutions for the substitution of critical raw materials in the electric power system
EIC-SMEInst, SIE, SMEInst	Horizon 2020 dedicated SME Instruments	Stimulating the innovation potential of SMEs for a low carbon energy system; Small business innovation research for Transport
SPIRE	Sustainable Process Industry (SPIRE)	Public Private Partnerships in research - Sustainable Process Industry through Resource and Energy Efficiency.

Source: JRC, based on publicly available data

³⁷ The European structural and investment funds are: European regional development fund, European social fund, Cohesion fund, European agricultural fund for rural development, European maritime and fisheries fund.

Figure 16 Funding distribution among various H2020 instruments (see also Table 17)



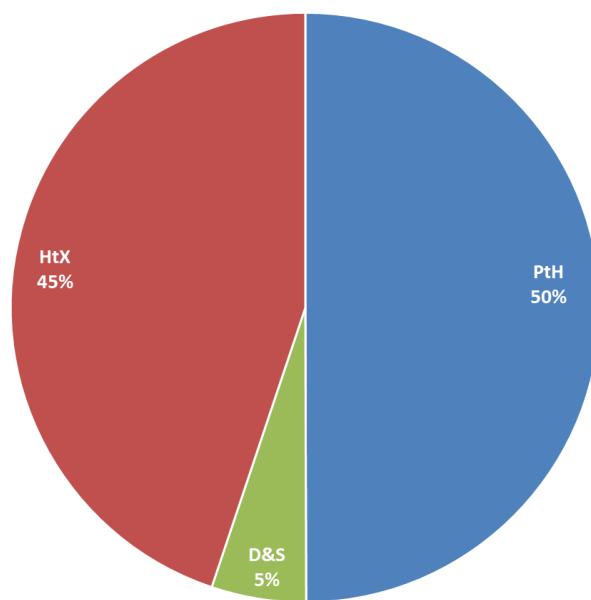
Source: JRC 2020, based on publicly available data.

3.4.1 Funding distribution per type of activity

The following figures display the results of the analysis performed using the methodology described in Section 2.2. Keywords have been assigned to each project based on the project scope, namely PtH, D&S and HtX (see also Table 1). Projects have been also classified according to eight different project classes depending on the technological maturity of the objectives pursued (see also Table 2 and section 3.4.3).

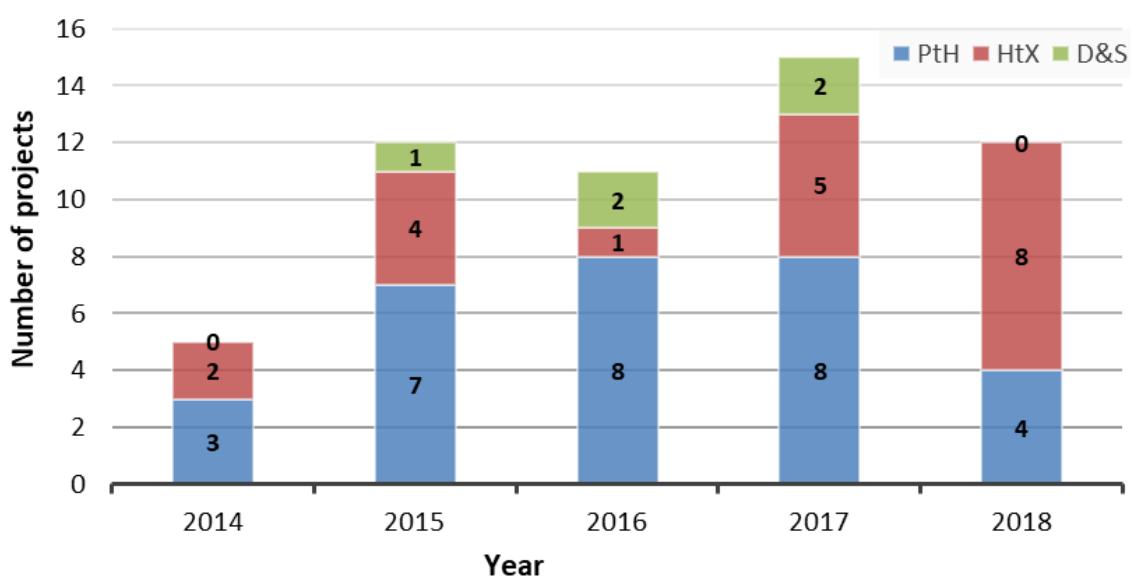
The funding distribution and participation across years, type of institution, geographical distribution, project class and keywords will be outlined in the rest of the chapter.

Figure 18 Funding per activity type



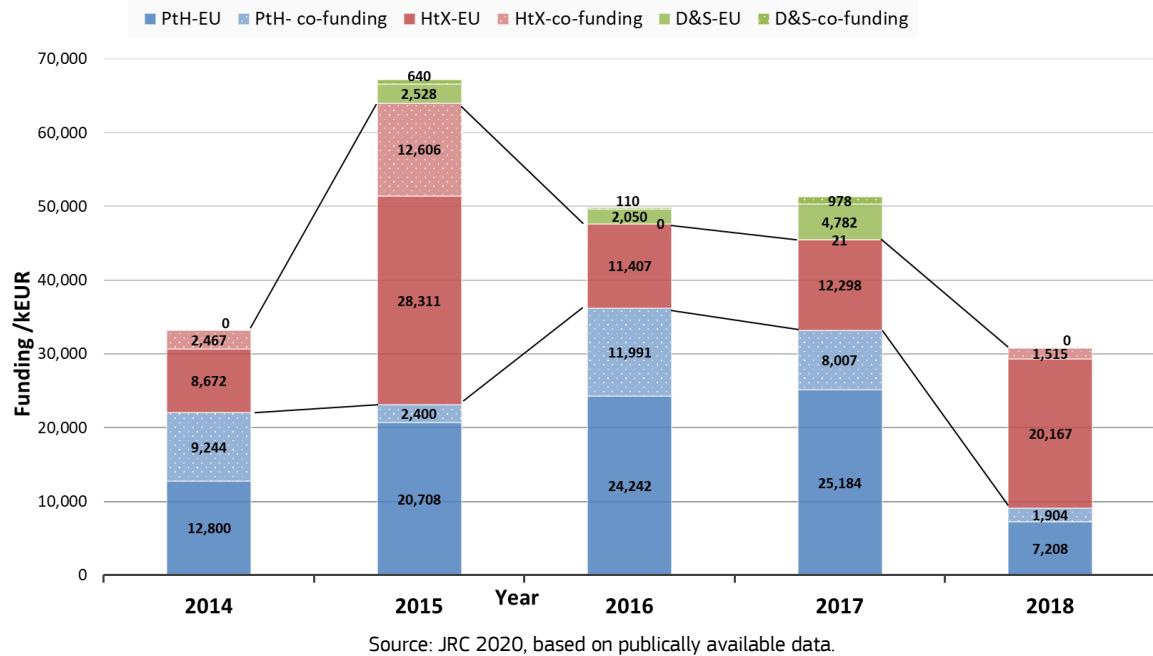
Source: JRC 2020, based on publicly available data.

Figure 17: The number of projects financed against H2020 topic call year.



Source: JRC 2020, based on publicly available data.

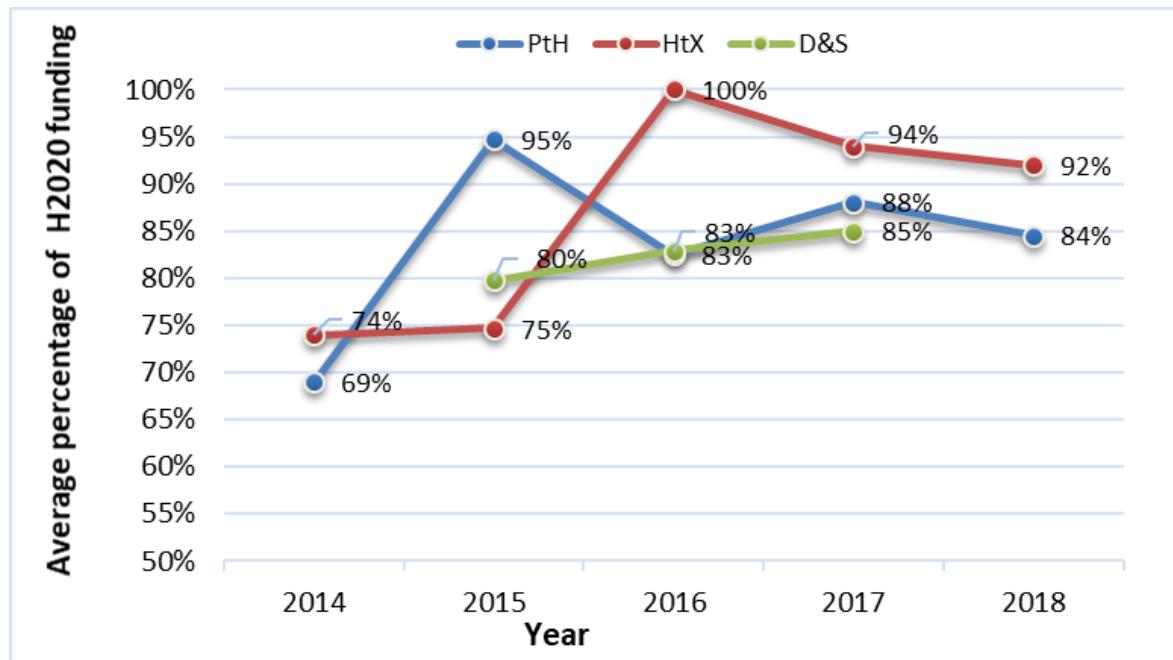
Figure 19: Total budgets for projects financed for H2020 topic call year. European funding and private co-funding are separated.



Source: JRC 2020, based on publicly available data.

In general power-to-hydrogen applications have received 50% of the funding and totalled the highest number of projects across each topic call year, with the exception of 2018, where the number of financed hydrogen-to-X projects increased significantly (see Figure 20 and Figure 17). Distribution and storage projects remain a minority both in terms of total funds and number of projects. Figure 19 shows how power-to-hydrogen projects have a total budget of around €22-23 million for H2020 topic calls in 2014 and 2015. The budgets of PtH projects rose to about €36 and 33 million for 2016 and 2017 respectively and dropped to about €9 million for 2018. In the same figure it is possible to see how hydrogen-to-X projects have totalled budgets of about €11-12 million for 2014, 2016 and 2017, and budgets of about €41 million and €22 million in 2015 and 2018 respectively. Distribution and storage total project budgets are significantly less prominent ranging from a minimum of about €2 million in 2016 to a maximum of about €5.5 million in 2017.

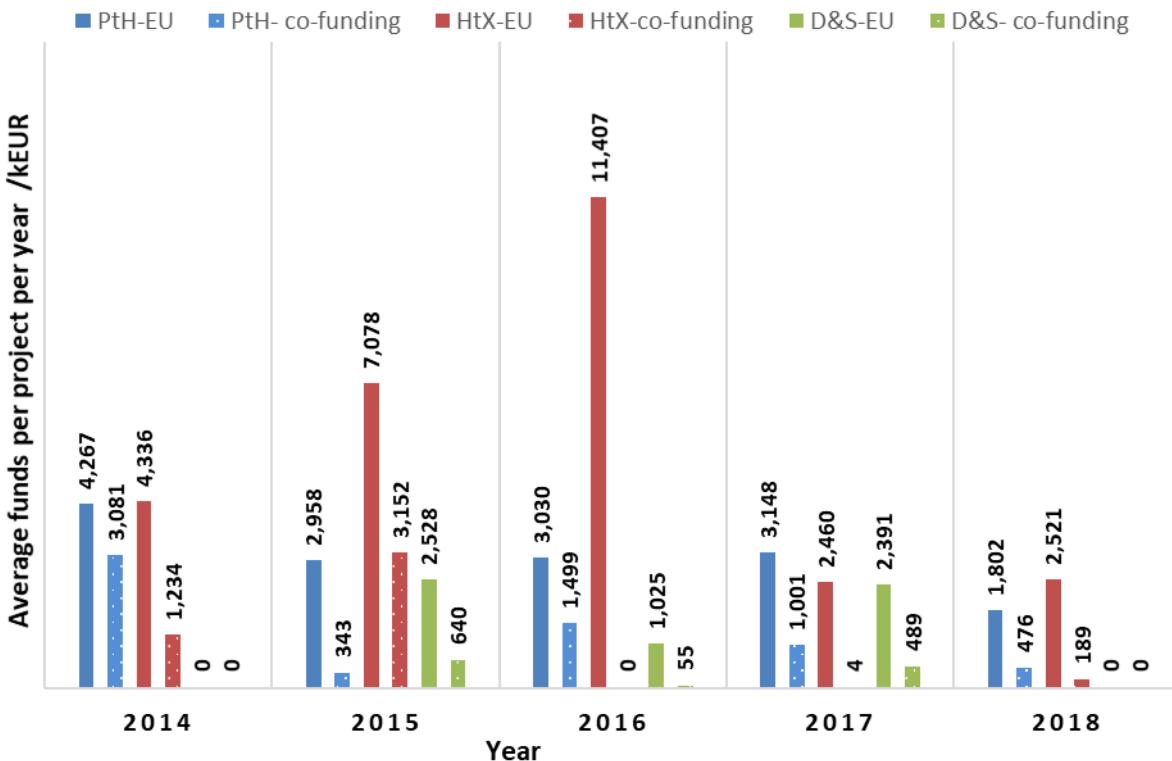
Figure 20 Percentage of European funds over total budgets for projects financed for H2020 topic call year.



Source: JRC 2020, based on publicly available data.

From the data presented in Figure 20 it is possible to see how the average public funding percentage for projects on hydrogen-to-X applications has consistently been higher in the last three years than for power-to-hydrogen and distribution and storage applications.

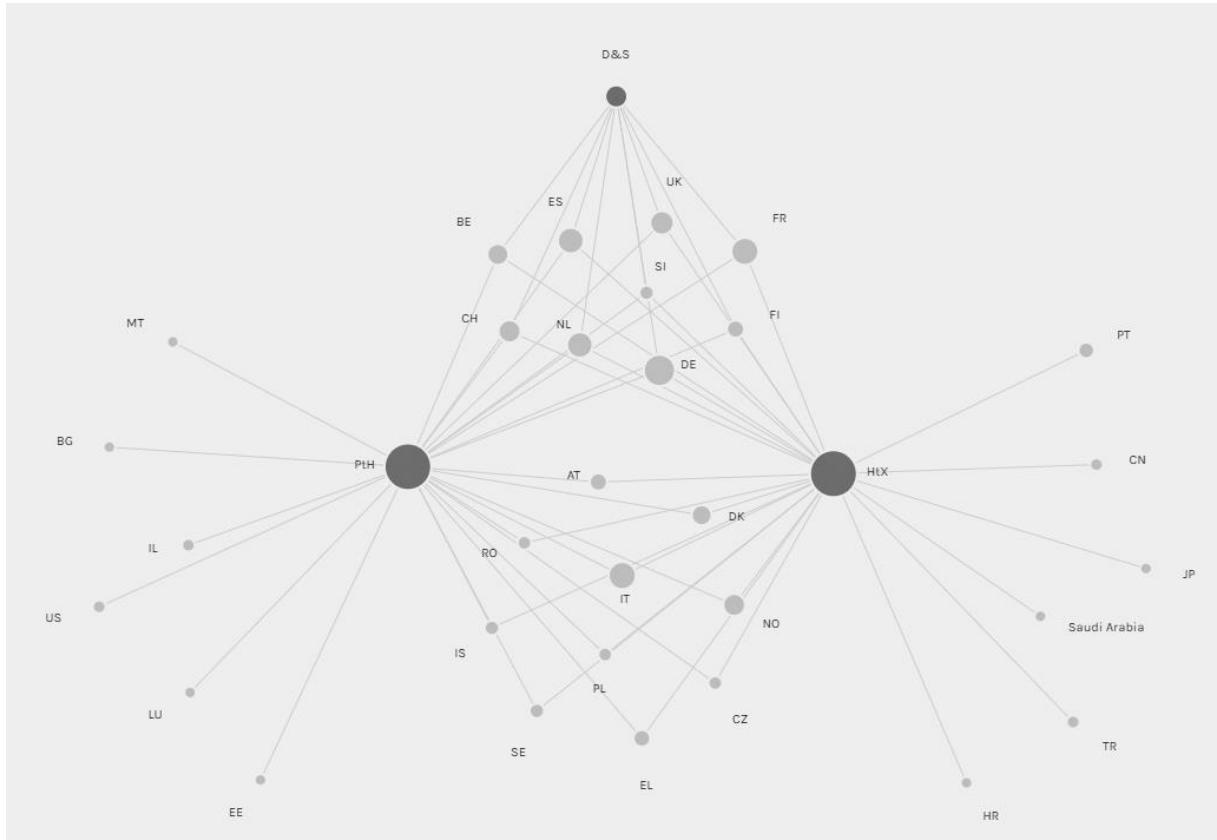
Figure 21 Average project budgets (total budget divided by the number of projects) for projects financed for H2020 topic call year. European and non-public funding are separated.



Source: JRC 2020, based on publicly available data.

Figure 21 shows how for 2014, and in particular for 2015, 2016 and 2018, hydrogen-to-X applications have been supported by significantly larger projects in terms of public funding, with the average power-to-hydrogen project having a higher average total budget (public support and other funding) for 2014 and 2017. While power-to-hydrogen project scales (assessed from average project budgets) have been the highest in 2014, they remained roughly constant from 2015 to 2017, and decreased in 2018. The average budgets for hydrogen-to-X projects have been growing significantly from 2014 to 2016 and then dropped significantly after 2016. Average project budgets for distribution and storage are similar to those of the average power-to-hydrogen one in 2015 and 2017, with a very small average for 2016.

Figure 21: Project participant nationalities clustered according to the project categories. The area of the circles is proportional to the frequency of an occurrence.



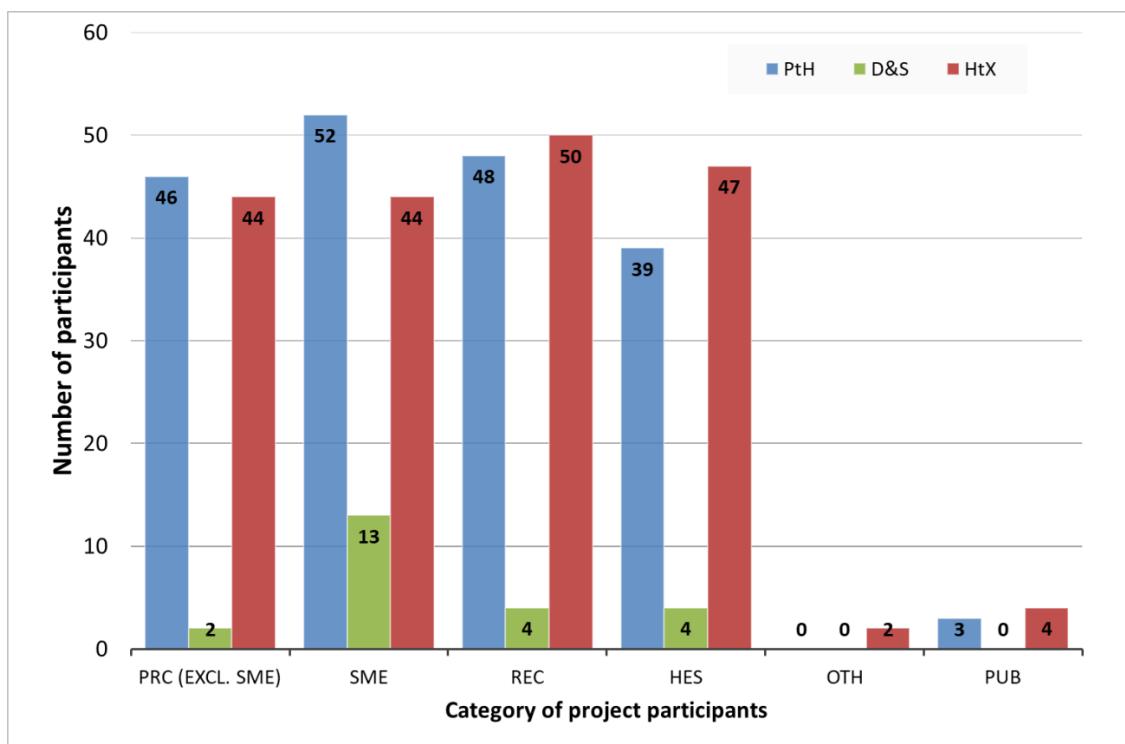
Source: JRC 2020, based on publicly available data.

Figure 22 shows a cluster graph evidencing the nationalities of participants in project belonging to the three different categories (Pth, Htx and D&S) used for CEST projects analysed in this report. It is clear how certain national players are active in projects in all three categories (e.g. Germany, France Spain, UK, the Netherlands), while others are active only in power-to-hydrogen and hydrogen-to-X projects (e.g. Italy, Norway, Denmark, Austria), and a few countries are only active in one type of projects category (e.g.: Portugal, Bulgaria, Estonia). It is also clear from Figure 22 that hydrogen-to-X projects attract a number of non-European participants.

3.4.2 Funding distribution per category of participant

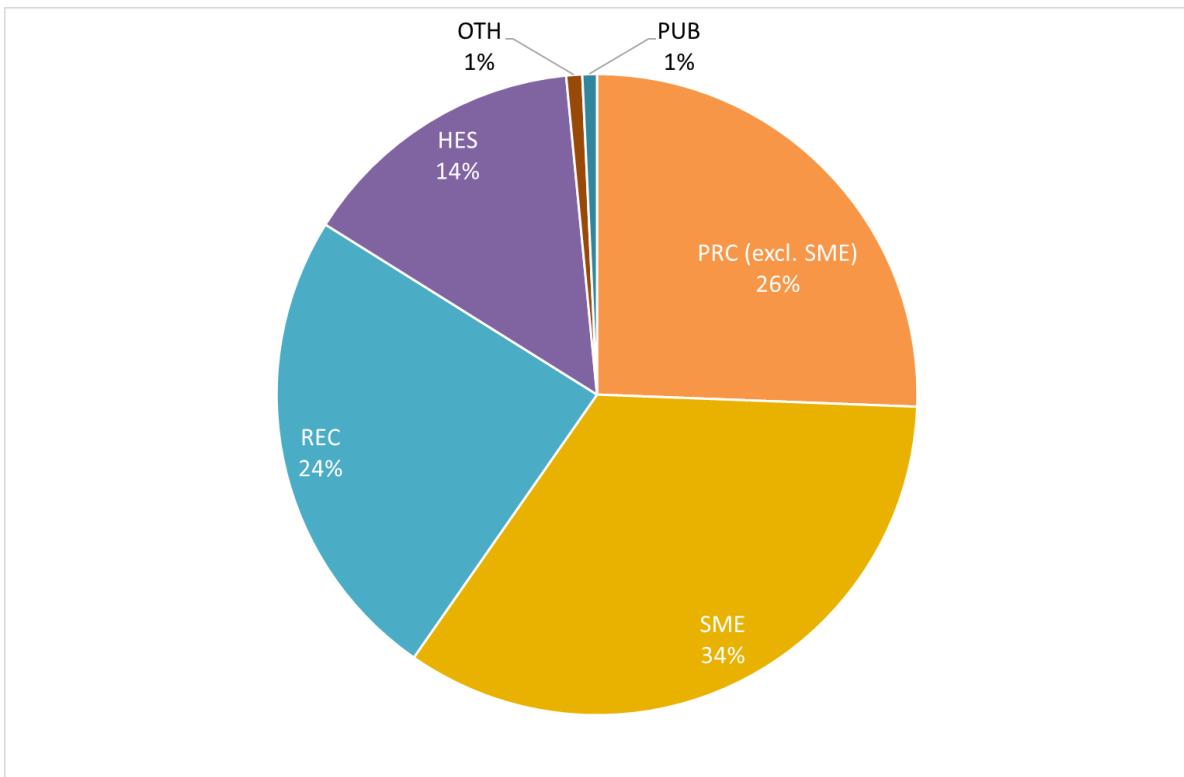
The average number of participants per type of activity is shown in Figure 23. Figure 24 and Figure 25 provide an overview of public funding per type of participant class. Public institutions (PUB) and others (OTH) receive a relatively high proportion of funds in power-to-hydrogen projects with respect to the number of participants belonging to this category. Private companies (PRC+SME) are dominating the public funds distribution in power-to-hydrogen projects, while PRC participants in hydrogen-to-X and distribution-and-storage projects, on average, receive €150,000-200,000 less. This is not true for SMEs, which receive > €600,000 on average per project for both PtH and HtX. The share of funding for SMEs is high with 34% of the total funding (46% of total funding for projects conducting field tests, see Figure 28). Participants belonging to research institutions (REC) and higher education (HES) classes receive on average about €70,000-80,000 more if they work on hydrogen-to-X projects.

Figure 22 Number of participants per activity type and per participant category.



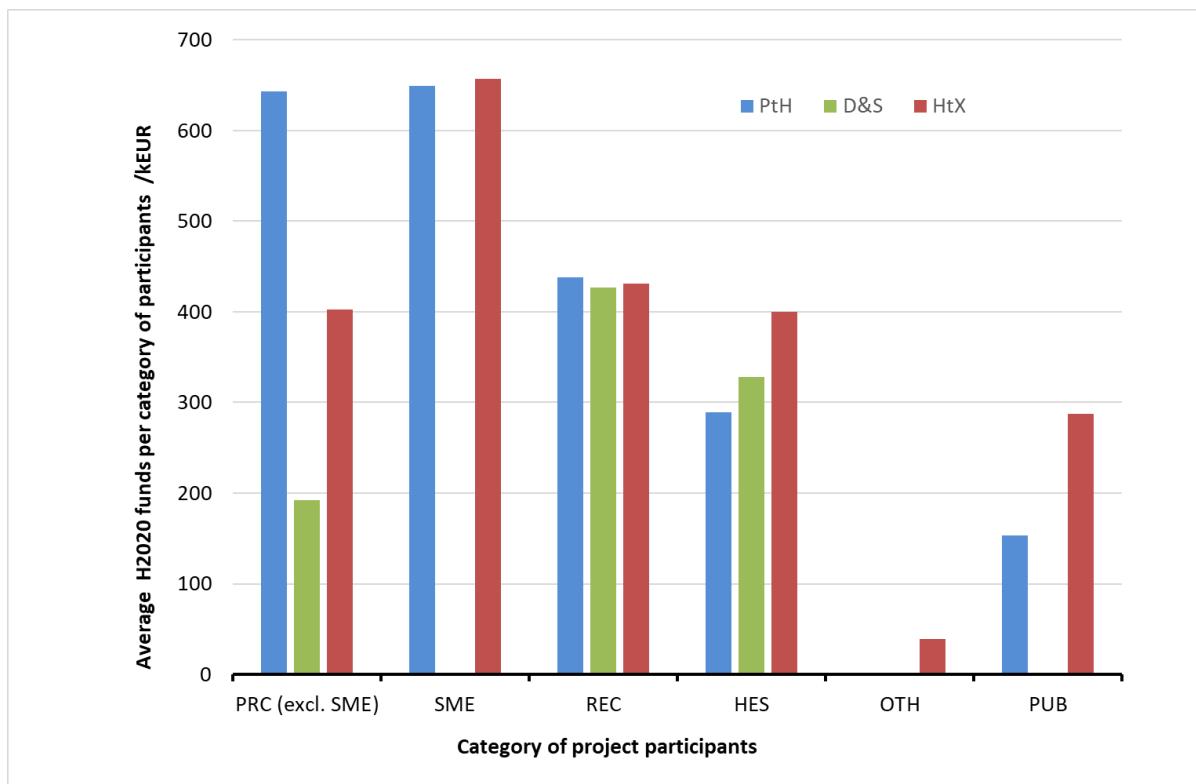
Source: JRC 2020, based on publicly available data.

Figure 23 Share of EU funding per category of project participant.



Source: JRC 2020, based on publicly available data.

Figure 24: Average public funds for every H2020 participant class.

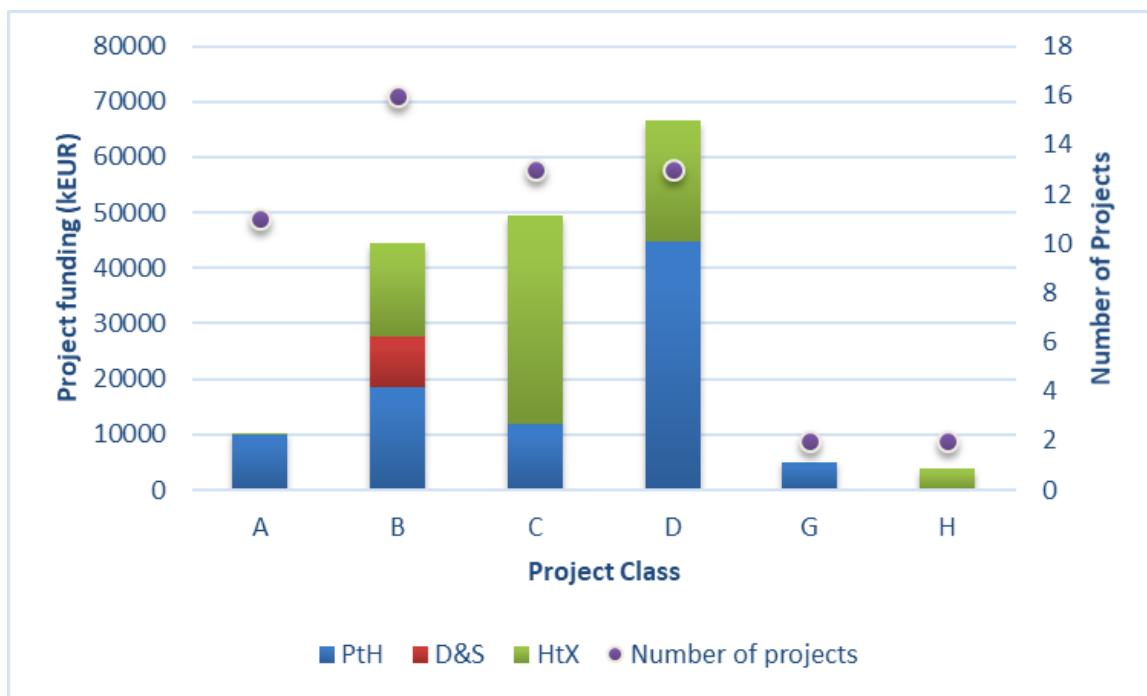


Source: JRC 2020, based on publicly available data.

3.4.3 Funding distribution per project class

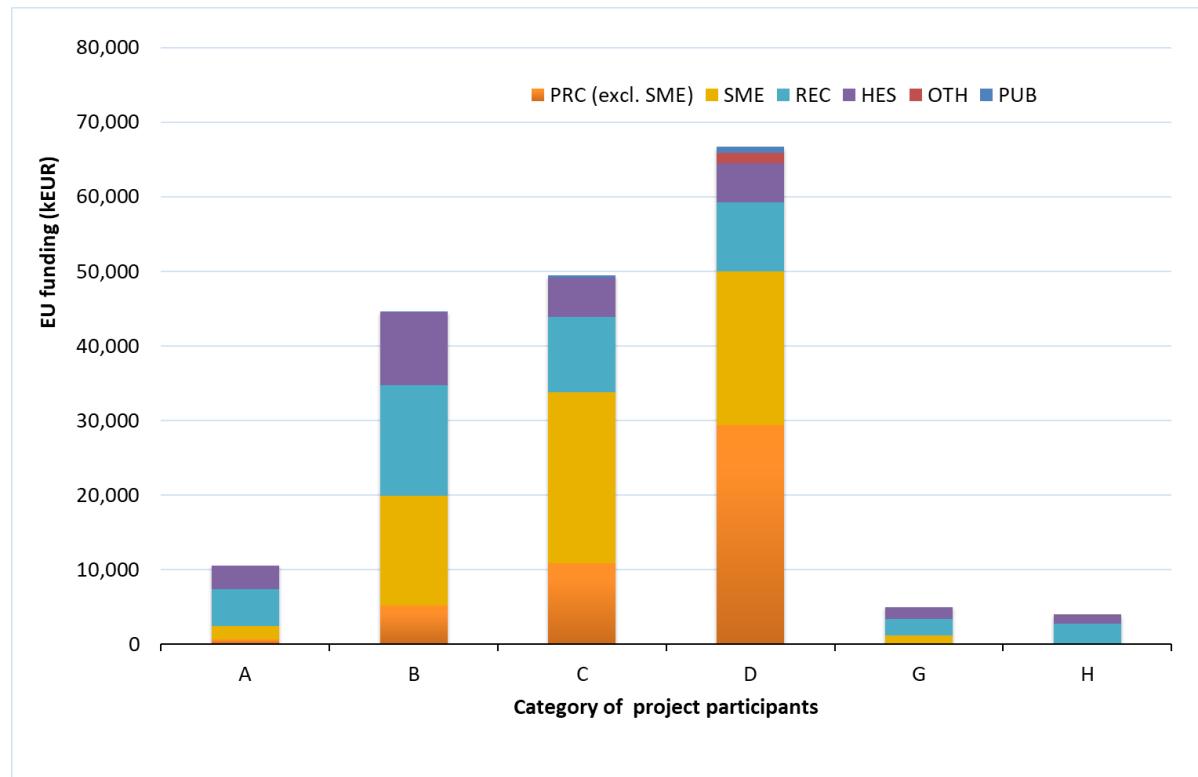
Projects were subdivided according to the definitions provided in Table 2. This allows a qualitative evaluation of the technical maturity of the technologies developed by the analysed projects. The assignation of project classes shows that although the highest number of CEST projects can be categorised as B “research to prototype”, the largest share of project funding is awarded to projects belonging to class D “large scale demonstration”, which is unsurprising due to the larger resources needed for demonstration activities. It is interesting to see that all D&S projects are in category B, and that PtH projects can be found among all classes except H “strategic planning/roadmaps”. Classes E and F, on manufacturing and diagnostics, respectively, have not been found among the portfolio of projects for H2020. A project on electrolysis diagnostics and monitoring had been funded under FP7, but not similar activities were supported under H2020. The project class manufacturing can be ascribed to a number of projects on fuel cells development, but not for electrolysis or any of the other technologies within the scope. Figure 27 shows the funding received per type of project participant per class of project. The share of funding for industry/SME participants is highest for project class D.

Figure 25: Distribution of funding and the number of projects according to Project Class



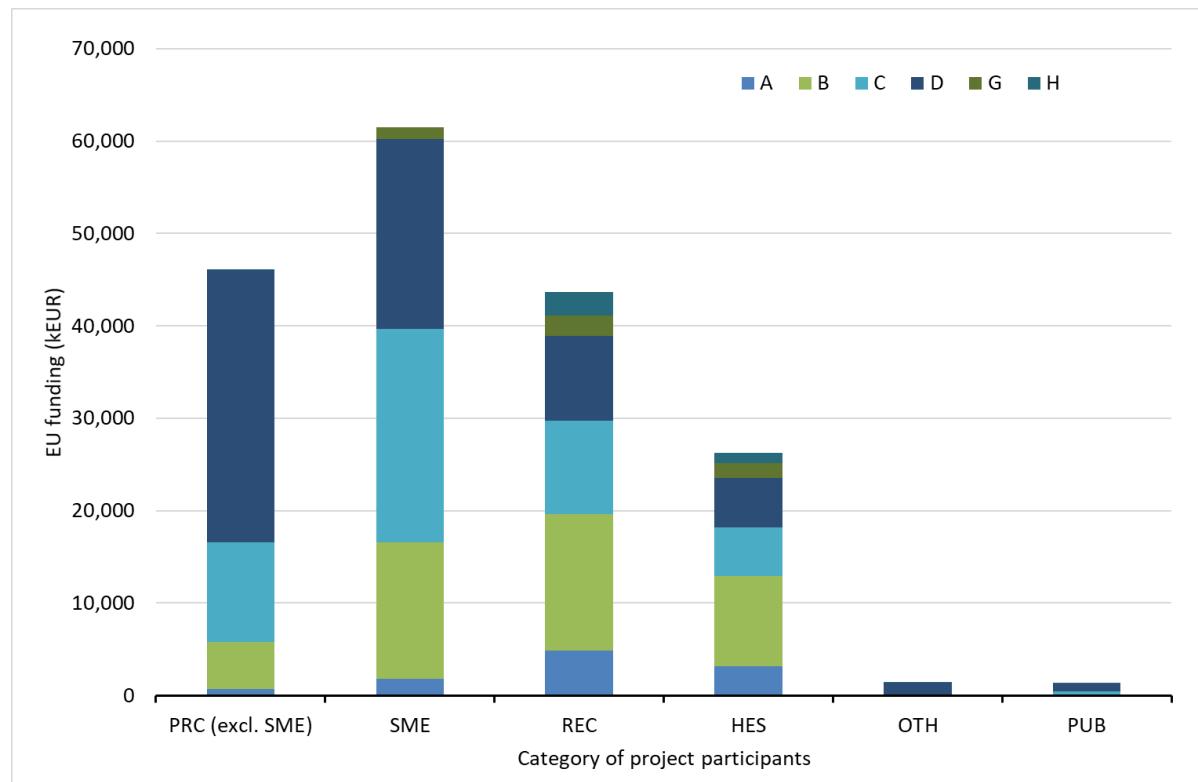
Source: JRC 2020, based on publicly available data.

Figure 26: Funding provided versus Project Class – distribution according to Partner Type



Source: JRC 2020, based on publicly available data.

Figure 27 EU funding per category of project participant and project class.



Source: JRC 2020, based on publicly available data.

3.4.4 General observations

A number of conclusions can be drawn from the funding analysis:

Types of activities

- Fundamental research (Class A) is low in terms of the number of partners involved and receives less money with respect to other CEST projects.
- Projects at the level of field tests (Class C) are especially prevalent for HtX projects rather than PtH. However, for Class D, large scale demonstration, the situation is reversed. This could be an indication of a higher technical maturity of PtH technology. PtH projects can be found for classes B through G (in general no classes E and F were assigned).
- Demonstrations are more demanding in terms of budgets than field tests or prototype development. The average project in class D has received funding around EUR 5 million, compared to EUR 3.8 million for class C and EUR 2.8 million for class B.
- Manufacturing projects (class E) are not yet being funded for any type of activity.
- D&S projects are currently being funded only at the prototype development stage and receive around 5% of the total funding for CEST projects. This technology is developed only at prototype level and driven mainly by private actors.

Types of participants

- Projects at the level of field tests and demonstration (Classes C and D) see a significant contribution from PRC/SME.
- HtX projects seem to have a good balance between PRC/SME, REC and HES participants, whilst PtH projects are dominated by PRC/SME. This could suggest that PtH projects are closer to market.
- SMEs contribute mainly to projects dealing with project categories B-D and are receiving around 38% of the EU funding for field tests and demonstrations.
- PRC non-SME players are receiving higher levels of financing than any other category for project class A (Fundamental Research).
- Research institutions are receiving more or less the same amount of financing than SMEs for project class B (Research to Prototype).

4 National and international R&I initiatives supporting CEST development and deployment

This section contains a description of CEST funding options available through national research programmes in selected Member States (MS) and worldwide. International initiatives (usually with industrial leadership) in support of the development and deployment of CEST are also described.

4.1 Funding programmes at MS level to support the development and deployment of CEST

4.1.1 Austria

CEST projects in Austria are commonly funded under the climate and energy funding scheme, with the aim of a „**Zero Emission Austria**“. The climate and energy fund supports a range of projects centred around the idea of producing and utilizing renewable hydrogen [192]. The funding is provided by the ministry of sustainability and tourism (BMNT) and the ministry for transport, innovation and technology (BMVIT). In 2018, a budget of €9 million was available for energy topics, including CEST and conversion technologies. Several relevant projects are, or have been, operating in Austria, some recently as part of the regional initiative WIVA P&G (Hydrogen Initiative Energy Model Region Austria Power & Gas). This initiative is also funded through the climate and energy fund, and seeks to demonstrate the transformation of the energy system with hydrogen as a central component [193]. As part of this initiative, the RENEWABLE GASFIELD project will demonstrate sector coupling through the production of hydrogen from PV, which will then be used for a methanation plant, injected into the gas grid, or used to refuel FCEV. The WIND2HYDROGEN project is assessing hydrogen for storage and transport in the natural gas grid. A novel concept is pursued in the UNDERGROUND SUN CONVERSION project, which looks into biological methanation within an underground porous rock storage facility [194]. The HYDROMETHA project on high temperature co-electrolysis and catalytic methanation is also supported through the climate and energy fund. The CEST projects (≥ 1 million euro) funded by Austrian national programmes relevant to the scope of this report are listed in Table 20 in Annex B. Projects were identified by a keyword search in a database [195]. Compared to CEST funding under H2020, Austria seems to have a stronger focus on HtX topics. Smaller projects are conducting research on hydrogen separation and SOEC.

4.1.2 Belgium

A Flemish Power to Gas Industry Cluster has been active since 2016. About 40 companies have joined it and have been selected for financial support in the framework of the “IBN” (Innovatieve Bedrijfsnetwerken) of the Flemish Government (“Agentschap Ondernemingen”)[196]. The partnership is coordinated by WaterstofNet and its members are active in renewable energy, hydrogen or gas technology, hydrogen mobility (fuel cell applications) or network operations (gas and electricity network). Demonstration project announcements have already taken place. In particular, Eoly (part of Colruyt Group), Parkwind and Fluxys are planning an industrial-scale power-to-gas facility of around 25 MW [197].

4.1.3 Denmark

Denmark plans to increase the fraction of RES up to 100 % by 2050 and is therefore investing in solutions to deal with corresponding challenges, such as intermittency. Funding for hydrogen and fuel cell technologies is mainly awarded through the Innovation Fund (Innovationsfonden) or the Energy Technology Development and Demonstration Program (EUDP). Both programmes support the development and demonstration of energy technologies. In 2017, the total annual budget awarded to hydrogen and fuel cell projects was around EUR 5.6 million, much lower than in previous years, such as 2012, when close to EUR 25 million was invested [198]. Nonetheless, there have been eight projects regarding CEST with budgets of over EUR 1 million, supported since 2014. A list of these projects, as identified through a project database [199] can be found in Table 21 in Annex B. Based on this limited list of projects, the Danish programme has awarded roughly similar amounts of funding to PtH projects as to those on HtX. We did not identify any projects in the D&S area.

Danish companies and research centres have built up a high level of competence relating to solid oxide fuel cells and electrolyzers over recent decades. Solid oxide electrolyzers (SOEL) are seen as a promising

technology for energy storage, synthetic fuel production and for grid regulation in the Danish power system, as stated in a recent energy strategy paper by the EUDP³⁸ [200]. The key players in this field are Risø National Laboratory, the Technical University of Denmark (DTU) and Haldor Topsoe. Co-electrolysis for the production of synthetic fuels or chemicals is also a target of research.

A Danish roadmap for large-scale implementation of electrolyzers was established in the project "TOWARDS SOLID OXIDE ELECTROLYSIS PLANTS IN 2020". The roadmap was divided into four main stages, covering the period from 2017 to beyond 2035 [201]. The installed electrolyser capacity should reach 30-50 MW by 2025 and 1000 MW by 2035. The ongoing "Solid Oxide Electrolyser Technology" project has the objectives to mitigate the degradation and robustness challenges at cell and stack level and to demonstrate pressurized reversible operation, which can reduce system cost and improve efficiency. Another ongoing project is SOC4NH3, "Solid-Oxide-Cell-based Production and Use of Ammonia", which is implemented by Haldor Topsoe. Hydrogen is to be produced by an SOEC, which also provides nitrogen, obviating the need for an air separation unit³⁹. The use of ammonia as fuel for a Solid Oxide Fuel Cell (SOFC) will also be investigated [202]. There are also projects aiming to improve PEM electrolysis by increasing power density (E-STORE), and DTU aims to demonstrate advanced, high temperature and high pressure alkaline electrolysis through a new system design in the EEE-HY project, which has a budget of EUR 5.06 million.

CEST projects in Denmark are often linked to methanation, possibly due to a strong driver in biogas upgrading. The MEGA-STORE project, which started in 2013, developed a catalytic methanation platform with support from Danish TSO Energinet (and funded through ForskEL⁴⁰). In 2018 it has been deployed in NGF Nature Energy's new biogas plant [203]. A pilot plant has been constructed to investigate biogas upgrading in synergy with a SOEC unit [204]. A predecessor project running until 2017 had received EUR 5.3 million from EUDP [205]. Biological methanation for biogas upgrading was the aim of the SYMBIO project (2013 – 2018), funded through the Innovation Fund. The P2G-BIOCAT project demonstrated the Electrochaea concept for biological methanation from 2016-2017 in a 1MW plant near Copenhagen. The project, with a total cost of DKK 49.9 million (EUR 6.7 million) received 55% funding through ForskEL and EUDP [206]. The POWER2MET project, is establishing a pilot plant at Aalborg University to produce biomethanol from biogas CO₂. The SYN FUEL project is also supported by the Innovation Fund with a grant of DKK 21.2 million (EUR 2.8 million), and seeks to combine high temperature electrolysis and thermal biomass gasification with a catalytic converter to synthesize methane or liquid fuels such as methanol.

Funded through the European Investment Bank (EIB), the EVERFUEL GREEN HYDROGEN project is aiming at large-scale production and distribution of green hydrogen, to supply a fleet of hydrogen fuel-cell electric buses. The EIB will finance around half of the total project budget of EUR 38 million [207].

Siemens Gamesa Renewable Energy and Energifonden Skive have signed an agreement to jointly explore eco-friendly ammonia production as a way to store surplus electricity from wind turbines in a pilot plant at GreenLab Skive [208].

Starting in 2014, the ENERGY STORAGE project conducted long term testing in order to determine whether the Danish natural gas distribution system can be operated in a stable and safe way with varying concentrations (up to 15%) of hydrogen. This project received additional funding through the EUDP [209]. A project running from 2005-2010 had already investigated transportation of hydrogen in natural gas pipelines, and the compatibility under long term hydrogen exposure. The test program included steel pipes from the Danish gas transmission grid and polymer pipes from the Danish and Swedish gas distribution grid.

The EUDP is providing additional funding of EUR 2.6 million to the FCH 2 JU HYBALANCE project which is implemented in Denmark. This project will demonstrate the concept of a MW scale PtH plant to provide both grid balancing services, hydrogen for industry and as a fuel for transport. The perspective of salt caverns for hydrogen storage will also be explored.

³⁸ The strategy paper directly names Haldor Topsoe as manufacturer of this technology.

³⁹ In a typical ammonia production process, an air separation unit would be needed to produce nitrogen.

⁴⁰ ForskEL projects are administered by EUDP since 2016.

4.1.4 France

In France, the ADEME (*Agence de l'environnement et de la maîtrise de l'énergie*), under the supervision of the *Ministère chargé de la Recherche et de l'Innovation* (Ministry of Higher Education, Research and Innovation) and the *Ministère de la Transition écologique et solidaire* (Ministry for the Ecological and Inclusive Transition), *et de l'Enseignement supérieur* (Ministry of Higher Education) is involved in the set-up and coordination of actions related to its mandate and expertise in the fields of environmental protection and energy management. In 2018, it had a budget of around €630 million, with an increase to €760 million expected for 2019. ADEME is financing several power-to-gas demonstration projects (JUPITER 1000, GRHYD and MÉTHYCENTRE). In the south of France, the cluster Capenergie, is also active in advancing the development and deployment of hydrogen technologies (including its involvement in the power-to-hydrogen project HyGreen Provence).

In June 2018, the French ministry announced the French national hydrogen plan ("plan national de déploiement de l'hydrogène" or "plan hydrogène") with expected funds of approximately €100 million [210]. The objective of the plan is to kick-start a French value chain for hydrogen technologies in the sectors of industry, transport and energy and this should be facilitated by the activities of ADEME. As of 2019 it appears that projects developing hydrogen technology applications will be supported with the ADEME budget "Fonds Air Mobilité" which should be assigned approximately €30 million in 2019 [211].

Activities on hydrogen technologies have also been financed through the ANR (*Agence Nationale de la Recherche*). Some French demos are also funded via the European funds for regional development (FEDER). The ANR has financed at least one project on methanation: CHOCHCO (while its predecessor MINERVE received funds from KIC InnoEnergy).

Private actors such as H2V Industry have announced plans to deploy electrolysis in industrial settings, and its first demonstration will occur in Port-Jérôme.

An overview of selected projects is provided in Table 22 in Annex B. Many of the projects listed in the table are targeting methanation (HtX).

4.1.5 Germany

The basic idea behind power-to-gas was proposed in 2007 by German researchers⁴¹. Initially projects implementing this concept were quite modest, but already in 2014 the industry and research organizations of the strategy platform "Power-to-Gas" of the German Energy Agency announced the goal of installing 42 plants with a 1 GW capacity by 2022. The largest number of PtG and HtX demonstration projects globally are located in Germany, with over 50 demonstration sites, some of which are entirely privately funded. The current installed capacity is 14 MW for projects producing hydrogen and 7.4 MW for those producing methane, with another 34 MW of planned projects (see also Figure 30) [212]. A national hydrogen strategy is currently under discussion, which aims to coordinate activities in different sectors and for different application.

The German Energiewende (energy transition) calls for substantial changes in the energy system, the challenges of which are in part addressed through R&D programmes. At the national level, funding for R&D in the energy sector is derived from the federal budget and the Energy and Climate Fund (EKF). The EKF is financed through the federal budget and via proceeds from the emissions trading scheme, and has allocated EUR 1.8 billion annually to R&D for renewable energy and energy efficiency measures in the period 2018 – 2021, mainly for large scale projects. The Federal Ministry of Economics and Technology (BMWi) and the Federal Ministry of Education and Research (BMBF) have been involved in a joint initiative on energy storage, which ended in 2017. Over a running time of 10 years, €184 €million in funding was awarded to over 200 projects, of which close to €80 million benefitted research on chemical energy storage, for example the 6 MW Energiepark Mainz PtG installation [213]. The 7th programme on energy research, with a budget of €6.4 billion in the period 2018 – 2022, is funded through a number of bodies, notably the BMWi⁴³ and the BMBF. Sectoral integration, PtG and PtX are mentioned as strategically important themes in the programme [214]. BMWi and BMBF are also involved in the National Innovation Programme Hydrogen and Fuel Cell Technology (NIP), which was created to make the German industrial base of FCH technology internationally competitive.

⁴¹ Dr. Michael Specht from Zentrum für Sonnenenergie-und Wasserstoff-Forschung and Prof. Dr. Michael Sterner of OTH Regensburg.

⁴² Early projects were often producing hydrogen, so they could be considered as PtH according to our classification.

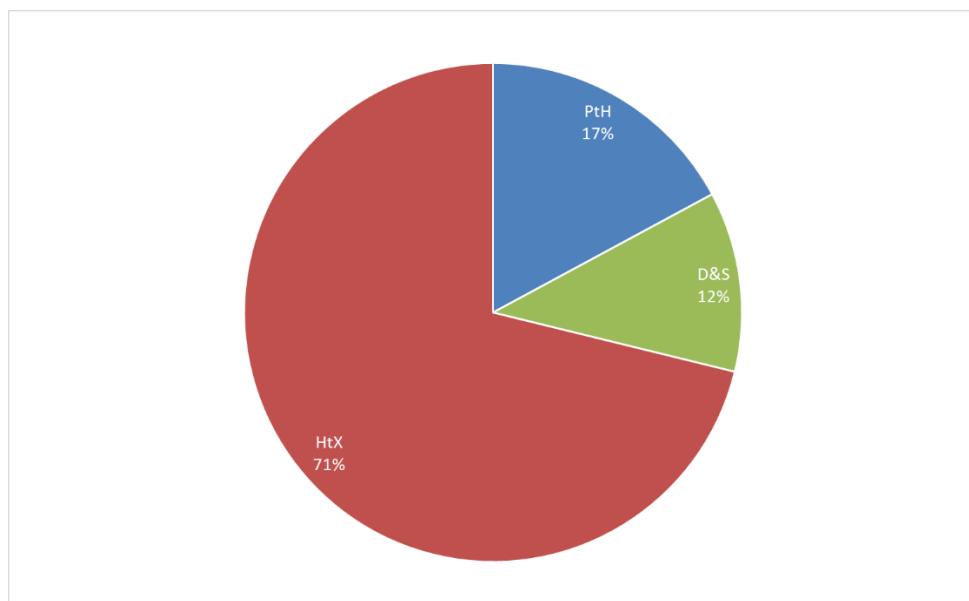
⁴³ In particular the BMWi is receiving EU structural funds for regional development and for special measures, but their role in funding for CEST is not readily traceable.

However, few projects on chemical energy storage are supported by the NIP⁴⁴, as it has a strong focus on mobility applications and batteries.

There are also relevant funding Programmes running at state level (for example in Baden-Württemberg and Nordrhein-Westfalen), but these have not been investigated further for this report. The German northern states have issued a Hydrogen strategy, which among other goals foresees the installation of at least 500 MW electrolyser capacity by 2025 [215].

During the time period considered for this report, starting from 2014, over 50 projects were identified as falling under the scope, with a total funding of close to €230 million. Of this budget, the largest share of funding (over 64%), came from the BMBF, 32% from BMWi and the rest from the Federal Ministry of Transport and Digital Infrastructure (BMVI) (a list of relevant projects and programmes with funding over EUR 2 million is given in Table 23 Annex B). Projects were identified through a keyword search in a project database [216].

Figure 28 German national funding per activity type (as defined in 2.1).



Source: JRC 2020, based on publicly available data.

On **Power-to-Hydrogen**, i.e. electrolysis, topics, 25 projects have been found, with a total funding of around €39 million. Nine projects are aiming at improving PEM electrolyser performance, and there are ten projects conducting fundamental research on general electrolyser projects, such as catalyst materials, bipolar plates, tubular electrolysis cells or recycling. Two projects are focussing on SOEL and four on AEL. One of the PEMEL projects is developing a reversible PEMFC. The TRL range seems to cover the whole spectrum from 1 through 9.

⁴⁴ These projects have received funding lower than EUR 2 million and are therefore not listed in Table 23.

Figure 29 Installed electrolyser capacity for German PtH and HtX projects.



Source: JRC, based on data from the IEA hydrogen project database [217]

On the topic of **hydrogen distribution and storage**, nine projects were identified, with a total budget of €26 million.

The NEW 4.0 programme seeks to provide a region of northern Germany (Schleswig-Holstein) with 100% renewable energy by 2035. One of the projects funded through this programme will demonstrate a hybrid storage system which will include a PtH plant with admixture of hydrogen to the gas grid.

The project HYINTEGER has performed research on the integrity of wells, materials and components for geological hydrogen storage. Focus of the project is the inorganic, organic microbiological and petro-physical reservoir characterizations as well as simulation and modelling approaches from pore to reservoir scale. ANGUS II is investigating the impacts of the use of the geological subsurface for thermal, electrical or material energy storage, for the options of hydrogen, synthetic methane, compressed air and heat or cold, in the context of the transition to renewable energy sources using the example of Schleswig-Holstein as a model area. In 2019 another project investigating underground hydrogen storage has started, HYCAVMOBIL. This project, apart from experimentally testing hydrogen storage in a salt cavern, will assess whether the purity of the stored hydrogen is suitable for mobility applications. There are other projects conducting research on the conduction of hydrogen in porous rock, on purification with membranes and operation of electrolyser plant for admixture of hydrogen.

The LLEC:PtG++ project is investigating LOHC for seasonal hydrogen storage, and is described further below.

The majority of the funding has been awarded to **Hydrogen-to-X** topics, with €162 million for 18 projects and programmes. One such programme, HYPOS, has funding available up to €45 million under the "Zwanzig20-Partnerschaft für Innovation⁴⁵" initiative from the BMBF. This programme seeks to establish itself as the cutting edge in sector coupling. It is focused on HtX (production of methanol, dimethylether and methane), and aims to reduce the CO₂ emissions of the chemical industry and refineries situated in eastern Germany. The programme currently supports over 10 projects, addressing multiple aspects from chemical conversion, transport and storage, business models and market, to safety and strategy.

The programme E2FUELS supports several subprojects on methanol synthesis and electrolysis, for emission reduction in power generation and maritime applications. The cluster of projects: METHQUEST, METHMARE, METHSYS, address innovative methanisation and its use in mobile and stationary applications, including maritime. Around €21.5 million is invested in projects directly dealing with methanation.

⁴⁵ partnership for innovation.

Coordinated by steel manufacturer Thyssenkrupp, CARBON2CHEM is a large project involving 17 other partners from research and industry. The technology aims to make around 20 million tonnes of the annual CO₂ emissions of the German steel industry commercially utilisable, by producing various chemicals. The pilot plant has been in operation since April 2018, where a 2 MW electrolyser produces hydrogen additional to that already contained in the steel mill top gas. This is a different concept to that demonstrated through two FCH 2 JU funded projects (GRINHY, GRINHY2), where hydrogen is used in the steel making process itself.

The BMBF also created an expert platform on the energy transition, which issues recommendations for research needs. An outcome of this work are the four KOPERNIKUS projects, one of which is also working on HtX [218].

The other HtX projects are looking into the development of catalysts for methanation or into co-electrolysis.

This distribution of funding with its focus on HtX and on demonstration and large-scale deployment projects reflects the high level of maturity of these technologies in Germany. In Figure 30 the installed electrolyser capacity per year is given, showing ambitious plans for 2020. There is a smaller share of funding going towards the development of electrolysis or hydrogen admixture to natural gas, which had been the aim of earlier projects. The use of hydrogen in higher value markets, such as for transport applications or for industry, is gaining in relevance. The production of methanol or other hydrocarbons is addressed by several large projects, and methanation is considered for the decarbonisation of particular transport sectors. Research on electrolysis ranges from the development of components, to investigating technology transfer from the automotive industry (for the manufacture of PEM electrolyzers).

Public support for CEST in Germany is likely to remain substantial in the future. Within the next 5 – 10 years, the government plans to make €400 million funding available for so-called Living Labs (Reallabore), which may become available for the large scale testing of CEST technologies. One of these projects is the Living Lab Energy Campus: P2G++ subproject, which will investigate how large quantities of renewable energy can be stored throughout the year in the form of chemically bound hydrogen using liquid organic hydrogen carriers (LOHC). For this concept, the hydrogen loading and release is to be performed in the a single reactor, which will enable a reduction of costs (for further information on LOHC, see Section 3.2.5.2.1) Amongst others, a possible beneficiary could be the pilot project HYBRIDGE, planned by Ampirion and Open Grid Europe, who seek to install 100 MW of electrolysis in northern Germany, to convert wind energy to hydrogen [219]. A smaller scale installation is already running in Brunsbüttel, where the 2.5 MW PEM electrolyser produces hydrogen for FCEV and for admixture to the gas grid supported by regional and private funding from a utility [220].

Funding by European structural fund ERDF has been used to install a 5 MW PEM electrolyser for supplying hydrogen to a refinery, for the production of chemicals [221]. Steelmaker Salzgitter Flachstahl, already involved in the GRINHY project, plans to deploy a 2 MW PEM electrolyser, which is to be coupled to seven new wind turbines. This hydrogen will then be fed into their existing hydrogen gas grid to be used for the inertisation of steel surfaces. The company states that public support would be necessary for this €50 million project [222].

A number of CEST projects in Germany have been undertaken without public funding. The first industrial size PtG plant, which started operation in 2013, produces “e-gas” in Wertle. This project by Audi combines CO₂ from a biogas plant with hydrogen from a 6 MW electrolyser linked to wind energy. In another example, a local utility is operating a 1.25 MW power-to-gas plant in Haßfurt, together with Greenpeace. Greenpeace Germany is supporting this WINDGAS initiative, offering customers the possibility to purchase gas with a percentage of hydrogen varying from 0.6-2vol%. In Klanxbüll, the German Gas and Water association (DVGW) conducted a field test on the effect of hydrogen admixture, together with other partners. Tests involved the injection of up to 9.9vol% H₂ into the local distribution grid, and subsequent testing of the performance of the end-user appliances of 176 customers [223]. According to a recent announcement, the German SOEL manufacturer Sunfire plans to install a 1MW plant in the Total refinery in Leuna to produce Methanol, using some of CO₂ emissions of the refinery [224].

4.1.6 Netherlands

In the Netherlands, CEST related projects are subsidised from funds governed by the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland) [225]. Top Sector Energy [226] is a part of the EZ-Subsidy Regulation (EZ-subsidies Regeling). Under this programme fundamental research, industrial research, experimental development and demonstration projects can be funded. In 2019 Top Sector Energy offers €130 million in subsidies to projects and research in the field of energy innovations.

In 2018, the Netherlands published the *Meerjarig Innovatieprogramma Waterstof* (MIW) [227], a multi-annual hydrogen integrated innovation programme focused on research, pilot projects and demonstrations, in infrastructure and wider hydrogen applications. In June 2019, the *Climate Agreement* was proposed, stating that there is a broad consensus that hydrogen will play a critical role in the transition to a carbon-neutral society, but that additional stimulus is required [228]. A large-scale hydrogen programme is to be introduced, focussing on green hydrogen as energy carrier in mobility, for industrial use and for the built environment. It is proposed to install 3-4 GW electrolysis capacity by 2030.

CEST projects (>€0.25 million) supported by the Netherlands relevant to this report's scope are listed in Table 24 (Appendix B). In addition to the projects mentioned in Table 16, a number of relevant projects and system studies on PtH and HtX have been funded. The Netherlands is involved in projects aiming at switching to a hydrogen economy and involving hydrogen from SMR i.e. by taking part in projects such as H21 and HYDEPLOY (see Section 4.1.10) or H100, which consists of three feasibility studies on the use of 100 % hydrogen in the gas distribution network. Furthermore, the Netherlands have participated in the HY4HEAT programme for developing demonstration projects in order to investigate replacement possibilities of natural gas by hydrogen for heating and cooking in homes, which includes studies on standards, odorization and gas quality. The subject of the possible use of hydrogen as a fuel for heating is further investigated in project WATERSTOFWIJK HOOGEVEEN.

In the field of hydrogen production the focus is on developing new alkaline stacks able to operate with higher current densities and a stack cost below 100 €/kW (ALKALIBOOST) or with increased flexibility and production capacity that should lower the cost of hydrogen to 2.0 €/kg in 2025 and 1.5 €/kg in 2030 (ALKALIFLEX). A further project on the cost reduction of industrial PEM electrolyzers focuses on the development of the next generation of PEM electrolyte. Hydrogen production via photolysis is also in the field of interest, which can be derived from the participation in FOTOH2 project under H2020.

In contrast to other countries, the Netherlands is interested in offshore electrolysis and offshore hydrogen production. Studies relating to the reuse potential of existing offshore gas infrastructure in a hydrogen supply chain have been performed and the "Pre-Pilot Power to Gas Offshore" (3P2GO) project is ongoing. The 3P2GO project is the world's first offshore power-to-gas pilot to produce hydrogen offshore and a test centre for other innovative PtG technologies. The 3P2GO project is the first step of a planned scale-up process for this type of system, starting at 1-10 MW, then 20-250 MW and ultimately >250 MW systems.

HYDROHUB is an open test centre, where the consortium partners, but also other knowledge institutions and companies, can test their innovative technology in electrolysis installations of 250kW. Tests on that scale demonstrate how novel technologies will behave when up-scaled. Once a technology has been proven in the HYDROHUB, it could immediately be translated into an electrolysis unit on the industrial gigawatt scale.

[The strong interest of Dutch industrial stakeholders is visible by their support for HtX projects, like MEGAWATT DESIGN DELFZIJL, H2M and H-VISION.

MEGAWATT DESIGN DELFZIJL consists of two subprojects. In one, the goal is to demonstrate and implement a hydrogen system on a large scale (20 MW) in an industrial and commercial environment, producing green hydrogen as a feedstock for producing green chemicals and fuel. The second aims to demonstrate the possibility of electricity cost reduction through more sophisticated procurement and arbitration strategies while providing balancing services to the electricity grid.

The H2M (Hydrogen To Magnum) project aims to use hydrogen produced by SMR in the Magnum power station at the Eemshaven port in Groningen. The H2M project involves the production of SMR hydrogen for use in industry, the use of hydrogen for electricity generation, and adjustments in the power plant for the use of hydrogen.

The H-VISION (Grootschalige Toepassing Van Blauwe Waterstof Als Vervanging Van Aardgas In De Rotterdamse) project's aim was to demonstrate that it is possible to convert "excess" electricity into hydrogen, subject it to methanation and feed the resulting methane into distribution networks.

The High Hydrogen Gas Turbines Retrofit To Eliminate Carbon Emissions project's main objective is to develop a cost-efficient and fuel flexible combustion system with a power output range between 1 and 300 MW and low emission values (sub 9 ppm NO_x and CO). This includes the flexibility of the fuel composition to be used, ensuring operational stability of the turbine. This stability should be ensured for a fuel mix range from 100% natural gas to 100% hydrogen. This is the most important challenge as such a variation of fuel composition with different flame reactivity may result in a large displacement of heat within the combustion chamber that could cause irreparable damage if not checked.

Rotterdam The Hague Airport, part of the Royal Schiphol Group, and a European consortium led by EDL Anlagenbau, have started a project that focuses on the development of technology to produce jet kerosene from captured CO₂ and solar energy from the solar panels of the airport [229]. A small installation at the airport site, with a capacity of 1,000 l/day of sustainable kerosene, is to be constructed. The innovative but proven techniques are planned to be linked together to extract CO₂ from outside air, produce syngas with the use of electrolytic cells, process the syngas into synthetic oil by Fischer-Tropsch synthesis and convert synthetic oil into kerosene.

The Northern Netherlands has a strong position in energy production. In 2016 the idea of developing a green hydrogen economy as a successor to the region's natural gas economy has been formalised. The Noordelijke Innovation Board issued the report *Green Hydrogen economy in Northern Netherlands* [230], which proposes a roadmap for the implementation of projects including pipelines, other, distribution centres, hydrogen refuelling stations, solar-hydrogen smart city areas and other activities. As shown in Table 16, investment of 17.5 to 25 €bn is foreseen up to 2025. The main subprojects included are shown in Table 16.

Table 16: Total investments for the development of Green Hydrogen Economy in Northern Netherlands up to 2025

Green Hydrogen Economy in Northern Netherlands	Investments (million €)
Production	15,000-20,000
- 4,000 MW Wind Offshore	12,000-15,000
- 1,000 MW Electrolysis hydrogen production	500-1,000
- 1,000 MW biomass-gasification	500-1,000
- 100 solar-hydrogen smart city areas	2,000-3,000
Markets	1,000-1,800
- 300,000 ton green methanol + 300,000 ton green ammonia	600-1,000
- 100 H ₂ Fueling stations in Northern Netherlands	100-200
- 5 Hydrogen fuel cell balanced Data Centers	200-400
- 3 Hydrogen Innovation/Start-up Community	100-200
Infrastructure	700-2,000
- Hydrogen pipeline to Rotterdam + Germany	200-1,000
- Hydrogen Trading Platform	50-100
- Hydrogen Harbor Facilities Eemshaven	400-800
- 5 Hydrogen Distribution Centres	50-100
Society	800-1,200
- Zero Emission Public Transport	800-1,200
- Hydrogen Trade Fair and Exhibition	0-10
- Hydrogen Regulatory Framework	0-10
- Green Hydrogen Certificates	0-10
TOTAL	17,500-25,000

Source: [231]

4.1.7 Italy

According to the accessible information, Italy does not have any structured public efforts in place for financing CEST projects. Some activities are financed through public research funds, such as those available through PRIN (Progetti di Ricerca di Interesse Nazionale), but there is no clear dimension relevant to power-to-gas or energy storage applications. When Italian actors are explicitly involved in these domains, it is usually through European funds.

It is possible to find some scattered information on early industrial initiatives of TSOs and DSOs, focussing on power-to-gas or energy storage applications, but the extent of the information available is minimal and it cannot be easily verified.

4.1.8 Poland

There is no dedicated funding scheme for CEST in Poland, hence funding is mainly obtained from the available RD&I funds. The CEST projects (≥ 1 million euro) funded by Polish national programmes relevant to the scope of this report are listed in Table 26 (Appendix B).

National funding for scientific research comes from the national budget [232] and is distributed by the National Science Centre (NCN) [233]. The NCN budget for 2019 is 1.28 billion PLN (€297 million). Since 2014, NCN has distributed €3.1 million for 25 fundamental research projects in CEST related areas [234]. These are Fundamental Research projects mainly in the field of materials development and testing, for electrolyzers, SOFC and hydrogen storage.

The funding of demonstration projects can be obtained through the Polish RD&I (Intelligent Development Program), which in 2019 is about €550 million. This budget is mainly distributed by the National Centre for Research and Development (NCBiR) [235] with the supervision and cooperation of the Ministry of Education. This money is accessible through the Sectoral R&D Programmes [236], which redistribute EU funds within the Intelligent Development Program (PO IR) co-financed by the industrial partners. The Polish sectoral programmes and joint undertakings which finance CEST related projects are: PBS/PBSE for electricity, INGA for the gas industry, INNOSTAL for the steel industry, INNOCHEM for the chemical industry and INNOLOT for aviation.

CEST projects funded in Poland since 2014 focus on metering and sensors, non-destructive testing of infrastructure and neutralising the effects of explosion hazards. In addition the HESTOR project, focusing on hydrogen storage in salt caverns and its utilisation in the refinery process, has been executed by a large consortium led by a Polish refinery (LOTOS S.A.) and accompanied by a gas TSO (GAZ-SYSTEM S.A.).

CO₂-SNG is a demonstration project led by TAURON [237]. The mobile methanation installation is able to convert 4.5 Nm³/h CO₂ to SNG. CO₂ is captured from flue gas coming from power generation units at Laziska Power Plant. This project utilises a CCP pilot installation (Carbon Capture Plant) operating on the basis of CO₂ absorption in amine solutions, which was developed and tested by TAURON and IChPW in 2013. The methanation reactor is based on the concept of structural reactors, where the methanation reaction is carried out in "reaction channels" filled with a fine-grained catalyst, while the heat reception from the reaction zone is carried out through the circulating factor (thermal oil) in the "cooling channels". Besides reactor development and testing, the aim of the project is to adapt the CO₂-SNG system to work with intermittent renewable energy sources, therefore the installation was designed to operate over a wide range (20-100 %) of rated power. The results of this demonstration project are foreseen to create a basis for scaling up of the CO₂-SNG installation to a capacity of about 7-10 MW, which would allow for SNG production of about 500 m³/h. The project leaders are planning the first commercial installation in 2020 [238].

4.1.9 Spain

In the period 2014-2020, several Spanish ministries have supported CEST projects at national level by means of the funding programme "Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad"; Ministerio de Economía Industria y Competitividad (Ministry of Economy, Industry and Competitiveness), Ministerio de Ciencia, Innovación y Universidades (Ministry of Science, Innovation and Universities) and Ministerio de Economía y Empresa (Ministry of Economy and Business). However, there has been no funding programme specifically for CEST.

Funds for Spanish CEST projects have been provided by the national budget and by the European Regional Development Fund (ERDF). A list of relevant projects with a budget greater than €0.1 million is in Table 27 (Appendix B). It is not clear how the funding received by the listed projects is shared by the two sources of funding (national and ERDF). The total amount of funding for CEST projects by Spanish national programmes is approximately €1.5 million. Almost a third of this was allocated to RENOVAGAS, focused on the production of natural gas by means of methanation of electrolytic hydrogen with CO₂ from biogas. Another project researching this topic is RECOBIOHY. Smaller projects were involved in such subjects as the production of liquid fuels from syngas (INPROCOL) and the use of hydrogen to support microgrids with energy supply from renewable sources (COOPERA, TOGETHER and CONFIGURA). At regional level, the Acció programme in

Catalonia is funding the project COSIN, with two lines of research: methanation and development of high temperature electrolysers. This funding programme is also supported by the ERDF.

4.1.10 United Kingdom⁴⁶

UK Research and Innovation (UKRI) is the non-departmental public body funded by the UK Government to invest in science and research in the UK. It has a budget of more than £7 billion and brings together the following organisations:

- The 7 Research Councils of the United Kingdom, including the Engineering and Physical Sciences Research Council (EPSRC)
- Innovate UK (the operating name of the Technology Strategy Board)
- Research England.

The UKRI Gateway [239] is a resource providing information regarding public funded research in the UK. For example, it can be determined that more than £24 million was spent on research projects which relate to, or include, electrolysers, through projects from the EPSRC and Innovate UK for the period 2008-2018. The EPSRC currently has 68 grants active in the broader Energy Storage Research Area with a total budget of £108 million. Funding can take many different forms including research grants, fellowships and studentships.

The other main source for research funding in the area of Energy Storage is Innovate UK. Innovate UK has a stronger business focus than EPSRC, assisting businesses to convert ideas into commercially successful products and services. Since 2007 Innovate UK has invested more than £2.5 billion to enable businesses to innovate. Matching funds from industry take the total funding to £4.3 billion.

In Appendix B, Table 29 shows a selection of some of the larger relevant projects (with budgets of > £0.5 million) along with their descriptions extracted from the UKRI Gateway. Further relevant projects, funded by Ofgem, the office of gas and electricity markets, are also included. The UK projects listed in Table 29 cover the whole range: PtH, D&S and Htx.

EPSRC projects include a £1.8 million grant to investigate flexible routes to liquid fuels (including methanol, DME and hydrocarbons) from CO₂ and sustainably produced hydrogen. This project is a collaboration between the University of Liverpool, ITM, Sasol and Johnson Matthey. The HYSTOPOR project recently received £1.1 million to perform laboratory tests to investigate the storage of hydrogen in porous rocks, prior to commercial trials. A further project, HYVE, aimed at assessing the potential demand for and value of hydrogen in different markets across the UK energy system. It received £0.7 million to analyse the supply chain, including the use of electrolysers to provide load balancing for a future UK electricity system with high penetration of RES.

A number of Innovate UK projects also tackle the subject of electrolysers. A 2017 project MEGASTACK, funded at £3.5 million, involved the implementation of a large 3 MW water electrolyser. The project aimed at a rapid response system so that it could interact with the National Grid's energy balancing markets. Further Innovate UK projects tackle material development and the scale-up of the manufacturing of existing electrolyser technologies.

In the £6.8 million project HYDEPLOY, funded through Ofgem and started in 2017, a 0.5 MW electrolyser is being deployed to demonstrate the use of blended hydrogen in the UK gas grid. The project will inject hydrogen into a private gas network at the University of Keele. It is then intended to perform a larger test on two public networks in the northwest and northeast of England in the proposed project HYDEPLOY 2. "Project Centurion" plans to build upon this work by deploying a 100 MW Power-to-Gas (P2G) energy storage project exploring the production via electrolysis, pipeline transmission, salt cavern storage and gas grid injection of hydrogen at the industrial scale. Innovate UK has provided £226 000 for a feasibility study exploring system design, cost and business case.

Ofgem has also provided £9 million to H21. This is a family of gas industry projects designed to support the conversion of UK gas networks to carry 100% hydrogen. Along with an additional £1.3 million from the UK's gas distribution networks, the money will help Northern Gas Networks build on its H21 Leeds Gate Project, which demonstrated that hydrogen conversion was technically and economically viable.

A further project that is currently underway is Hynet, a hydrogen energy and CCUS project. Based on the production of hydrogen from natural gas and with the aim of reducing carbon emissions from industry, homes and transport in the North West of England, Hynet aims to take advantage of the Government's Hydrogen

⁴⁶ For the time period considered in this report, the United Kingdom was a member state of the EU.

Supply Programme. This is part of a recently announced £390 million program to help industry cut emissions. This includes a £20 million Hydrogen Supply Programme and £100 million to enable greater supply of low carbon hydrogen for use across the economy in order to help businesses to decarbonise.

Other recent initiatives include H100, by the gas distribution company SGN, who aim to make their network the first to carry 100% hydrogen; and the Hy4Heat programme, which aims to establish whether it is technically possible, safe and convenient to replace natural gas with hydrogen in residential and commercial buildings and gas appliances, in order to advise policymakers. The CymruH₂Wales project is part of a £24 million research operation FLEXIS (Flexible Integrated Energy Systems), designed to develop energy system research capability in Wales.

It should also be noted that the UK became the first major economy to pass a net zero emissions law, requiring GHG emissions to be net zero by 2050.

4.1.11 Other member states

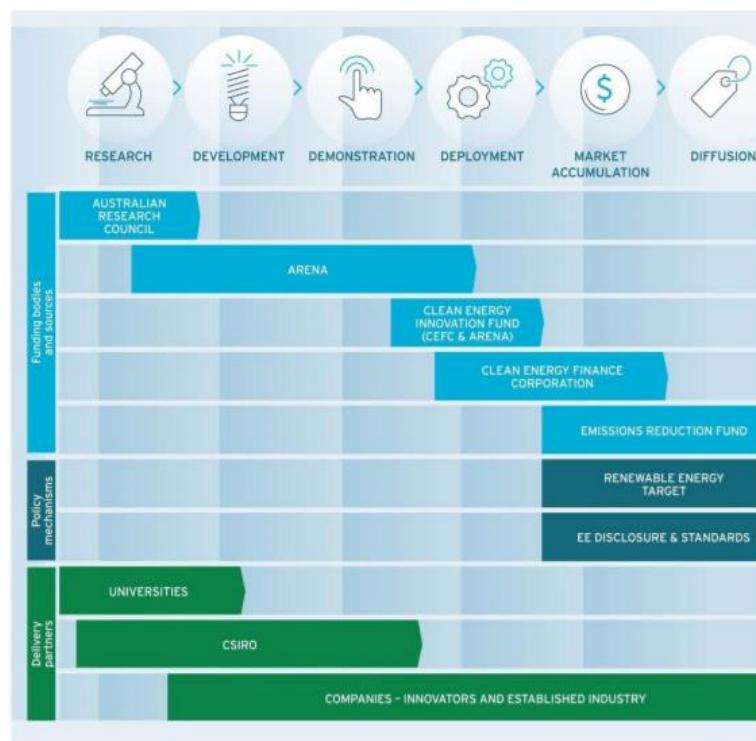
We are not aware of dedicated funding schemes to support CEST in member states other than those listed above.

4.2 Funding programmes at international level to support the development and deployment of CEST

4.2.1 Australia

In Figure 30, a schematic showing the role of Australian Government funding agencies and programs in the overall energy innovation chain can be seen.

Figure 30 The role of Australian Government funding agencies and programs in Australia's energy innovation chain, relative to supporting policy mechanisms and delivery partners.



Source: ARENA General Funding Strategy 2017/2018 – 2019/2020 [240].

The Australian Research Council [241] advises the Australian Government regarding research, administers the National Competitive Grants Program and is responsible for Excellence in Research for Australia (ERA) – the national research evaluation framework. The ARC supports fundamental and applied research, and research training, across all disciplines.

In late 2018, they granted AUD\$7.5 million for two research hubs to advance Australia's energy storage sector. An Australian Research Council Training Centre for Future Energy Storage technologies has received AUD\$4.4m to be set up at Deakin University, whilst an additional AUD\$3.1m will be used to set up the ARC Research Hub for Integrated Energy Storage Solutions (which will include novel power-to-gas systems).

The Australian Renewable Energy Agency (ARENA) [242] provides complementary support to that of the ARC during the early stages of the innovation chain. ARENA directs its support at improving the technological and commercial readiness of early stage clean energy innovations. It recently announced AUD\$22.1 million to fund 16 projects to support innovation and the export of renewable hydrogen [243].

For the deployment phase, the Clean Energy Innovation Fund (CEIF) helps in the commercialisation of emerging clean energy projects and businesses. This fund has an allocation of AUD\$200m for debt and equity investment purposes and is jointly managed by ARENA and the Clean Energy Finance Corporation (CEFC).

A list of relevant projects with a budget in excess of AUD\$1 million is given in Appendix B Table 19. A number of projects funded by ARENA look at novel or improved electrolysis technologies, such as the "Hydrogen Generation by Electrocatalytic Systems" project and the "Direct Water Electrolysis" project, both coordinated by

the Australian National University. A number of projects coordinated by CSIRO look at the production of synthetic fuels. The "Methane Fuel Carrier" project will investigate the production of methane from hydrogen produced from RES and atmospheric hydrogen, whilst the "Liquid Fuel Carrier" project will use solar energy via a SOEL to produce hydrogen and syngas, which are then converted to transportable liquid fuels. Two further projects look at the production of ammonia from RES via electrochemical means including the Monash University project "Ammonia Production from Renewables at ambient pressure and temperature". Queensland University of Technology has received AUD\$3.35 million in funding from ARENA for their "Hydrogen Process" project, evaluating the viability of decentralised and regional-scale systems to produce hydrogen from RES. A large demonstration project, the "Jemena Power-to-Gas Project" received AUD\$7.5 million in funding in 2018 to construct a large P2G facility using RES to produce hydrogen and then inject it into the gas network to meet the cooking, heating and hot water requirements of 250 homes. Additionally, Aqua Hydrex has been funded AUD\$5 million to build an electrolyser pilot plant, also for injecting hydrogen into the local gas grid.

The Australian and Victorian governments have committed AUD\$50 million towards the Hydrogen Energy Supply Chain (HESC) Project which aims to establish a commercial-scale hydrogen supply chain, encompassing production, transportation and storage to deliver liquefied hydrogen to Japan. Japanese funds are providing the remainder of the AUD\$496 million budget. The pilot stage of the project will demonstrate the supply chain between Australia and Japan by 2021.

The first Australian hydrogen demonstration plant (Hydrogen Park SA) to produce hydrogen from renewable energy was announced in February 2018. It will cost AUD\$11.4 million and will be constructed by the Australian Gas Infrastructure Group (AGIG) following an AUD\$4.9 million grant from the South Australian Government's Renewable Technology Fund.

In a further development of note, Hydrogen Utility (H2U) announced, in July 2018, that they are planning a AUD\$117.5 million project to build a demonstration plant in South Australia to produce ammonia using hydrogen produced from electrolyzers operating on intermittent RES. Alkaline electrolyser manufacturer ThyssenKrupp has been awarded a contract to carry out a feasibility study.

EvoEnergy and CIT (Canberra Institute of Technology) have partnered to build a hydrogen test facility at CIT's Fyshwick campus. Phase one will test existing Australian [gas?] network components, construction and maintenance practices for 100% hydrogen [244].

ATCO's AUD\$3.3m Clean Energy Innovation Hub in Jandakot will explore using solar panels, hydrogen and natural gas to provide reliable, low cost and low emission energy in Western Australia [245].

In November 2019 Australia announced its National Hydrogen Strategy which aims to catalyse commercial investment, streamline regulation and develop international relationships. It aims to "set a vision for a clean, innovative, safe and competitive hydrogen industry that benefits all Australians...[and] position [Australia's] industry as a major player by 2030" [246].

4.2.2 Canada

Canadian activities on power-to-gas/power-to-hydrogen topics seem varied, even if fragmented (combining an active private sector, federal initiatives and local ones), making it difficult to obtain an overview.

In 2019 the National Research Council of Canada (NRC)⁴⁷ announced the establishment of the Materials for Clean Fuels Challenge programme [247], a 7-year (CAN\$57 million) collaborative research programme. This program brings together Canada's national labs at the NRC with academic and small- and medium-sized enterprise (SME) collaborators. It will develop high-risk, high-reward technologies at a low technology readiness level (1-5) towards prototype and demonstration. A strong emphasis is put on catalysts, membrane materials and associated devices for artificial photosynthesis and renewable fuels/chemical feedstock production.

The programme focuses on three themes:

- CO₂ conversion
- industrial hydrogen

⁴⁷ The National Research Council (French: Conseil national de recherches Canada) is the primary national research and technology organization of the Government of Canada.

- AI-accelerated materials discovery.

The Natural Sciences and Engineering Research Council of Canada (NSERC⁴⁸) has supported the creation of a "Database for Energy Storage Activity in Canada", which contains three entries on chemical energy storage ('Bella Coola HARP System', 'Glencore RAGLAN Mine Renewable Electricity Smart-Grid Pilot Demonstration', and 'Hydrogenics Power-to-Gas' facility in Ontario). The dimensions and scope of these projects vary significantly [248].

In February 2019, Hydrogenics announced that they had received an award from Air Liquide Canada to design, build and install a 20 MW electrolyser system for hydrogen production from renewable energy sources in Quebec. The facility is expected to be in commercial operation by the end of 2020, with an output of just under 3,000 tH₂/y [249].

Canada has had past programmes aimed at developing and accelerating deployment of hydrogen technologies such as the Hydrogen Canada Strategic Research Network (2008-2013) - H2CAN⁴⁹ [250]. In 2016 a \$4 million investment through the Discovery Frontiers initiative of the NSERC went to a Canada-wide team for the development of water splitting technologies based on nickel catalysis [251].

4.2.3 China

Chinese investment programs at national level are guided by a series of documents known as Five-Year plans. They address all the topics of interest for the development of the country. No specific funding program for hydrogen technologies exists in China. Funding for hydrogen technologies has been provided under the National Hi-Tech Research and Development Program (863) and the Basic Research Program (973). In the 12th Five-Year plan (2011-2015), €14 million were allocated for fuel cell and hydrogen research projects within the 863 program. Under the 973 program, development of solid-oxide fuel cells (SOFCs) and platinum-free fuel cells received USD\$11.1 million. The current Five Year plan (2016-2020) includes hydrogen in the topic *Energy storage and distributed energy*, although it seems that the most of the efforts are focused on hydrogen technologies for mobility applications [252].

The Energy Innovation Action Plan (2016-2030) includes, among its 15 areas for technological innovation, hydrogen and fuel cell technologies and advanced energy storage. The plan highlights the need for research along the entire hydrogen value chain. Since 2016, the Rugao project has been analysing the economic viability of hydrogen production and transportation [252].

China has several manufacturers of large scale alkaline electrolyzers, but no information is available on whether there is on-going, publically supported research on electrolysis or HtX topics.

4.2.4 Japan

Japan has developed a Basic Hydrogen Strategy with the goals of decreasing the overall carbon footprint of the energy supply, including that of hydrogen [253], and achieving cost parity of hydrogen with fossil fuels [254]. There is a strong focus on developing hydrogen supply chains with direct reference to hydrogen

⁴⁸ The NSERC (Natural Sciences and Engineering Research Council) is a departmental corporation of the Government of Canada created in 1978. It is funded directly by Parliament, reports to it and has branched out of the NRC (National Research Council of Canada). This institution: "The agency supports students in their advanced studies, promotes and supports discovery research, and fosters innovation by encouraging Canadian organizations to participate and invest in postsecondary research projects".

⁴⁹ From 250. NSERC Hydrogen Canada Strategic Research Network (2008-2013). Available from: http://www.nserc-crsng.gc.ca/Business-Entreprise/How-Comment/Networks-Reseaux/H2CAN-H2CAN_eng.asp.

"In 2008, NSERC awarded \$5 million in research funds to H2CAN for five years. This amount is leveraged at a ratio of 4:1 through related R&D activities by network researchers and facilities currently available at participating institutions. Total industrial partner contributions represent 50 percent of the overall network budget, while pledged cash contributions represent 35 percent of the partner contributions."

imported from abroad. A secondary aim is to develop domestic PtG⁵⁰ for renewable hydrogen supply by 2030, by improving electrolyser technology [256]. Key funding bodies for supporting the development of hydrogen technologies are the New Energy and Industrial Technology Development Organization (NEDO) attached to the Ministry of Economy, Trade and Industry (METI) and the Japan Society for the Promotion of Science (JSPS). Fundamental research on hydrogen technologies is supported through JSPS, which also promotes international collaboration. Of NEDO's operational budget for 2018 of €240 million⁵¹ for hydrogen, the bulk goes towards projects for hydrogen mobility and stationary fuel cells (subsidies and research grants). Funding of US\$ 9.8 million is available specifically for RD&D on hydrogen gas turbines, hydrogen supply chain and PtG [257]. There is no publicly available information regarding funding awarded to individual projects.

In 2017 three PtG⁵² projects were supported, which are to be completed by 2020. In one project, hydrogen is produced from wind power and admixed to the distribution grid for a residential area [258]. In 2019, construction of Fukushima Hydrogen Energy Research Field (FH2R) has started. This will operate a 10 MW hydrogen production facility. Hydrogen produced in this project will be used to power fuel cell vehicles, improve grid stability and support factory operations. Another "PtG" initiative is in the Yamanashi Fuel Cell Valley, where a 1.5 MW PEM electrolyser will be deployed to take advantage of the solar energy available in this area [259].

Considering the high level of funding for hydrogen in Japan, there seem to be few activities regarding methanation or in general PtH or HtX, although large capacity alkaline electrolyzers are being developed by Asahi Kasei and deployed in two demonstration projects, in Germany, for the H2020 funded ALIGN-CCUS project, and in the above mentioned FH2R project [260]. Asahi Kasei received support to develop their alkaline electrolyser as part of an overarching project funded from 2014-2017 with a budget of around \$10 million. A new project will support basic research activities for all electrolyser technologies [256]. In terms of KPI's, there is the aim to reduce the cost of EL to 50000Y/kW by 2020 (corresponding to around 425 EUR/kW) [261].

Due to the limited availability of renewable energy to produce hydrogen in Japan, supply chains need to be established to import hydrogen. There are two main options being explored for the large scale distribution of hydrogen over long distances, either Liquid Organic Hydrogen Carriers (LOHC) or Liquid Hydrogen (LH2). Japanese industry, notably the Chiyoda Corporation, is investing in a supply chain demonstration project supported by NEDO, which is building a hydrogenation plant in Brunei and a dehydrogenation plant in Japan. Chiyoda's SPERA Hydrogen Technology is based on methyl-cyclohexane (MCH), for which they have developed a dehydrogenation catalyst. A demonstration plant has completed 10 000 h of operation. The project is scheduled to begin supply operation between Brunei and Japan in 2020 [262].

The other option for long distance/high volume hydrogen distribution pursued in Japan is based on LH2. As mentioned above, the Hydrogen Energy Supply Chain (HESC) Pilot Project is jointly funded and implemented by Australia and Japan, with a total budget of AUS\$496 million [263]. Part of the project involves the direct import of brown coal to Japan, but gasification of brown coal will also take place in Australia, with the hydrogen being transported to Japan as LH2. There is a plan to store CO₂ in off-shore gas fields. The Japanese HYSTRA subproject of HESC, which involves Kawasaki Heavy Industries and Shell, is currently focusing on the design and construction of the LH2 tanker and the unloading facilities [264].

4.2.5 Norway

Norway has established a national energy strategy to promote targeted efforts for R&D. Priorities include the decarbonisation of maritime transport and industry, for both of which hydrogen is mentioned. It is also seen as an option for decentralised and large scale energy storage [265]. In Norway, research funding is provided through the ministries responsible for the respective sector. The Ministry of Research and Education coordinates research policy. Public R&D funding is allocated either directly to research institutions or through funding agencies. The ENERGIX programme, which is implemented through the Norwegian Research Council, provides funding for research on renewable energy, efficient use of energy, energy systems and energy policy. The programme is a key instrument in the implementation of Norway's national strategy for research and development of climate friendly energy technologies. The Research Council of Norway allocates around 30%

⁵⁰ In spite of the fact that the case for PtG in Japan is currently rather weak given a poorly developed natural gas infrastructure and very little excess renewable electricity (255. Shibata, Y., *Is Power to Gas Feasible in Japan?* IEEJ, 2016.)

⁵¹ Excluding subsidies for FCEV.

⁵² In our terminology, this would be PtH, as the final product is hydrogen.

of public R&D funding, through a variety of funding instruments, with a focus on supporting research organisations. The Council is also involved in the Pilot E funding scheme, which seeks to promote the development and deployment of environmentally friendly technologies. The projects supported through this scheme are mostly outside the scope of this report, for example those funded through the 2018 call on zero emission maritime applications. In 2019 a call was launched with the title zero emission hydrogen value chain. Apart from funding projects, the Council also supports the participation of Norwegian companies/organisations in the EU's FCH 2 JU programme. The Research Council operates a project database [266], and only the projects gathered there were reviewed, apart from two projects funded through the Pilot E programme. There may be more CEST projects funded through other sources.

Electrolysis projects funded within the time period considered on electrolysis cover a wide range of TRLs, with a focus on basic research. For an overview of projects, see Table 25. The project FUNKEYCAT "Functional Grading by Key doping in Catalytic electrodes for Proton Ceramic Cells" tries to improve the efficiency of electrochemical cells through materials research. The research institute Sintef is conducting research on pressurised PEM electrolyzers in the HIEFF PEM project, and seeks to reduce cost through improving bipolar plates in another project. It is also investigating a novel approach based on spinning electrodes, in the ELEROT project. In a spinning stack the produced gas and the electrolyte are quickly separated because of increased buoyancy of the gas. NEL is being funded for the further development of their alkaline electrolyzers, focussing on electrodes and catalysts. The NEXTGAME project, with partners from Norway, Taiwan and Israel, is looking at taking the anion exchange membrane (AEMFC) technology to the next level.

Basic research is being conducted on porous ceramic materials that have a thin layer of water on the surface, which is stated to help increase the efficiency of high temperature fuel cells and electrolyzers. The primary objective of the AH2A project is to develop a proton conducting electrolyser assembly operating at 600°C for the efficient use of heat and steam supplied by geothermal, solar, or waste energy from industrial plants. There is also research on metal supported proton conducting ceramics.

Several projects on hydrogen membranes are being supported. The project Nanocomposite Facilitated Transport Membranes for H₂ purification (FAT H₂) aims at developing efficient and low-cost separation technology for purification of hydrogen from various production processes. The H2MEMX aims to improve Pd alloy membranes for hydrogen separation for industrial applications.

Hydrogen distribution is being investigated by the HYLINE project, which seeks to use Norway's 8800 km subsea pipeline network for transporting hydrogen to the market. Materials issues, in particular material degradation through hydrogen embrittlement, need to be addressed. There are several other projects also looking into the effect of hydrogen on subsea components and pipeline steel. Related to the topic are ongoing studies on the export of energy to Europe, also in the form of hydrogen. A Pilot E project seeks to develop hydrogen production and bunkering for ferries/cruise ships in the Norwegian world heritage fjord "Geirangerfjorden". The hydrogen production facility is based on surplus hydropower.

Through system simulation, component modelling and process design, the HYPER project is looking to the improvement of hydrogen liquefaction. Hydrogen liquefaction is assumed to be provided by 4 parallel Claude-type cryogenic liquefiers, each with 125 ton-per-day capacity, which would be sufficient for one 160000 m³ ship load about every three weeks. Not directly part of the scope, but a strong focus on the use of hydrogen for maritime applications is notable in the Norwegian programme. Several large scale demonstration projects are supported through the Pilot E programme. As announced at the end of 2019, Wilhelmsen, NorSea and partners will receive €3.3 million to develop a liquid hydrogen supply chain for maritime applications.

4.2.6 South Korea

In 2019, the government will invest KRW 902.9 billion (€700 million) in clean energy research and development (R&D), according to the Ministry of Trade, Industry and Energy [267]. Korea invests heavily in R&D, at a rate of over 4% of GDP, mostly conducted by big companies [268]. There is also public sector funding for R&D, administered through, for example, the national research foundation of Korea Technology Development Program to Solve Climate Changes (covering a broad range of topics, among which are hydrogen technologies). The Korean economy, according to the Moon administration, should transition to a hydrogen economy. Their roadmap is focused on three elements: increasing the production and use of hydrogen vehicles, expanding the production of fuel cells, and building a system for the production and distribution of hydrogen [269]. Heavy investment has been made in the past in the deployment of stationary fuel cells. Fuel cells are considered a new and renewable energy (NRE) source by the South Korean

Government, however, the fuel cells run mostly on natural gas. There does not seem to be much activity in CEST at present, but Korea plans to invest more in hydrogen production, distribution and storage technologies in the future [270].

4.2.7 Switzerland

The first⁵³ commercially operating PtG plant (2MW) will be built in Dietikon, supplied by electricity from a waste incineration plant and CO₂ from a waste water treatment plant. The installation will produce synthetic methane through biological methanation [271]. A Power-to-Methane plant was operated from 2015 to 2017 in Rapperswil by the research centre IET⁵⁴. Work on this concept was continued as part of the HEPP project (High Efficiency Power-to-Gas Pilot). Project results will be used in the H2020 PENTAGON project (see Section 3.3.4.3). A small (10kW) pilot plant has been installed encompassing a SOEC and methanation unit with heat management. IET is also involved in the H2020 STORE&GO (see Section 3.3.4.3) project, and one of the sites of the project is located in Solothurn. The Swiss public utility "Regio Energie Solothurn" has setup a hybrid power plant Hybrid Plant Aarmatt, based on two 350 kW PEM electrolyzers. The hydrogen is fed into the gas grid [272]. Project funding for PtG topics is available from the Swiss National Fund for Research (SNF). A project on Renewable Methane for Transport and Mobility (RMTM) looked into carbon sources for PtG plants, to investigate the potential of synthetic fuels. A recently published White Paper on the Perspectives of Power-to-Product (P2X) Technology in Switzerland aims to identify the contributions that could be made to Switzerland's energy strategy by different technologies based on conversion and storage of various forms of energy. This work was supported by Innosuisse, with complementary funding from the Swiss Federal Office of Energy (SFOE). Research on PtG and PtX is regarded as important for the Swiss energy transition [273], and its focus seems to be on CO₂ utilisation through methanation or methanol synthesis. Several projects were funded under the National Research Programme "Energy Turnaround", which aims to contribute towards solutions that will ensure a sustainable energy policy for Switzerland, with a budget of CHF 37 million.

4.2.8 United States

In the United States of America, the Department of Energy (DoE) is responsible for the Hydrogen and Fuel Cells Program (HFCP). The HFCP was initiated by the DoE in 2002, based on the National Vision of America's Transition to a Hydrogen Economy (February 2002) and the National Hydrogen Energy Roadmap (November 2002) [274]. These two documents focus on early stage research and development activities and stakeholder engagement to enable the widespread market acceptance of hydrogen and fuel cell technologies across diverse applications.

"In Fiscal Year (FY) 2018, Congress appropriated approximately \$115 million for hydrogen and fuel cell activities in EERE's FCTO and approximately \$30 million for FE's solid oxide activities. In addition, funding within ARPA-E, NE, and SC relevant to hydrogen and fuel cell activities amounted to approximately \$20 million, \$2 million, and \$19 million, respectively. This represents a total DOE budget for FY 2018 of approximately \$185 million related to hydrogen and fuel cell technologies." [274]

Currently the FCTO, as the primary office related to hydrogen and fuel cells in DoE, is responsible for budget distribution and reporting of the progress, accomplishments, technology status and performance. Table 17 presents the historical budget breakdown and transformation of the key activities since 2014. The key activities within HFCP have changed over time. It can be observed that the programme has entered a period with a significant increase of funding dedicated to technology acceleration and infrastructure development, whereas component development, fuel studies and system analysis funding is decreasing.

⁵³ Globally, according to the source.

⁵⁴ Institut für Energietechnik an der HSR Hochschule für Technik Rapperswil

Table 17: Historical breakdown of the FCTO budget for the DOE Hydrogen and Fuel Cells Program [10^3 \$]

Key activity	2014	2015	2016	2017	2018	2019
	[1000 \$]					
Fuel Cell R&D	33,383	33,000	35,000	32,000	32,000	30,000
Hydrogen Fuel R&D	35,200	35,200	41,050	41,000	54,000	39,000
Technology Acceleration ⁵⁵				18,000	19,000	21,000
Technology Validation	6,000	11,000	7,000			
Manufacturing R&D	3,000	3,000	3,000			
Market Transformation	3,000	3,000	3,000			
System Analysis	3,000	3,000	3,000	3,000	3,000	2,000
NREL Site-wide Facilities Support	1,000	1,800	1,900			
Safety Codes and Standards	7,000	7,000	7,000	7,000	7,000	7,000
Hydrogen Infrastructure R&D						21,000
Total [10000 \$]	92,928	97,000	100,950	101,000	115,000	120,000

Source: DOE, 2019

DOE funded projects are grouped according to the key areas given in Table 17. There are specific initiatives and consortia which manage the progress and monitor the accomplishments of the projects, in order to facilitate collaboration in these specific areas.

The Hydrogen Fuel R&D subprogram focuses on cost reduction (i.e. <2 \$/kg for hydrogen production) and improvement in the reliability of technologies used to produce hydrogen from diverse domestic energy resources, and in its subsequent storage. The 2018 activities focused primarily on early stage R&D funded through two consortia: HYDROGEN aiming at hydrogen production and HYMARC for hydrogen storage materials. Significant progress in this subprogram has been reported for low temperature electrolysis, however the greatest interest seems to be in materials for photo electrochemical (PEC) and solar thermochemical (STCH) technologies.

The activities within the Technology Acceleration and Hydrogen Infrastructure R&D area are designed to accelerate the transition of early-stage hydrogen and fuel cell research to subsequent stages of development, and to leverage the private sector in order to enable deployment. In 2018, significant progress has been made to advance cost-competitive hydrogen technologies and establish the viability of hydrogen in emerging applications. The R&D goal is to lower the cost of hydrogen delivery and dispensing to 5 \$/kg by 2025. Activities within the Technology Acceleration and Hydrogen Infrastructure R&D area support the H2@Scale initiative. One of the indicated key accomplishments in this area is the creation of the H-Mat national laboratory consortium, which will be responsible for materials research to reduce the costs and enhance the durability of steels and polymers in hydrogen service. Novel coatings for hydrogen compressor seals (developed by GVD Corporation) which reduce erosion by 70%, are also mentioned. These coatings comprise polymeric and inorganic layers that enhance seal flexibility and lubricity, and are expected to reduce hydrogen permeation by one order of magnitude.

The Safety, Codes and Standards subprogram identifies early-stage R&D for the fundamental understanding of the physics, critical data and safety information, and development of the codes and standards by industry.

⁵⁵ Category proposed in the course of planning the budget for 2017. Under Technology Acceleration fell the following categories: Manufacturing R&D, Technology Validation and Market Transformation

The System Analysis activities, which also support the H2@Scale activities (see below), are aimed at identifying technology gaps, impacts and future R&D needs. Focus in this area was recently directed towards the cost of ownership of truck and powertrain technologies and reduction in the cost of fuelling stations.

H2@Scale is the initiative to advance the affordable production, transport, storage and utilisation of hydrogen, and to increase revenue opportunities and impact in multiple energy sectors. In 2018, the activities within H2@Scale were in focus of the FCTO [275]. The projects supported by the H2@Scale initiative are executed under the cooperative research and development agreement (CRADA).

The Advanced Clean Energy Storage (ACES) project is a privately funded joint initiative between a gas turbine producer and an industrial leader in natural gas transportation and storage to develop renewable energy storage [276]. ACES will utilize four technologies: renewable electrolytic hydrogen production and storage, compressed air energy storage (CAES), battery storage, and solid-oxide fuel cells. The batteries and fuel cells will cover instantaneous generation for short durations of hours. To enable large scale energy storage, the ACES system will most probably be developed in Central Utah. The stored hydrogen will be utilized as fuel for dispatchable on-site turbines, and CAES will provide multi-day or longer storage and generation. By 2025, the ACES project aims to have enough renewable hydrogen to power 250 MW of electricity supply. When completed, the site will be able to supply 1,000 MW of instantaneous electricity. As one of the medium-sized caverns considered for this project would be able to store 5 million kilograms of hydrogen gas it means that it should be providing more energy storage than the combined capacity of all the grid-scale batteries currently installed in the world.

The US ARPA-E programme had been supporting the development of electrofuels from 2010-2014 [277], but further funding does not seem to have been available during the timeframe considered for this report.

4.3 Standardisation activities in support of CEST

This section presents selected European and international standardisation activities related to CEST. The list of the related standards is huge, and their description is outside the scope of this report. SFEM WG Hydrogen Report 2019, mentioned below, provides a fairly recent overview. The present status of the individual technical documents is available at the webpages of the individual standardisation bodies mentioned below.

Due to the many sectors and applications that are part of the scope of chemical energy storage, several European and international standardisation technical committees (TC) deal with its various aspects:

- European Committee for Standardisation CEN:
 - CEN/CLC/JTC 6 on Hydrogen in Energy Systems⁵⁶
 - CEN/TC 234 on Gas Infrastructure
 - CEN/TC 268 on Cryogenic Vessels and Hydrogen Technologies
- International Standardization Organization ISO:
 - ISO/TC 197 on Hydrogen Technologies
 - ISO/TC 193 on Natural Gas
 - ISO/TC 158 on Analysis of Gases
 - ISO/TC 58 on Gas Cylinders
- International Electrotechnical Commission IEC:
 - IEC/TC 105 on Fuel Cell Technologies (also covering electrolysis)

In the following some of these Committees will be presented in some details.

4.3.1 CEN Sector Forum Energy Management Working Group Hydrogen (SFEM WG Hydrogen)

Founded in 2015, the main objective of the SFEM WG Hydrogen is to perform an analysis on the state-of-the-art technology and standardisation, and a gap analysis on the main barriers including challenges and needs on the topic of hydrogen in the energy system. The scope of the working group covers the production of

⁵⁶ A JTC is a Joint CEN and CENELEC Committee.

hydrogen through electrolysis and the transportation, distribution and usage of pure hydrogen or hydrogen in natural gas dominant mixtures (H2NG). In addition, actions in cross-cutting fields such as safety and training of personnel are identified. A second objective is to establish contact with key stakeholders from the gas sector, electricity supply, mobility and the Fuel Cells and Hydrogen Joint Undertaking (FCH 2 JU) in order to perform the work in the most effective way and to have broad support from the stakeholders to identify the key challenges. The final objective is to set a long term collaborative framework with major bodies for strengthening cooperation between regulatory work, standardisation work and research programs. There is a regular exchange of information with the RCS strategy coordination group of the FCH 2 JU, and European Commission is participating as well. The WG has issued two reports, summarizing the outcome of their work [278, 279]. The first report, published in 2016, sets out a roadmap for pre-normative research (PNR) and standardisation activities, the second report, published in 2019, is an update which has taken into account the RCS progress of the previous years.

4.3.2 CEN/CENELEC JTC 6 “Hydrogen in energy systems”

One of the recommendation made in the first CEN SFEM report [279] was addressing the CEN and CENELEC Technical Boards regarding the establishment of a new joint technical Committee on hydrogen, aiming at the coordinated development of the necessary standards. The new Joint Technical Committee has been launched in 2016 as CEN/CENELEC JTC 6 “Hydrogen in energy systems”. JTC 6 is the mirror committee⁵⁷ to ISO/TC 197 ‘Hydrogen technologies’⁵⁸ (see below). The scope of the JTC 6 covers those topics not yet covered by another CEN/TC. (see next Section).

The current structure of the CEN-CLC/JTC 6 is as follows:

- WG 1 Terms and Definitions
- WG 2 Guarantee of Origin
- WG 3 Hydrogen safety
- Ad-hoc group interface electrolyser to the e-grid.

Meanwhile the WG 2 has joined the CEN/CLC/JTC 14 on Energy management, energy audits and energy savings.

4.3.3 CEN/TC 268/WG 5 ‘Specific hydrogen technologies applications’

The CEN/TC 268 focuses on Cryogenic vessels and specific hydrogen technologies applications, with a WG 5 on Specific hydrogen technologies applications. The European Directive on the Deployment of Alternative Fuel Infrastructure was adopted in 2014⁵⁹. The main alternative fuel options are electricity, hydrogen, biofuels and natural gas. This Directive aims to ensure the build-up of alternative fuel infrastructure in all Member States. One of its technical provisions regards the implementation of common technical specifications for the interoperability of this infrastructure throughout the European Union. The preparation of these interoperability standards, including those for hydrogen transport, has been requested to the CEN/TC 268/WG 5 under the standardisation request M533. Of direct interest for CEST is the European standard on hydrogen purity, which is however limited to requirements for road transport⁶⁰.

4.3.4 CEN/TC 234 ‘Gas Infrastructure’

CEN/TC 234 focuses on Gas infrastructure. This Technical Committee has decided to take hydrogen in natural gas (H2NG) into account with the intention to extend the existing standards for hydrogen in gas infrastructure where necessary. A series of Work Items (WI) for a series of standards on injection/blending facilities for renewables (H₂/Biomethane) are under preparation at the time of writing⁶¹. Further needs for new standards, e.g. pressure control, have still to be identified. The standardisation work will be prepared by a Technical

⁵⁷ CEN-CENELEC/JTC 6 will be the mirror committee to ISO/TC 197 ‘Hydrogen technologies’ for those topics not yet covered by another CEN/TC, in particular the work covered by Standardisation Request M/533 on hydrogen vehicle refuelling stations and associated equipment and procedures. These topics are being dealt with by CEN/TC 268/WG 5.

⁵⁸ The specific standardisation framework is established according to the Vienna Agreement.

⁵⁹ Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014, available at <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=EN>

⁶⁰ EN 17124:2018 Hydrogen fuel - Product specification and quality assurance - Proton exchange membrane (PEM) fuel cell applications for road vehicles

⁶¹ For hydrogen the Working Item is 00234090 - Gas infrastructure - Plants for the injection of renewable gases into natural gas networks - Part 3: Specific requirements regarding hydrogen

Report (TR) on 'Consequences of hydrogen in the natural gas infrastructure' to prepare for future standardization and provide guidance on the impacts of the injection of H₂ into the gas infrastructure⁶².

The report will rely on previous studies, and assess the impact of hydrogen injection on each part of the gas infrastructure in the scope of the CEN/TC 234 Working Groups, including covers underground storage in salt caverns. It will also provide justifications for pre-normative research.

4.3.5 ISO/TC 197 'Hydrogen Technologies'

The scope of ISO/TC 197 is standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen. Recent years have been dedicated to international standardisation aspects of the hydrogen refuelling station, its components and the interoperability between the station and the vehicles. Fuel Cells vehicles, including the required fuel purity. Among the future ISO/TC 197 activities planned at the plenary meeting of December 2019, there are typical CEST themes, such as new electrolyser test requirements for active grid balancing, PtH technologies and blends with natural gas and new requirements for non-industrial use for liquid hydrogen.

4.4 European and International initiatives to support the development and deployment of CEST

This section provides information regarding European and international initiatives which are acting to support the development and deployment of CEST. Their role is mainly to gather the key stakeholders with knowhow and an interest in supporting the further development and large scale deployment of CEST worldwide. They function on the basis of dues paid by participants, contributing to knowledge development in the form of reports, technical guidelines or the organisation of events, which express the readiness of the market for new technologies or concepts deployment, and often serve as a base for standardisation activities and legislative adjustments.

4.4.1 Clean Energy Ministerial

The Clean Energy Ministerial (CEM) is a global forum to promote policies and programmes to advance clean energy technology. Initiatives are based on areas of common interest among participating governments and other stakeholders. The Hydrogen Initiative, which was launched in 2019, focusses on the role of hydrogen and fuel cell technologies in the global clean energy transition. The Initiative will drive international collaboration on policies, programmes and projects to accelerate the commercial deployment of hydrogen and fuel cell technologies across all sectors of the economy. Initial work carried out through the initiative will focus on three different areas:

- Helping to ensure successful deployment of hydrogen within current industrial applications.
- Enabling deployment of hydrogen technologies in transport (e.g. freight, mass transit, light-rail, marine).
- Exploring the role of hydrogen in meeting the energy needs of communities.

On September 25, 2019, the Japan Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO) held a Hydrogen Energy Ministerial Meeting to enable discussions on future directions of policies for global utilization of hydrogen, and support international collaboration.

4.4.2 Hydrogen Initiative

On the 18th of September 2018, Energy Ministers from twenty-five European countries signed a joint declaration for the promotion of hydrogen produced from renewable energies through a new initiative. The Hydrogen Initiative is supported by Switzerland, Iceland and all EU member states except Ireland, Slovakia, Slovenia and Sweden. The initiative is also supported by the European Commission. The declaration states the aim of the initiative is to maximise the potential of sustainable hydrogen technology for the decarbonisation of multiple sectors, the energy system and the long-term energy security of the EU.

⁶² Decision CEN/TC 234 09/2017

4.4.3 IEA Hydrogen TCP Task 38: Power-to-Hydrogen and Hydrogen-to-X

"System Analysis of the techno-economic, legal and regulatory conditions", is a Task of the Hydrogen Technology Collaboration Programme (TCP) of the International Energy Agency. It was approved by the TCP's Executive Committee (ExCo), to examine hydrogen as a key energy carrier for a sustainable and smart energy system.

Over 50 experts from 15 countries are involved in Task 38 which is coordinated by the French CEA/I-tésé, [are you sure this is right, I couldn't find it on line] supported by the French ADEME. Participating ExCo Members are Australia, Denmark, the European Commission, France, Germany, the Hydrogen Council, HyChico, Japan, New Zealand, Norway, Southern Company, Spain, Sweden, The Netherlands, and the United Kingdom.

The general objectives of the Task are to:

- Provide a comprehensive understanding of various technical and economic pathways for power-to-hydrogen applications in diverse settings
- Provide a comprehensive assessment of existing legal frameworks for hydrogen systems
- Present business developers and policy makers with general guidelines and recommendations which enhance hydrogen system deployment in energy markets

The final objective is to develop hydrogen visibility as a key energy carrier for a sustainable and smart energy system, within a 2 or 3 horizon time frame: e.g. 2020, 2030 and 2050.

The task is organized in subtasks (ST) and task forces (TF). Task forces aim at supplying the subtasks with data and methodology throughout the task duration. Subtask workshops are organized in order to advance the project, along with plenary meetings which are organized on a semi-annual basis. A Workshop titled "Power-to-X: Review & Analysis of demonstration projects" was organized on 20 November 2018 in Aix-en-Provence, and put together actors involved in Power-to-X demos. The task has also built a database of relevant demonstration projects, which has been used for this study.

Relevant sources have been reviewed by the task, and there are already some published works:

- A review of existing legal frameworks and policy measures for hydrogen systems [50]
- A proposal of definitions for Power-to-X systems [172]
- A review and analysis of the existing techno-economic studies on Power-to-Hydrogen and Hydrogen-to-X [280]

4.4.4 Hydrogen Council

The Hydrogen Council is a global initiative, launched at the World Economic Forum 2017, in Davos, of leading energy, transport and industry companies with a united vision and long-term ambition for hydrogen to foster the energy transition. It is a global CEO coalition bringing together 50+ leaders in the energy, transport and industry space and is committed to ensuring that 100% of hydrogen fuel used in transport is decarbonised by 2030 [281]. Four strategic reports have been issued by the HC:

1. Path to hydrogen competitiveness A cost perspective, January 20, 2020 [282]
2. Hydrogen Meets Digital, September 13, 2018 [283]
3. Hydrogen, Scaling Up, November 13, 2017 [284]
4. How Hydrogen Empowers the Energy Transition, January 15, 2017 [285]

4.4.5 European Energy Research Alliance (EERA)

The European Energy Research Alliance (EERA) is an association of European public research centres and universities active in low-carbon energy research. EERA's members work together in 17 Joint Programmes, which are aligned with the priorities of the SET-Plan. There are JPs on energy storage, with a sub-programme on chemical storage, and a JP on fuels cells and hydrogen. The overall objective of the latter is to align medium to long term precompetitive research activities at EERA institutes and associated institutions to

create a technical-scientific basis for further improvement of fuel cell and hydrogen technologies. The JP has sub-programmes for hydrogen production and handling and hydrogen storage, setting out research objectives and expected outcomes.

4.4.6 Mission Innovation (MI)

Mission Innovation is a global initiative of 23 countries and the European Commission (on behalf of the European Union) working to reinvigorate and accelerate global clean energy innovation with the objective of making clean energy widely affordable. MI was announced at COP21 on November 30, 2015. High-level leadership is provided by MI members' Ministers with responsibility for clean energy innovation. The MI Steering Committee, comprised of member representatives, provides strategic guidance to foster implementation of MI's Enabling Framework. Core administrative functions are carried out by the MI Secretariat, a small, flexible team supporting the Steering Committee.

The goal is to help deliver the following outcomes by the end of 2020 [286]:

1. A substantial boost in public-sector investment in clean energy RD&D at the national level of MI members.
2. Increased private sector engagement and investment in energy innovation, particularly in key Innovation Challenges.
3. Many new or strengthened voluntary cross-border networks and partnerships on energy innovation, greater engagement from innovators, and accelerated progress in addressing specific Innovation Challenges.
4. Greater awareness amongst MI members and the wider clean energy community of the transformational potential of energy innovation, the progress being made, and the remaining critical clean energy innovation gaps and opportunities.

At the third MI Ministerial in 2018, members endorsed the addition of an Innovation Challenge on Renewable and Clean Hydrogen. Innovation Challenge 8: Renewable and Clean Hydrogen has the objective to accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale. In 2019, MI together with IPHE and NOW (German funding body) organised a workshop on hydrogen in the gas grid.

4.4.7 International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)

IPHE serves as a mechanism to organize and implement effective, efficient, and focused international research, development, demonstration and deployment activities related to hydrogen and fuel cell technologies. Originally organized as "The International Partnership for the Hydrogen Economy," the organization changed its official title to "The International Partnership for Hydrogen and Fuel Cells in the Economy" in December 2009 (still abbreviated to IPHE). The organization also provides a forum for sharing information, lessons learned and best practices among member countries on initiatives, programs, and policies, as well as safety, codes and standards, to accelerate the widespread deployment of hydrogen and fuel cells in the economy, in order to reach energy, economic and environmental goals. The formation of IPHE was facilitated by the U.S. Department of Energy and the U.S. Department of Transportation in 2003 to foster international cooperation on hydrogen and fuel cell R&D, common codes and standards, and information sharing on infrastructure development. Today, IPHE's 18 partners organize, evaluate, and coordinate multinational research, development, and deployment programs that advance the introduction of hydrogen and fuel cell technologies on a global scale.

IPHE's strategic priorities are to:

1. Accelerate the market penetration and early adoption of hydrogen and fuel cell technologies and their supporting infrastructure.
2. Share information, lessons learned and best practices among member countries on initiatives, programs, policies, and regulatory actions - including safety, codes and standards, to enable affordable and sustainable widespread deployment across sectors.
3. Provide accurate factual and unbiased information to policy-makers, including government officials at the federal, regional and state level, as well as to the public, students, industry and non-governmental associations.

4. Monitor hydrogen, fuel cell and complementary technology developments worldwide to help inform future government research, development, demonstration, and analysis activities.

4.4.8 IRENA – International Renewable Energy Agency

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future. It aims to be "the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy". It promotes the widespread adoption and sustainable use of all forms of renewable energy and pursues sustainable development, energy access, energy security and low-carbon economic growth and prosperity. It aims to assist countries in reaching the full potential use of renewable resources and technologies. Currently more than 170 countries are actively engaged with IRENA. In September 2018, IRENA published the document "Hydrogen from renewable power: Technology outlook for the energy transition" [8] and the report Hydrogen: A renewable energy perspective [287], examining the potential of hydrogen for hard-to-decarbonise energy uses, including energy-intensive industries, trucks, aviation, shipping and heating applications.

4.4.9 HIPS-NET

The partnership HIPS-NET aims to establish a common European understanding on the hydrogen tolerance of the existing natural gas grid [288]. It is composed of about 40 partners from the public and private sector. The network partners share available information from both running and completed projects. The network is coordinated by DBI-Gut and is considered as a GERG project (European Gas Research Group).

5 Summary and outlook for CEST

5.1 CEST development under H2020

As outlined in Section 1, CEST are likely to have a key role in the decarbonisation of the energy system, which has been reflected in current and previous research framework programmes. Public funding for R&D on CEST has been of the order of €180 million, of which 60% has been awarded to private companies. Half of the H2020 funding has been given towards research on PtH, where most projects are in the demonstration phase (project class D). HtX projects are still more in the field testing stage (project class C). In this time period, there has not been much activity on D&S topics. Almost half of the funding has been awarded through the FCH 2 JU programme, followed by LCE calls (22%). It is notable that there has been little fundamental research, and no projects have been identified focussing on development of innovative manufacturing methods, which would seem to be a prerequisite for upscaling the technologies⁶³.

5.1.1 Power-to-Hydrogen

The FCH 2 JU is committing funds towards the three main type of electrolyser technology (alkaline electrolyzers, PEM electrolyzers, solid oxide electrolyzers) which are at different stages in their development and deployment. This work is supplemented by several projects from other parts of the Horizon 2020 programme which are discussed in detail in Section 3.1. The projects range from basic research to field testing and demonstration. Under FP7, a project on diagnostics and monitoring had been supported, but not under H2020. Clear KPIs and targets for all three technologies have been set by the FCH 2 JU, which will need to be updated for the next framework programme.

5.1.2 Hydrogen Distribution and Storage

Only very few projects are being funded under H2020 related to hydrogen distribution and storage (projects related to mobility applications were considered out of scope). Two projects address hydrogen separation/purification and two projects are developing LOHC concepts for large scale distribution of hydrogen. All projects are at the “research to prototype” stage, project class B. The technological improvements needed for separation technologies have been set out in the corresponding call topics, for small scale systems (<25kg/H₂/d). KPIs and targets for hydrogen carriers are less clear. There is also some uncertainty on whether the projects will reach all of their objectives, so further research may be needed.

The FCH 2 JU has issued two call topics related to hydrogen admixture in the AWP 2019, and two projects are likely to be supported. One would address the effect of various admixture levels on components of the high pressure grid, the other would test gas appliances for admixtures up to 100% H₂.

Even if no corresponding projects have been supported, targets for large scale hydrogen storage have been set in the FCH 2 JU MAWP [14], see Section 3.2.4.1.

This area of research seems underfunded in H2020, when compared with international activities and in particular in light of the challenges ahead if hydrogen is to play a significant role for decarbonisation of industry and of the energy system, as large amounts of hydrogen will have to be distributed and stored.

5.1.3 Hydrogen-to-X

Projects pursuing hydrogen-to-X applications are still recent and in some cases their academic dimension is still preponderant. No KPIs or targets could be identified at H2020 programme level. It seems that, for now, the only pathways supported are those relying on CCU. Synthesis of methanol and synthetic methane clearly dominate the portfolio of activities. Production of synthetic fuels is also targeted by several projects, especially through co-electrolysis, and secondly by conversion of methanol to olefins. Rather minor efforts are aimed at formic acid synthesis. There are no significant European activities aimed at producing ammonia with electrolytic hydrogen, probably because this technology has been already been proved. The level of development of the conversion pathways varies, with the processes aimed at obtaining liquid and gaseous “synthetic fuels” as final products having the lowest development level. There are several publicly supported methanation projects, at national level often combined with biogas production. Although the technology of chemical methanation can be considered mature, its application for CEST implies further development in

⁶³ Several examples of manufacturing-oriented projects (e.g. MAMA-MEA, SOSLem, etc.) are available for fuel cell productions and assembly. It can be argued that the solutions developed in these projects can be translated to electrolyzers’ production. Since no H2020 action was specifically dedicated to electrolysis manufacturing no project was assigned to the specifically dedicated E project class.

terms of scaling the reactors and dynamic operation. Activities on biological methanation have been rather limited under the H2020 programme.

5.1.4 Comparison to (inter)national activities

Compared to national funding, PtH seems to have received a higher level of support at EU level through the FCH 2 JU programme. By contrast, projects for D&S are largely funded through national sources. The UK is pursuing ambitious projects for the conversion of the existing gas grid to distribute hydrogen, a topic which is also gaining traction in Germany and in the Netherlands. HtX is a particular focus in Germany, but there are also significant activities at EU level and in other member states. Research on methanation is supported in most of the countries providing public funding for CEST.

The total H2020 funding for CEST development is at a similar level to that awarded through German national funding sources. The various German funding programmes have provided support of over €200 million for CEST projects since 2014. In Germany, the portfolio of projects covers a large variety of topics. Compared to the EU, a higher share of national funding goes towards D&S and HtX project (see Figure 31). Although PtH research is being conducted in Germany, it is seeing less support than that awarded through H2020 projects. The storage of hydrogen and subsequent conversion to chemicals is given a higher level of support for research and development activities in Germany than at European level. The high level of funding available reflects the fact that in Germany hydrogen is seen as a necessary component of the energy transition. Already since the founding of the national innovation programme for hydrogen (NIP) in 2006, Germany has invested heavily in hydrogen technologies. More recently, and typically not funded through the NIP, which remains focused on transport applications, research on the use of hydrogen in industry and hydrogen derived chemicals has gained in importance. Significant funding has been made available by the public sector through various sources in the time period since 2014, and these activities are also co-funded by the project participants.

Among other European countries, Denmark and the UK seem to have the highest level of public investment in CEST. Denmark has a strong interest in SOEL, in particular coupled to methanation.

At international level, Australia and Japan are particularly interested in the large scale distribution of (liquefied) hydrogen, linked to the Japan's plans of importing hydrogen. Norway is clearly focussing on the production, distribution and storage of hydrogen, rather than on HtX. The US DOE has supported CEST projects with funding of around USD\$50 million, which is low when compared to Europe. The integration of RES is not a priority topic in the US, and funding in general for FCH technologies has decreased in recent years. In the future this situation may change, as in 2020 the Senate Appropriations Committee has recommended \$160 million for the Hydrogen and Fuel Cell Technologies Program run by the Fuel Cell Technologies Office (FCTO). This is an increase of \$40 million over enacted appropriations for FY 2019.

5.2 Conclusions and outlook for CEST

It is recommended that energy system modelling studies should be performed in order to assess the role of CEST in a future energy system. An appropriate industrial policy should support the "valorisation" of hydrogen and HtX products and the creation of business cases and markets. For example Important Projects of Common European Interest (IPCEI) can help to strengthen the hydrogen value chain, which has been recognised as being strategic for Europe. The reduction of the cost of all technologies will need further investment, in particular through the development of manufacturing processes and increasing their capacity.

5.2.1 Power-to-Hydrogen

Electrolysis is the first fundamental step upon which all PtX applications are built. Therefore, any advance in these technologies will benefit all other associated applications. It should also be noted that simply achieving the targets set out in Section 3.1 will not guarantee breakthroughs in the specific technology as their competitiveness will be dependent on the cost of electricity and the degree of development of the market applications. For example, the CAPEX of the electrolyser system may be less significant to the cost of hydrogen than the cost of electricity, depending on the operating strategy⁶⁴. An improvement in efficiency could have a major impact not only on the cost of hydrogen, but also on the RES capacity needed to produce the hydrogen. However, an increase in efficiency can be achieved through high PGM loading of PEMEL, which could increase cost and environmental impact, and even eventually hinder the upscaling of the installed

⁶⁴ CAPEX is has less impact on the cost of hydrogen for full load hour operations, but is increasingly important if electrolyzers operate on a cycling / partial load profile for grid balancing.

capacity if sufficient resources are not available. Degradation, as the third major KPI, has to be considered for the operating regime as well, and the appropriate definitions and testing protocols (including accelerated stress testing) need to be defined.

Considering the life cycle performance of hydrogen production systems, the source of energy is a key factor. In general, the environmental performance of this type of system strongly depends on the energy source of the electricity. However, the manufacturing process of the electrolyser itself can have a high environmental impact. A study by the ELY4OFF project found that the manufacturing process can have high associated emissions, up to 90% of the total emissions of the installation [289, 290]. Further reductions in environmental impact should be aimed for, already at the stack design phase. Of the three main electrolyser types, alkaline electrolyzers are the most established technology with relatively cost-effective stacks available in the MW range. They are capable of lifetimes in excess of 100 000 hours and do not use precious metal catalysts. In the past they have been mainly implemented for the production of hydrogen for industrial processes. In order to implement this technology with RES, such as solar and wind, the technology needs to be capable of responding to variable loads, which has provided additional challenges. The main focus of the FCH 2 JU programme has been to overcome these challenges. Over time a clear transition from research to demonstration projects has been observed, with the focus moving from component and stack development to large-scale demonstration of multi-MW systems for grid balancing. In the future, the ability of large-scale alkaline electrolyzers to withstand flexible loads with acceptable degradation rates will be important to the technology's outlook in this particular application. However, it should be noted that the FCH 2 JU have recently announced the funding of a project for a 20 MW alkaline electrolyser for the industrial production of green fuels (green methanol) in the Netherlands (DJEWELS project), and the future of this technology in industrial hydrogen production seems positive.

PEM electrolyzers are not as mature a technology and therefore still display greater potential for cost reduction. They have the advantage of being highly responsive and being able to operate across a wide range of partial load, and are therefore well equipped for coupling with RES technologies. Remaining issues relate to cost, due to the use of platinum group metal catalysts, and lifetime/durability issues. Funding by the FCH 2 JU has shown a similar trend from fundamental research in early projects to increasingly larger demonstration projects, now reaching multi-MW levels where the electrolyzers are being incorporated into wider hydrogen territories demonstrating integration with RES and the potentials for a wider hydrogen based energy system. However, some low TRL projects are still funded for "game changer" PEMEL technologies (focussing mainly on current density improvement and operation at higher pressures) suggesting there are still improvements to be made regarding current density, PGM usage, efficiency and degradation before wide-scale adoption for this application. Depending on the outcome of these projects, further R&D may be needed in order to achieve the objectives of significantly improved power density and pressurised operation. Research needs have been identified regarding the tolerance of water impurities for electrolyzers, including exploring the feasibility of seawater electrolysis. Future developments may need to consider a compromise between efficiency/performance and the levels of PGM used. The impact of wide-scale adoption on PGM price and availability will need to be considered, along with the potential for recycling/reuse of these materials. In particular for PEM electrolyzers, recyclability should receive further attention, especially regarding iridium.

Solid oxide electrolyzers are at a much earlier stage of development and issues regarding material degradation, lifetime and cost still need to be overcome before any wide-scale adoption can be foreseen. It is recommended to support further efforts to develop SOEC operating at lower temperatures, which will reduce some of the materials and sealing issues. In addition, the reversible operation of SOFC/EC needs more research and should receive funding in the next framework programme. During the FCH 2 JU programme progression has been made from more fundamental materials research to the larger scale where in the recently approved GrInHy2.0 project a 720 kW electrolyser will be installed in an iron and steel works. Long term durability and reliability still need to be demonstrated for this technology at MW scale. In general it is expected that hydrogen produced from renewable energy sources will have a major impact on the decarbonisation of industry, and with that in mind, the FCH 2 JU have very recently announced the funding of the MULTIPLHY project which will install and operate the world's first multi-megawatt scale SOEL system at a chemical refinery in Germany. The high temperature operation of SOEL technology could make it particularly suitable for deployment in industrial settings, as waste heat can be used to improve efficiency.

Other electrolyser types which could be expected to have an impact in the mid- to long-term are PCEL (for applications where it is advantageous to produce dry hydrogen at pressure) and anion exchange membrane electrolyzers, which combine the use of an anion exchange membrane (AEM) with ionomer dispersion in the catalytic layers to enable OH-ion conduction. These systems combine features of both AEL and PEMEL and also operate with pure water. Both of these technologies are at a lower TRL (up to TRL5) but it is notable that

the latest FCH 2 JU call specified anion exchange membrane electrolyzers and recently funded three low TRL research projects in this area.

For all EL technologies, future work should focus on the up-scaling of systems to the required multi-MW scale. This should be supported by ongoing PNR activities which are being performed to feed into the appropriate standardisation work [279]. It is likely that large amounts of green hydrogen will be needed to decarbonise the current industrial use of hydrogen and to supply new applications and sectors, notably in heavy transport. There are various options for how this green hydrogen⁶⁵ will be produced, and it is presently not yet clear what share of electrolyzers will be grid connected or off grid, and what role they will play in the future in balancing the electricity grid. It is however likely that electrolyzers will need to be able to operate with some flexibility. Therefore the performance and durability of electrolyzers operating dynamically needs to be assessed, and potential safety issues addressed. The development of testing protocols, in particular for accelerated stress testing should be continued and expanded to cover all technologies. Safety challenges, for example those related to cross-over of gases at part load, need further investigation. Furthermore, in particular for PEMEL and SOEL, the continued development of manufacturing techniques and production lines at the scale necessary for wide-scale adoption will be required.

5.2.2 Hydrogen Distribution and Storage

In general the development and deployment of the appropriate infrastructure for the handling, distribution and storage of hydrogen needs further investment and public support. The assessment of the environmental impact of the various distribution and storage means has not been covered sufficiently.

5.2.2.1 Hydrogen admixture

As mentioned in Section 3.2.1.2, there are not many research needs related to the hydrogen injection point itself, as the components are at a high TRL, but some safety issues related to leak tightness and material durability issues might need to be addressed. However the effect of hydrogen on the gas grid itself, and on end-user applications poses some challenges. The RD&I needs related to hydrogen admixture have been investigated in the SFEM WG Hydrogen reports and summarised. Other reports on challenges for grid components are available, see Section 3.2.1.2. Research into some of these challenges is being undertaken at national level, and there are efforts on making the results of this research available to stakeholders, for example through HIPS-Net or the HYREADY project (see Sections 4.4.9 and 3.2.1.3). Some of the challenges should be addressed at European level, in particular those related to PNR and standardisation. Therefore it is positive that projects are being funded through FCH 2 JU (namely HIGGS and THYGA through the call 2019), which will be investigating some of these aspects, but many knowledge gaps are likely to remain. Critical issues are, for example, the effect of hydrogen on sensitive industrial end-users, or on porous rock underground storage. Hydrogen also has to be considered in the context of natural gas quality, such as defined in national or EU level standards.

The concept of hydrogen admixture is controversial. There are views that PtG (referring to either admixture of hydrogen or in conjunction with methanation) can help overcome energy storage and grid congestion problems (e.g. [291]), while others are questioning whether PtG makes sense from an economic and environmental perspective (e.g. [292]). More research is needed into the economic factors in progressing from natural gas to H2NG blends within the gas grid, as these have yet to be established. Strategies for adapting the infrastructure might then be developed to support a transformation path towards higher limits for allowable hydrogen concentrations in the gas system.

In recent years there has been increasing focus on the alternative path of converting the existing natural gas infrastructure for distributing 100% hydrogen (see for example relevant activities in the U.K., in Section 4.1.10).

5.2.2.2 Hydrogen separation

With the growing maturity of the on-going P2H and energy storage related projects the different possible concentrations of hydrogen, depending on the foreseen usage, have become apparent. Hydrogen is of greater value when used as a high purity technical gas/fuel, than mixed as H2NG. Furthermore there could be the need to reduce the H₂ concentration for sensitive end use technologies. Therefore the development of H₂ separation technologies from a carrier gas at the required scale should be supported.

⁶⁵ Blue hydrogen (produced from fossil sources with CCS) will also play a role, but is not covered in this report, as it is not considered as a form of chemical energy storage.

5.2.2.3 Distribution of hydrogen through pipelines

The distribution of hydrogen through purpose built pipelines is well established and there are no further research needs to our knowledge. The conversion of natural gas infrastructure to distribute hydrogen is being investigated by projects at national level. For example in the UK projects are investigating the conversion of the existing natural gas infrastructure into a 100% hydrogen network in one of the largest UK cities (Leeds). Feasibility studies are ongoing in Scotland. Some projects indicate remaining knowledge gaps regarding grid corrosion (i.e. pipeline integrity). The materials compatibility and tightness of the existing natural gas grid components exposed to hydrogen still raises concern among some stakeholders. Apart from the Norwegian projects (see Section 4.2.5), there is little activity on pipeline integrity in terms of corrosion phenomena. PNR related to pipeline integrity for hydrogen admixture is performed as part of several ongoing national projects, but not likely at sufficient level to cover all the knowledge gaps, as defined for example in the SFEM WG Hydrogen report [278]. The phenomena of hydrogen embrittlement and hydrogen assisted crack growth still need further investigation for the repurposing of natural gas pipelines. Some of the issues encountered for hydrogen admixture are also relevant for the conversion of gas grids to 100% hydrogen.

5.2.2.4 Large scale hydrogen storage

There are currently no activities at H2020 level, but some research is being supported by member states funding. Technology components for underground hydrogen storage (e.g. compressors) appear to be in a good state of development. Future research efforts should be focused on a study of feasibility and optimization of large scale hydrogen storage systems when part of a micro/macro grid system based on renewables by means of pilot/demonstration projects. The SFEM WG H2 identified some research needs for underground hydrogen storage in salt caverns. The experts indicated that further investigation is needed regarding materials compatibility and durability of especially cement mixtures, but also steels and non-metallic materials for use in hydrogen storage facilities. Research efforts are also needed for other underground hydrogen geologies since salt caverns are not available everywhere. These efforts should focus on reduction of hydrogen losses during storage, due to the porosity of the rock and/or the presence of microorganisms able to consume the hydrogen stored.

Liquefied hydrogen technologies are likely to be relevant in a scenario with high deployment of hydrogen. While storage technologies for liquefied hydrogen are at a good level of efficiency and the already low hydrogen losses could be in addition further minimized with good system integration, liquefaction technologies require an improvement in terms of cost and efficiency to reach competitive costs for liquefied hydrogen. Both storage and liquefaction capacities need to be increased significantly to meet the (expected) level of liquefied hydrogen demand, this improvement will be also beneficial for cost and efficiency. Therefore, support should focus on scaling up the current capacities of hydrogen liquefaction facilities (5-30 tpd) Safety of liquefied hydrogen is another topic that requires additional effort. Leaks of cryogenic hydrogen are potentially dangerous since they can affect the integrity of surrounding materials. In addition, the leaked (liquid) hydrogen may suddenly evaporate, quickly building an explosive atmosphere. LH₂ gas leaks are even more complex than normal hydrogen gas leaks due to the presence of hydrogen in two phases (liquid and gas).

5.2.2.5 Hydrogen carriers

Hydrogen carriers may be an option for transport of large quantities of hydrogen over long distances, or for medium to large scale storage of hydrogen. However, there are high conversion losses. Future research should be focussed on the most promising carrier systems. In order to assess the best options, reference techno-economic benchmarking is needed. In order to provide reliable comparisons among different possibilities, well founded calculations on transport options should be done. It is important that actually comparable pathways are chosen and that all the relevant transport and conversion steps are taken into consideration. The actual impacts of a transport path should be analysed with an agreed LCA methodology, and complemented with suitable techno-economic indicators. As far as possible, hydrogen carriers should be analysed not only in terms of their GHG emissions, but also with respect to other environmental impacts (toxicity, abiotic depletion, etc.).

Due to its poor performance (see Table 11), supporting the use of formic acid as a hydrogen carrier on a large scale should be reconsidered.

In the case of ammonia, potential NO_x emissions should be taken into account.

5.2.3 Hydrogen-to-X

Any economically sustainable HtX process will rely heavily on the availability of low cost hydrogen and green electricity and, depending on the business cases, on adequate supplies of feedstock chemicals (hydrogen, if not produced on site, and/or CO₂). The technical maturity of HtX processes seems advanced and in many cases current challenges are associated with developing suitable business cases and scale-up of innovative processes. Fundamental research on synthesis and catalyst optimisation, especially for innovative processes, is still needed, but does not seem to be a showstopper.

Stakeholders and policy makers should prioritise and define the required infrastructure investments needed for enabling HtX. Moreover, the economics of different HtX pathways in Europe should be thoroughly evaluated.

Assessment of CO₂ potential and sources is needed (see project STRATEGY CCUS). The issue of decarbonisation and direct air capture infrastructures (in the context of 2050 targets) should be faced at a political level even before a technical one. The nature of captured CO₂ and its associated economic value should be clarified before the definition of any future business case becomes possible. Is CO₂ a pollutant to be avoided, a feedstock which should be traded, or both? Under which incentives?

The production of e-fuels, especially production of e-fuels for applications which cannot be easily electrified, such as jet fuels, should be covered by more European actions. Different HtX conversion pathways leading to the same product should be benchmarked using an accurate and versatile methodology for assessing environmental impacts, to enable a decision on which pathway should be prioritised.

5.2.4 General recommendations

Chemical energy storage technologies can support the integration of renewable electricity and help decarbonise various end-use sectors. The key role hydrogen can play in a future carbon neutral energy system is due to its ability to link the electricity sector to transport, industry and – in principle – commercial/residential sectors. This implies that there are a large variety of pathways, which are at different levels of technological readiness, and which might need further public support. To determine which of these pathways and technologies should receive support, it is recommended to first perform an assessment of the decarbonisation potential and overall sustainability. This needs, in addition, to make the performance of hydrogen pathways comparable with that of electricity and biomass pathways.

A sound and universally accepted LCA (and Life Cycle Cost (LCC) analysis) methodology is required for effective benchmarking of PtX pathways. Consistent boundary conditions should be defined. The impact of a technological energy chain should be captured and compared against specific KPIs. For instance, the amount of emissions avoided by producing the target hydrogen carrier/fuel by using a unit of available electric power produced by renewables and not fossil fuels, can be used to capture a general "global warming impact" parameter [293]. Such a parameter can help in assessing the most efficient way to employ electricity coming from renewable sources for decarbonisation purposes, but is strongly dependent on the system boundaries chosen and the conversion process details taken into consideration. Moreover comparisons should always be made on the basis of the same functional unit. At the same time, the environmental impacts of any PtX pathway should be also taken into account whenever it is necessary to compare them. Any KPIs used to monitor a power-to-X pathway should capture all steps and materials flows involved in the synthesis process under analysis (from electrolysis to synthesis).

It is recommended to develop appropriate assessment methodologies and perform further studies (LCA, techno-economic assessment) in order to identify the most advantageous uses of green hydrogen in terms of limiting pollution, CO₂ abatement potential, critical raw materials, environmental impacts and cost – and the sectors where it is advantageous specifically in relation to direct electrification or the use of biomass – in order to prioritize future public funding for those options with the highest potential.

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List of abbreviations and definitions

AEL	Alkaline Electrolyser
AEMWE	Anion Exchange Water Electrolyser
AFI standards	Alternative Fuels Infrastructure
AFID	Alternative Fuels Infrastructure Deployment (Directive)
AWP	Annual Workplan of the FCH 2 JU
BT	Technical board
CAPEX	Capital Expenditure
CEST	Chemical Energy Storage Technologies
CCMC	CEN/CENELEX Management Centre
CEN	Comité Européen de Normalisation
CEN/TC	Technical Committee within CEN
CENELEC	Comité Européen de Normalisation Électrotechnique
DIS	Draft international standard
EARTO	European Association of Research and Technology Organisations
EC DG ENER	European Commission - Directorate-General for Energy
EC DG GROW	European Commission Directorate – General Internal Market, Industry, Entrepreneurship and SMEs
EC JRC	European Commission – Directorate General Joint Research Centre
EC DG RTD	European Commission - Directorate-General for Research and Innovation
EMPIR	European Metrology Programme for Innovation and Research
EMSA	European Maritime Safety Agency
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking (FP 7)
FCH 2 JU	Fuel Cells and Hydrogen 2 Joint Undertaking (H2020)
GoO	Guarantee of Origin
GTR	Global Technical Regulation
H2	Hydrogen
H2020	Research and innovation framework programme
H2Future	Project: European flagship project for the generation of green hydrogen from electricity from renewable energy sources.
H2-NETZ	Project: Development of innovative infrastructures to supply consumers in the hydrogen village
H2NG	Hydrogen and Natural Gas mixture
HES	Higher Education Establishments
HIGG	Hydrogen Injection in the Gas Grid
HIPS(-NET)	Hydrogen in Pipeline System - Network
HPEM2GAS	Project: High Performance PEM Electrolyser for Cost-effective Grid Balancing Applications
HRS	Hydrogen Refuelling Stations
HTE	High Temperature Electrolysis
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IED	Industrial Emissions Directive

ISO	International Organization for Standardization
JWG	Joint Working Group
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LOHC	Liquid Organic Hydrogen Carrier
LTWE	Low Temperature Water Electrolysis
NSB	National Standards Body
NWIP	New work item proposal
O&M	Operation and Maintenance
OEMs	Original Equipment Manufacturers
OPEX	Operational Expenditure
PEM	Proton-Exchange Membrane
PEMEL	Proton-Exchange Membrane Electrolyser
PGC	Process Gas Chromatograph
PNR	Pre-Normative Research
PtG	Power-to-Gas
PtH	Power-to-Hydrogen
PRC	Private Companies
PUB	Public Sector
REC	Research Organisations
RCS	Regulation Codes and Standards
RDI	Research Development and Innovation
RED	Renewable Energy Directive
RES	Renewable Energy Sources
SFG	Sector Forum Gas
SNG	Substitute Natural Gas or Synthetic Natural Gas
SFEM/WG Hydrogen	Joint CEN/CENELEC Sector Forum Energy Management – Working Group Hydrogen
SoA	state-of-the-art
SOEL	Solid Oxide Electrolyser
SOFC	Solid Oxide Fuel Cell
SWD	Staff working document
TC	Technical Committee
TF	Taskforce
TR	Technical report
UGS	Underground Gas Storage
UNECE	United Nations Economic Commission for Europe
WG	Working Group

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Annexes

6.1 Annex A

Table 18 CEST projects within H2020

Acronym	CALL	Call year	Keyword 1	Project Class	EU Financial Contribution (euro)	Total cost for project (euro)
3D-POWER	MSCA-IF-2016	2016	PtH	A	195,455	195,455
AD ASTRA	FCH-2018-1	2018	PtH	G	3,008,426	3,008,426
BALANCE	LCE-33-2016	2016	PtH	B	2,500,596	2,856,096
BIG HIT	FCH-03.2-2015	2015	PtH	D	5,000,000	7,246,103
C2FUEL	CE-SC3-NZE-2-2018	2018	HtX	D	4,130,291	3,999,840
CASCADE-X	MSCA-IF-2017	2017	HtX	A	196,400	196,400
CELBICON	ISIB-06-2015	2015	HtX	B	5,429,202	6,211,040
CIRCLENERY	SMEInst-09-2016-2017	2017	HtX	D	50,000	71,429
CO2COFs	MSCA-IF-2018	2018	HtX	A	239,723	239,723
CO2Fokus	CE-SC3-NZE-2-2018	2018	HtX	C	3,994,950	3,994,950
COZMOS	CE-SC3-NZE-2-2018	2018	HtX	C	4,752,386	3,997,164
CREATE	NMBP-03-2016	2016	PtH	B	4,318,478	4,480,978
CritCat	NMP-23-2015	2015	PtH	A	4,369,293	4,369,293
DELIVERS	SMEINST-1-2016-2017	2016	D&S	B	71,429	50,000
Demo4Grid	FCH-02-7-2016	2016	PtH	D	2,932,554	7,736,683
DOLORES	MSCA-IF-2015-EF	2015	PtH	A	183,455	183,455
ECo	FCH-02.3-2015	2015	HtX	B	2,500,514	3,239,139
eCOCO2	CE-SC3-NZE-2-2018	2018	HtX	B	4,447,979	3,949,979
ELECTHANE	SIE-01-2014-1	2014	HtX	C	50,000	71,429
ELECTROCAT	ERC-PoC-2016	2016	PtH	B	149,959	149,959
ELECTROGAS	SMEInst-2018-2020-1	2018	HtX	C	71,429	50,000
ELY4OFF	FCH-02.1-2015	2015	PtH	C	2,315,217	2,315,218
ELYntegration	FCH-02.8-2014	2014	PtH	D	1,861,309	3,301,391
ENERGY-X	FETFLAG-2018-01	2018	HtX	H	976,115	976,115
FReSMe	LCE-25-2016	2016	HtX	C	11,406,725	11,406,725
GAMER	FCH-02-2-2017	2017	PtH	B	2,998,951	2,998,951

GrlnHy	FCH-02.4-2015	2015	PtH	B	4,498,150	4,498,150
GrlnHy2	FCH-2018-1	2018	PtH	C	5,882,492	3,999,993
H2Future	FCH-02.7-2016	2016	PtH	D	11,997,820	17,823,264
Haeolus	FCH-02.4-2017	2017	PtH	D	4,997,739	6,921,215
HPEM2GAS	FCH-02.2-2015	2015	PtH	C	2,499,999	2,654,250
HyBalance	FCH-02.10-2014	2014	PtH	D	7,999,371	15,631,196
Hydrogenlogistics	SMEInst-10-2016-2017	2017	D&S	B	2,282,188	3,260,269
HyGrid	FCH-02.5-2015	2015	D&S	B	2,527,710	2,847,710
HyLYZER	EIC-SMEInst-2018-2020	2018	PtH	D	50,000	71,429
HYMEFCECS	ERC-PoC-2016	2016	PtH	A	150,000	150,000
HySTOC	FCH-02.6-2017	2017	D&S	B	2,499,921	2,499,921
KEROGREEN	LCE-06-2017	2017	HtX	B	4,951,959	4,951,959
LOTER.CO2M	NMBP-19-2017	2017	HtX	C	4,264,453	4,264,453
MefCO2	SPIRE-02-2014	2014	HtX	C	8,622,293	11,068,324
MEMBRASENZ	SMEInst-02-2016-2017	2017	PtH	A	50,000	71,429
MEMPHYS	FCH-03.1-2016	2016	D&S	B	1,999,925	2,088,195
NEPTUNE	FCH-02.1-2017	2017	PtH	B	1,926,221	1,927,335
PENTAGON	LCE-01-2016-2017	2017	HtX	C	2,834,758	4,437,834
PRETZEL	FCH-02.1-2017	2017	PtH	B	1,999,089	1,999,089
ProGeo	SIE-01-2015	2015	HtX	C	2,443,875	3,493,750
QualyGridS	FCH-02.1-2016	2016	PtH	G	1,996,795	2,811,263
REFHYNE	FCH-02.5-2017	2017	PtH	D	9,998,044	16,058,563
REFLEX	FCH-02.3-2017	2017	PtH	C	2,999,575	2,999,575
SEARCH	MSCA-IF-2017	2017	PtH	A	214,828	214,828
SElySOs	FCH-02.1-2014	2014	PtH	A	2,939,655	2,939,655
STOREandGO	LCE-09-2015	2015	HtX	D	17,937,359	27,973,370
STRATEGY CCUS	LC-SC3-2018-NZE-CC	2018	HtX	H	3,069,474	2,959,534
THIN-CATALYZER	MSCA-IF-2018	2018	PtH	A	150,040	150,040
ULTRA-SOFC	ERC-CoG-2015	2015	PtH	A	1,841,387	1,841,387

Source: JRC 2020, based on publicly available data.

6.2 Annex B – Selected relevant CEST projects funded through national programmes

The information provided in the tables is presented according to the information available, which was not uniform for the different countries. Often only funding information was accessible, not the total project budget. For some countries the lead organisation of the project could be identified.

Table 19 Selected relevant CEST projects (budget ≥ AUD 1 million, equivalent to €0.6 million) funded by Australian national programmes

Lead organisation	Funding Body	Name and topic	Funding \$m (AUD)	Total Budget \$m (AUD)	Year funding approved
Australian National University	ARENA	<p><i>Hydrogen Generation by Electrocatalytic Systems</i></p> <p>Electrolysis uses electrical energy to convert water into the clean fuel, hydrogen, with pure oxygen as a bi-product. This project, using inspiration from nature, will develop a new electrolysis technology, more simple and efficient than any known, to operate from pure water and renewably generated electricity.</p>	0.62	1.40	2018
Australian National University	ARENA	<p><i>Direct Water electrolysis</i></p> <p>This project aims to demonstrate a photo electrochemical system using III-V multi-junction semiconductors through cost-effective epitaxial lift-off techniques that are surface-modified for robust operation.</p>	1.24	3.45	2018
CSIRO	ARENA	<p><i>Hydrogen to Ammonia</i></p> <p>The project is to develop an ammonia production process which is less energy intensive than the conventional Haber-Bosch process and does not contribute to any greenhouse gas emissions.</p>	1.12	2.83	2018
CSIRO	ARENA	<p><i>Methane Fuel Carrier</i></p> <p>The project will investigate the production of synthetic methane as a readily exportable, renewable fuel, derived from atmospheric carbon dioxide and hydrogen produced from renewable sources.</p>	1.09	2.17	2018
CSIRO	ARENA	<p><i>Liquid Fuel Carrier</i></p> <p>This project proposes a game changing technology for conversion of solar energy to liquid fuels. Both solar heat and solar PV electricity will be used to drive a solid oxide electrolyser device for a production of hydrogen and syngas which can then be converted onsite into transportable liquid fuels enabling large-scale energy export and storage.</p>	1.01	2.51	2018

Monash University	ARENA	<p><i>Ammonia Production from Renewables at ambient pressure and temperature</i></p> <p>The project will develop high-performing electrodes for direct electrochemical conversion of atmospheric nitrogen to ammonia – a readily exportable carrier of renewable energy.</p>	0.92	2.70	2018
Queensland University of Technology	ARENA	<p><i>Hydrogen Process</i></p> <p>The QUT project develops a scalable and systematic process to evaluate the viability of decentralised and regional-scale renewable energy hybrid systems to generate hydrogen from sustainable resources.</p>	3.35	7.74	2018
Jemena	ARENA	<p><i>Jemena Power-to-Gas Project</i></p> <p>The project involves designing and constructing a Power-to-Gas (P2G) facility which will source renewable electricity and convert it into hydrogen via electrolysis. The majority of the hydrogen produced will be injected into the gas network, providing enough energy to meet the cooking, heating and hot-water requirements of approximately 250 homes. A portion of the hydrogen will be utilised, via a gas engine generator, for electricity generation, with the remainder stored for use in an onsite Hydrogen Refuelling Station (HRS).</p>	7.5	15.0	2018
Aqua Hydrex Ltd.	ARENA	<p><i>Connecting the Power and Gas Grids – High-Efficiency, Low-Cost Hydrogen Production as a Means of Decarbonizing Natural Gas Pipelines and Enabling Greater Deployment of Renewables</i></p> <p>The project aimed to design and build an electrolyser pilot plant and to test it in partnership with Australian Gas Networks (AGN) as a demonstration of ‘power to gas’ injection of hydrogen into the natural gas grid.</p>	5.00	12.21	2017
Hydrogen Engineering Australia (consortium)	Australian Government and Victorian Government	<p><i>Hydrogen Energy Supply Chain (HESC)</i></p> <p>The project aims to establish an integrated commercial-scale hydrogen supply chain that encompasses production, transportation and storage, with a goal of delivering liquefied hydrogen to Japan.</p>	50	496	2017-2021 (planning and pilot)
Australian Gas Infrastructure Group	South Australian Renewable's fund	<p><i>Hydrogen Park SA</i></p> <p>A hydrogen from renewables demonstration</p>	4.9	11.4	2018-onwards

Source: JRC 2020, based on publicly available data.

Table 20 Selected relevant CEST projects (≥ 1 million euro) funded by Austrian national programmes

Funding Body	Lead organisation	Name and topic	Budget €m	Funding €m	Duration
Climate and energy fund	Rohöl-Aufsuchungs Aktiengesellschaft	UNDERGROUND SUN CONVERSION: Renewable energy storage and conversion by in-situ biological methanation in porous Underground gas reservoirs	7.9	5	2017-2021
Climate and energy fund	AVL List GmbH	HYDROMETHA: Development of a stationary electricity storage system via high temperature co-electrolysis and catalytic methanation	4.5	3,1	2018 - 2021
Vorzeigeregion Energie 2. AS	Energie Steiermark Technik	RENEWABLE GASFIELD: PEM electrolysis coupled to biogas methanation, admixture to gas grid and hydrogen refuelling.	4.2	1.8	2018-2021
Climate and energy fund	OMV Gas & Power GmbH	Conversion of renewable electricity to hydrogen for storage and transport in the natural gas grid (WIND2HYDROGEN)	2.8	1.3	2014-2016

Source: JRC 2020, based on publicly available data.

Table 21 Selected relevant CEST projects (≥ 1 million euro) funded by Danish national programmes

Funding Body	Lead organisation	Name and topic	Budget €m	Funding €m	Duration
ForskEL	ELECTROCHAEA.DK ApS	Power-to-Gas via Biological Catalysis (P2G-BIOCAT)	8.03	3.7	2014-2017
Innovationsfonden	DTU Energi	EEEHy Efficient and Economic Electrolytic Hydrogen production	4.5	3.0	2018 -2022
Innovationsfonden	Danmarks Tekniske Universitet	SYNFUEL is researching how to combine electrolysis and gasification of biomass in a way that produces more biofuel from the same amount of biomass.	3.8	2.8	2015-2019
EUDP	HALDOR TOPSØE A/	SOC4NH ₃ - Solid-Oxide-Cell-based Production and Use of Ammonia. Demonstration of a SOEC-based ammonia synthesis gas production without an air separation unit and use of ammonia in SOFC in parallel with techno-economic studies.	3.59	2.14	2019-2022
Innovationsfonden	Aalborg Universitet	E-STORE: Further improvement of PEM electrolysis for flexible energy storage	3.5	2.51	2015 - 2019
EUDP	GREENHYDROGEN.DK ApS	The purpose of the POWER2MET project is to develop, design and build a pilot plant for a complete, standardised and modular power-to-methanol plant that can be offered to upgrading biogas plants, utilizing their CO ₂ and hydrogen in a synthetic process to produce green methanol and providing for a positive business case from day one.	3	2.1	2019-2022
ForskEL	HALDOR TOPSØE A/S	TOWARDS SOLID OXIDE ELECTROLYSIS PLANTS IN 2020. The goal of the proposed project is to further improve performance and durability of SOEC cells and stacks targeting applications specifically for regulating the future Danish power system with a high amount of fluctuating renewable energies.	2.51	2.07	2015-2017
EUDP	HALDOR TOPSØE A/S	SOLID OXIDE ELECTROLYSER TECHNOLOGY. In the project the ceramic electrolyser technology will be matured towards present markets as off-grid electricity storage and production of gasses for the chemical industry.	3.1	1.84	2016-2019
ForskEL ⁶⁶	Air Liquide	The POWER2HYDROGEN project seeks to promote a new green energy market by demonstrating feasible load shifting and the possibility of balancing the electricity grid via dynamic operation of a PEM water electrolysis plant while producing green hydrogen for high value markets such as transportation and process.	1.44	1.02	2015-2017

Source: JRC 2020, based on publicly available data.

⁶⁶ Last call for ForskEL was in 2016. New calls are passed over to EUDP. The ForskEL program focuses on technologies for environmentally friendly power generation and integration due to the effort of achieving the goal of a fossil free society.

Table 22 Selected relevant CEST projects (≥ 1 million euro) funded by French national programmes

Funding Body	Lead organisation	Name and topic	Budget €m	Funding €m	Duration
ADEME/ FEDER (European Fund)/ Regional	GRTGAZ	JUPITER 1000: This project aims to build and run a Power-to-Gas demonstrator with methanation, carbon capture and valuation of CO ₂ .	28	10.6	2015 - 2022
ADEME	ENGIE	GRHYD (Grid Management by Hydrogen Injection for Reducing Carbonaceous Energies): GRHYD's objective is to produce H ₂ from renewable electricity, supply it to customers as H ₂ -NG gas by means of the gas distribution grid, and consume it locally (Residential use, heating, cooking, hot water, CHP, and buses). Injection into the gas grid started in June 2018.	15.3	4.9	2014 - 2020
Regional	Financed through the cluster, CAPENERGIES	HyGreen Provence: An ambitious project which aims to produce hydrogen from renewable sources available in Provence, and store large quantities in salt caverns. Mobility applications are also integrated within the project.	300 allocated 1000 announced total.		2018-2028
ADEME / Regional	STORENGY	MÉTHYCENTRE: the main objective of the project is to develop Power-to-Gas technology and suitable business cases by Storengy. As a first step, PEM electrolyzers will be coupled with a catalytic methanation process optimised for CO ₂ coming from biomass. The secondary objective is the development of an industrial supply chain for electrolyser technology.	10.5	2.6	2018-2023
ANR / Regional		The project CHOCHCO (Chaîne Optimisée flexible de Co-électrolyse de CO ₂ et d'eau et d'Hydrogénéation de CO en méthane de synthèse) aims at producing synthetic methane by a flexible co-electrolysis process involving of water and CO ₂ , by absorbing surplus renewable electricity.	2.4	1.0	2014- 2017
ADEME / Regional		MINERVE aims at using renewable energy for producing synthetic methane by combining electrolytic hydrogen with CO ₂ . The produced synthetic methane is to be used as a fuel in mobility applications. The installed electrolyser power is 12 kWe and the source of CO ₂ is coming from biomass.	1.6		2014-2019
ADEME / Regional	STORENGY	HyCAUNAIS V2. The main objective of the HYCAUNAIS project is to demonstrate the technico-economic feasibility and replicability of Power-to-gas. The HyCaucasian project proposes action at the level of the various technological building blocks, in particular the flexibility of the electrolyser and the adaptation of biological methanation.	10.9	3.4	2019-2025

Table 23 Selected relevant CEST projects (≥ 2 million euro) funded by German national programmes

Funding Body	Lead organisation	Name and topic	Funding €m	Duration
BMBF	Thyssenkrupp AG Akzo Nobel Industrial Chemicals GmbH Linde Aktiengesellschaft Evonik Resource Efficiency GmbH Covestro Deutschland AG BASF SE	The CARBON2CHEM programme aims at using emissions from steel production as raw material for chemicals. Subprojects tackle system integration, water electrolysis and grid integration, as well as methanol and other chemical production.	63	2016 - 2020
BMBF and Zwanzig20 programme	Miltitz Aromatics GmbH Forschungszentrum Jülich GmbH KUMATEC Sondermaschinenbau & Kunststoffverarbeitung GmbH DBI Gas- und Umwelttechnik GmbH (for three subprojects) inhouse engineering GmbH Helmholtz-Zentrum für Umweltforschung GmbH - UFZ Kurt-Schwabe-Institut für Meß- und Sensorotechnik e.V Technische Universität Bergakademie Freiberg	The aim of the programme HYPOS is to produce, store, distribute and widely use green hydrogen in the chemical industry, refinery, mobility and energy supply sectors. More than 100 HYPOS partners are members of the network. In various project collaborations innovative ways of hydrogen usage are being developed. Central Germany is regarded as a suitable region for early implementation due to the already existing infrastructure (pipeline and storage caverns) and various medium-sized enterprises located in the area.	16, up to 45	2016 - 2020
BMBF	Rheinisch-Westfälische Technische Hochschule Aachen	The Kopernikus-programme subproject P2X „Flexible use of renewable resources“ unites 50 partners in research and development to reach market entry level of chemical Power-to-X technologies (PtX). These areas encompass aviation and marine fuels, fuels for high-temperature industrial applications as well as the chemical feedstock as raw material basis for the chemical industry.	33 +8 from industry	2016 - 2019
BMWi	Technische Universität München	E2FUELS – programme on electricity based fuels. Several subprojects on methanol synthesis, electrolysis, for emission reduction in power generation and maritime applications.	13.8	2018 - 2021
BMWi	DVGW Deutscher Verein des Gas- und Wasserfaches e.V. - Technisch-wissenschaftlicher Verein MTU Friedrichshafen GmbH	METHQUEST and METHMARE - innovative methanisation and their use in mobile and stationary applications, including maritime.	13.4	2018 - 2021
BMWi	SunFire GmbH	Syngas production for electricity based fuels, co-electrolysis demonstration.	7.0	2019 - 2021
BMBF	Forschungszentrum Jülich GmbH	PtG++: seasonal storage through P2G. Demonstration of large scale hydrogen storage with LOHC technology.	6.0	2019-2022
BMWi	Christian-Albrechts-Universität zu Kiel	ANGUS II – underground energy storage	6.0	2017 - 2022
BMVi (NIP)	EWE GASSPEICHER GmbH	HYCAVMOBIL – hydrogen storage in underground salt cavern	5.5	2019 - 2022
BMWi	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	GREENH2: electrode materials for alkaline electrolysis	4	2015 - 2017

Funding Body	Lead organisation	Name and topic	Funding €m	Duration
BMBF	Technische Universität Berlin	CO2EKAT: Catalyst development for CO-methanisation	3.9	2015 - 2019
BMBF	Albert-Ludwigs-Universität Freiburg	POWERMEE: lifetime and performance optimization of MEA for PEMEL	3.7	2016 - 2019
BMWi	Forschungszentrum Jülich GmbH	NEW 4.0 Norddeutsche Energiewende. Subproject MW hybrid storage for provision of grid services	3.6	2016 - 2020
BMWi	IAV GmbH Ingenieurgesellschaft Auto und Verkehr	ECOPTG: Technology transfer from automotive industry to develop a low cost electrolyser system on the 100kW scale	3.4	2015 - 2019
BMBF	Sondervermögen Großforschung beim Karlsruher Institut für Technologie (KIT)	ENERGY LAB 2.0: MW-Electrolysis plant	3.2	2015 - 2019
BMWi (NIP)	Friedrich-Schiller-Universität Jena	HYINTEGER: integrity of materials for geological underground hydrogen storage	2.5	2016-2019
BMBF	Friedrich-Alexander-Universität Erlangen-Nürnberg	TUBULYZE: development of tubular SOEC	2.5	2019 - 2022
BMWi	Helmut-Schmidt-Universität - Universität der Bundeswehr Hamburg	STBZUEL: Development and testing of PEM FC and EL MEA with methanation.	2.4	2018 - 2021
BMWi	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	AEL3D: Novel porous 3-D electrode materials for highly efficient alkaline electrolysis.	2.4	2016 - 2020
BMWi	Robert Bosch Gesellschaft mit beschränkter Haftung	DESS2020+: District Energy Storage and Supply System 2020+	2.4	2015 - 2018
BMWi	SunFire GmbH	Verbundvorhaben: Funktionsoptimiertes Stackdesign und Skalierung SOEC; Teilvorhaben: Gesamtsystem	2.4	2015 - 2018
BMWi	Zentrum für Brennstoffzellen-Technik GmbH	H2TestOpt: Aufbau eines Hochdruck-Wasserstoff-Teststands zur Optimierung von Wasserstofferzeugern, speichern und -abgabesystemen	2.2	2015 - 2018
BMBF	Forschungszentrum Jülich GmbH	Mid-temperature alkaline electrolysis with in-situ diagnostics (FZ Jülich)	2.2	2018 - 2020
BMWi	ARCUS Technologie GmbH & Co. GTL Projekt KG	FlexDME - Entwicklung einer flexibel operierenden Demonstrationsanlage zur Erzeugung von Dimethylether aus Biogas und Wasserstoff Teilvorhaben: Koordination des Projekts und des Designs des DME-Reaktors	2.0	2019 - 2022
BMWi	SunFire GmbH	Optimized stack design and scaling of SOEC	2.0	2015 - 2018

Source: JRC 2020, based on publically available data.

Table 24 Selected relevant CEST projects (≥ 0.25 million euro) supported by the Netherlands

Key Area	Name and topic	Funding €m	Duration
Hydrogen production	COST REDUCTION INDUSTRIAL PEM ELECTROLYSERS - involves several sub-projects to arrive at the next generation of PEM electrolyte	0.9	11/2017 – 10/2019
Flexible Energy Infrastructure	SYSTEEMONTWERP POWER TO X The aim of the Urban Energy project "System design Power to X" (SPX) is to generate knowledge and insight for the development of a blueprint in order to achieve a full-scale demonstration of the PtX system.	0.7	N/A
Greening of hydrogen in industry	H-VISION: Large-scale deployment of blue hydrogen to replace natural gas in the Rotterdam	0.6	08/2018 – 06/2019
Gas turbines and burners	High hydrogen gas turbine retrofit to eliminate carbon emissions	0.5	01/2019 – 02/2020
Hydrogen production	ALKALIBOOST - develop and test new alkaline stack designs that allow operating at a much higher current density, thereby reducing the effective costs of the electrochemical stack to less than EUR 100/kW.	0.5	05/2019 – 05/2023
Hydrogen production	FLEX-P2G - Integration of PEM Electrolysis technology in the energy system	0.5	Finished in 2017
System studies	HYDROGREENN - pilot in Nijstad-Oost; research and development of a central heating boiler on hydrogen, including the associated infrastructure	0.470	N/A
Hydrogen for boilers	WATER DISTRICT HOOGEVEEN - techno-economic blueprint and associated technology to make heat supply, based on hydrogen boiler to 100 % hydrogen (H ₂).	0.47	N/A ⁶⁷
System integration without program line	POWER2GAS AND THE POWER OF METHANE - surplus electricity conversion into hydrogen and processing it through methanization, with or without the use of green carbon dioxide from fermentation processes, and to feed this methane into distribution networks	0.375	Finished in 2015
Geo Energy	Large scale energy storage in salt caverns and depleted gas fields TSE-18-19-01-Geo-energie	0.3	N/A
Knowledge exchange and imaging	SYSTEEMSTUDIE VOOR P2G ROUTES The main question that addresses this project is: Under what circumstances and in which situations do P2G applications play a role in the transition to a more sustainable energy system, taking into account the complexity of the energy system?	0.28	2012
Gas	PURIFHY - selective hydrogen removal from a sustainable gas flow; enabling to inject renewable methane into the Dutch gas grid. The methane is produced in two separate processes: biomass gasification and methanation, and methanation of H ₂ and CO ₂ . From both processes, the remaining hydrogen concentration has been reduced down to at least 0.5%, the Dutch limit of the H ₂ concentration in the natural gas grid.	0.25	Finished in 2015
Hydrogen production	ALKALIFILEX - increase of flexibility and production capacity of alkaline water electrolysis	0.25	02/2018 – 08/2019

Source: JRC 2020, based on publicly available data.

⁶⁷ The start of construction of these houses is planned for early 2020.

Table 25 Selected relevant CEST projects (≥ 0.5 million euro) supported by Norway

Lead organisation	Name and topic	Funding €m	Duration
FLAKK GRUPPEN	Development and realization of hydrogen production and bunkering for ferries/cruise ships in the Norwegian world heritage fjord "Geirangerfjorden"	3.7	2020 - ?
EQUINOR	Liquid hydrogen supply chain for maritime applications	3.3	2020 - ?
SINTEF AS	HyLINE will address the pipeline material challenges related to transporting clean hydrogen gas in the existing subsea pipeline infrastructure	2	2019 - 2022
SINTEF AS	HYPER – hydrogen liquefaction	1.4	2015 - 2019
SINTEF AS	SUPROX porous ceramic materials	1.22	2018 - 2021
NEL HYDROGEN ELECTROLYSER AS	Alkaline Electrolysis	1.1	2018 - 2020
NORGES TEKNISK-NATURVITENSKAPE LIGE UNIVERSITET NTNU	Multiscale Hydrogen Embrittlement Assessment for Subsea Conditions	1	2019 - 2022
NORGES TEKNISK-NATURVITENSKAPE LIGE UNIVERSITET NTNU	H2MemX – ultrathin Pd membranes for hydrogen separation	1	2018 - 2021
SINTEF AS	Alkaline polymer electrolysis	1	2017 - 2020
SINTEF AS	EleRot – electrolyser with spinning stack	1	2015 - 2019
NORGES TEKNISK-NATURVITENSKAPE LIGE UNIVERSITET NTNU	Nanocomposite Facilitated Transport Membranes	0.9	2019 - 2022
SINTEF AS	AH2A proton conduction electrolyser	0.9	2017 - 2020
NORGES TEKNISK-NATURVITENSKAPE LIGE UNIVERSITET NTNU	MOxiLAYER - development of efficient catalysts for PEM water electrolysis	0.9	2016 - 2020
UNIVERSITETET OSLO	Functional Grading by Key doping in Catalytic electrodes for Proton Ceramic Cells" (FunKeyCat)	0.62	2019 - 2022
SINTEF AS	NEXTGAME - Next Generation Electrodes for Anion Exchange Membrane Fuel Cells	0.6	2016 - 2019
SINTEF AS	Hieff PEM, a game changing High efficiency PEM electrolyser for hydrogen production	0.5	2018 - 2020
HYDROGEN MEM-TECH AS	Palladium membranes for hydrogen separation	0.5	2017 - 2021
SINTEF AS	High performance coatings for PEM electrolyser metallic bipolar plates	0.5	2014 - 2017

Source: JRC 2020, based on publically available data.

Table 26 Selected relevant CEST projects (≥ 0.5 million euro) funded by Polish national programmes

Funding Body	Programme / Action	Name and topic	Budget €m	Funding €m	Duration
NCBiR	R & D projects of enterprises / Fast Track	Development of an innovative hydrogen sensor demonstrator based on a nanocomposite C-Pd layer	2.95	2.07	01/01/2017
NCBiR	R & D projects of enterprises	An innovative reduction and metering station with equipment for gaseous fuels	2.92	1.36	01/04/2017
NCBiR	National programs - R & D commercialization / GEKON I	Energy storage in the form of hydrogen in salt caverns	2.37	1.85	02/07/2015
NCBiR	National programs - applied research / PBSE/1	Development of an industrial structure of carbonaceous fuel cells and ceramic electrolyzers giving the possibility of integration with power-to-gas power installations	2.02	1.25	01/10/2017
NCBiR	Sectoral R & D programs / INGA	Development of non-destructive diagnosis of gas pipelines based on non-contact magnetic method and sensors integrated with the use of machine learning algorithms	1.21	0.50	2018
NCBiR	Sectoral R & D programs / INGA	Development of an autonomous analytical system type GC / DMS for continuous and remote analysis of transported gaseous fuel and its admixtures for the purpose of streamlining the management of smart gas network (smart grid)	1.13	0.52	2018
NCBiR	Development projects 6/2014 - Defense and Security	Development of methods to neutralize the explosion hazard of selected tanks with technical gases, including alternative sources of supply in a fire environment for the needs of rescuers participating in rescue and extinguishing operations	1.11	1.11	2014 - 2017

Source: JRC 2020, based on publicly available data.

Table 27 Selected relevant CEST projects (≥ 0.1 million euro) funded by Spanish national programmes

Funding Body	Programme / Action	Name and topic	Funding €m	Duration
Ministerio de Economía, Industria y Competitividad	Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad (State Research, Development and Innovation Program, Oriented to Societal Challenges)	COOPERA Control of distributed energy systems that integrate renewable sources and hybrid storage, both stationary and mobile (distributed in hybrid/electric vehicle fleets). The project will develop different control strategies in the framework of Distributed Model Predictive Control (D-MPC) in order to efficiently manage the operation of this kind of system.	0.12	2014-2016
Ministerio de Ciencia, Innovación y Universidades	Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad	TOGETHER To improve energy efficiency in air conditioning, DHW and electricity production by a modular system that includes power generation, storage based on renewable energies and hydrogen cycle. It will be used in heating and cooling cogeneration systems with geothermal and absorption machines. The developments of the project will be studied in two laboratories with different system components and modes of operation and one global system in a living-lab, under real conditions of use to improve their performance. Stationary fuel cells such as micro-CHP will be used in cogeneration of electricity and heat of different powers in order to identify niche technology markets	0.28	2018-2020
Ministerio de Ciencia, Innovación y Universidades	Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad	CONFIGURA Energy control in microgrids (a set of loads, generators and storage systems that can be managed in a coordinated way in order to operate isolated or connected to the main grid). The project will address several issues related to the connection between electric vehicles and microgrids, as well as the problems associated to the change in topology due to the switching on/off of any generator, storage unit or load. The project will develop several control strategies in the framework of Model Predictive Control (MPC), designed to manage in an efficient way the operation of these systems, addressing their re-configurability both in one microgrid or a network of them. Control strategies will also consider operating criteria which include the degradation of storage systems, with the objective of increasing their lifetime	0.17	2017-2020
ACCIÓ	RIS3CAT	COSIN This project studies the production of renewable gas from the biogas generated by anaerobic digestion at waste water treatments plants (WWTPs). Furthermore, it is encompassed within the Power-to-Gas concept, which consists in converting and storing the surplus of electricity coming from renewable resources, such as photovoltaic and wind power, into methane. It consists of two lines of research: a) the generation of biomethane from biogas enrichment and residual CO ₂ methanation b) the development of high temperature electrolyzers and co-electrolyzers	0.48	2016-2018

Funding Body	Programme / Action	Name and topic	Funding €m	Duration
Ministerio de Economía, Industria y Competitividad	Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad	RENOVAGAS Development of a synthetic natural gas (SNG) pilot plant based on electrolytic hydrogen production using renewable energy and its methanation with CO ₂ from Biogas, producing totally renewable natural gas of a high enough quality to be directly injected into the natural gas network	0.46	2014-2016
Ministerio de Economía y Empresa (es)	Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad	INPROCOL Process intensification to obtain liquid fuels	0.24 ⁶⁸	2017-2019
Ministerio de Economía y Empresa (es)	Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad	RECOBIOHY Joint valorization of biogas and electrolytic H ₂	0.21 ⁶⁹	2017-2019

Source: JRC 2020, based on publicly available data.

⁶⁸ 50% of funding is from EU ERDF.

⁶⁹ 50% of funding is from EU ERDF.

Table 28 Selected relevant CEST projects (≥ 0.2 million euro) funded by Swiss national programmes

Funding Body	Lead organisation	Name and topic	Project funding €m	Duration
SNF	Assistant Professor (AP) Energy Grants	Tunable synthesis of size-selective nanopores in graphene for energy-efficient hydrogen purification and carbon capture	1.2	2018-2021
SNF	Sinergia	Carbon Dioxide Hydrogenation: New Synthetic Perspectives for Chemical Energy Carriers	1.1	2014-2018
SNF	NRP 70 Energy Turnaround	Renewable Methane for Transport and Mobility (RMTM)	0.7	2014-2019
SNF	Project funding (Div. I-III)	Catalytic activation of small molecules: towards ecological energy storage - carbon dioxide utilization	0.36	2015-2020
SNF	NRP 70 Energy Turnaround	Catalytic methanation of industrially-derived CO ₂	0.34	2014 - 2018
SNF	Project funding (Div. I-III)	Power-to-gas and network seasonal storage for promoting the safe penetration of renewables in Switzerland	0.24	2019 - 2023
SNF	NRP 70 Energy Turnaround	Sustainability assessment of the CO ₂ methanation value chain: environmental impacts and socio-economic drivers and barriers	0.2	2014-2018

Source: JRC 2020, based on publicly available data.

Table 29 Selected relevant CEST projects (≥ 0.5 million euro) funded by UK national programmes

Funding Body	Programme / Action	Name and topic	Budget €m	Funding €m	Duration
EPSRC	Research Grant	<p><i>HyStorPor – Hydrogen Storage in Porous Media</i></p> <p>This project will use state of the art laboratory experiments to investigated the underground storage of hydrogen in porous rocks prior to commercial trials.</p>		1.1	2019-2022
EPSRC	Research Grant	<p><i>Flexible Routes to liquid fuels from CO₂ by Advanced Catalysts.</i></p> <p>The conversion of sustainably produced hydrogen to high density liquid fuels, including methanol, DME and hydrocarbons which are more easily transported and are compatible with existing fuel distribution networks.</p>		1.8	2016-2020
EPSRC	Research Grant	<p><i>Hydrogen's Value in the Energy System (HYVE)</i></p> <p>The HYVE project aimed at assessing the potential demand and value of hydrogen in different markets across the UK energy system. It analysed the supply chain, including the use of electrolyzers to provide load balancing for a UK electricity system with a high penetration of RES.</p>		0.7	2014-2017
Innovate UK	Small Business Research Initiative	<p><i>MEGASTACK – creating affordable transport fuel from renewable electricity</i></p> <p>This project involved implementing a large 3MW water electrolyser with the potential to convert electricity to hydrogen at a price which is affordable for its use in the transport sector. This involved novel technology specifically for highly responsive Megawatt scale electrolyzers which aimed to bring the capital and maintenance costs of electrolysis down to the point where they contribute a manageable fraction of the cost of hydrogen production for transport applications, without compromising the system efficiency. The rapid response and scale of the system meant it could be allowed to interact with the National Grid's electricity balancing markets.</p>	3.5	3.5	2017-2018
Innovate UK	Collaborative R&D	<p><i>Enabling Electrolyser Manufacturing Ability</i></p> <p>This project was aimed at addressing technical challenges related to the production scale up and low cost manufacturing of PEM MEAs for electrolyzers, in order to meet future demand.</p>	0.83	0.50	2016-2017

Funding Body	Programme / Action	Name and topic	Budget €m	Funding €m	Duration
Innovate UK	Collaborative R&D	<p><i>LOCATE - LOw Cost cATALysts for water Electrolysers</i></p> <p>Amalyst had developed a class of low-cost, high-performance catalysts for fuel cell anodes and water electrolyser cathodes that are designed as 'drop-in' replacements for platinum. The aim of this project was for ITM Power to validate the 'drop-in' credentials of this catalyst by fabricating full-sized catalyst coated membranes and validate it in a pilot-scale version of ITM's production electrolyser.</p>	0.52	0.36	2014-2016
Ofgem	Network Innovation Competition	<p><i>H21</i></p> <p>H21 is a family of gas industry projects designed to support the conversion of UK gas networks to carry 100% hydrogen. This NIC grant is being used to help Northern Gas Networks build on its H21 Leeds Gate Project, which demonstrated that hydrogen conversion was technically and economically viable.</p>	10.3	9.0	2018-2020
Ofgem	Network Innovation Competition	<p><i>HyDeploy</i></p> <p>A 0.5MW electrolyser is being deployed to demonstrate the use of blended hydrogen in the UK gas grid. The project aims to demonstrate that national gas containing levels of hydrogen beyond those in the GS(M)R specification can be used safely and efficiently in a section of the UK gas distribution network.</p>	7.6	6.8	2017-2020

Source: JRC 2020, based on publicly available data.

Table 30 Selected relevant CEST projects (≥ 1 million US\$) funded by U.S. DOE

Funding Body	Programme / Action	Key Activity	Name and topic	Budget \$m	Duration ⁷⁰
DOE	DOE HFCP	Safety, Codes and Standards	H-Mat Materials Overview: Polymers	7.8	09/2018 – 09/2022
DOE/	DOE HFCP	Technology Acceleration	Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation	5,74	06/2015 - 09/2019
DOE	DOE AMO ⁷¹	Technology Acceleration	Roll-to Roll Advanced Materials Manufacturing Lab Collaboration This is materials for electrodes development project.... A general one, led by AMO. FCTO got connected with this project by Proton OnSite and now FCTOs contribution is negotiated	4.0	10/2016 - 09/2018
DOE	DOE HFCP	Technology Acceleration	Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation	3.89	06/2015 - 09/2018
DOE	DOE HFCP	Technology Acceleration	Modular SOEC System for Efficient H2Production at High Current Density	3.75	10/2016 - 09/2019
DOE	DOE HFCP	Technology Acceleration	High Temperature Electrolysis Test Stand	3.09	4/2017 – N/A
DOE	DOE HFCP	Technology Acceleration	Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service	2.65	10/ 2015 – 10/2018
DOE	DOE HFCP	Hydrogen Fuel R&D / Testing and Analysis - Storage	System Level Analysis of Hydrogen Storage Options	> 2.44	10/2009 - N/A
DOE	DOE HFCP	Technology Acceleration	High Temperature Electrolysis Test Stand	2.29	2017-2018
DOE	DOE HFCP	Hydrogen Fuel R&D / HydroGEN Consortium	Benchmarking Advanced Water Splitting Technologies	2.2	09/2017 – 02/2019
DOE	DOE HFCP	Infrastructure and Systems / Hydrogen Infrastructure R&D	H-Mat Overview: Steels Science-based advancement of materials for hydrogen technologies	2,2	10/2018 – 09/2022
DOE	DOE HFCP	Technology Acceleration	In-line Quality Control of PEM Materials	2.15	06/2015 – 08/2020
DOE	DOE HFCP	Technology Acceleration	H2@Scale Analysis	2.0	1/2017 – N/A
DOE	DOE HFCP	Technology Acceleration	Continuous Fiber Composite Electrofusion Coupler: Design and Validate pipe coupler for FRP Hydrogen Delivery for yet to be installed pipes, without use	1.88	12/2015 - 4/2019

⁷⁰ Projects continuation and direction is determined annually by DOE, therefore in those cases the end date is N/A

⁷¹ Advanced Manufacturing Office

Funding Body	Programme / Action	Key Activity	Name and topic	Budget \$m	Duration ⁷⁰
			of elastomeric seals		
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	High-Temperature Alkaline Water Electrolysis (Project ID:	1.7	01/2017 – 12/2019
DOE	DOE HFCP	Hydrogen Fuel R&D / Hydrogen production analysis	Analysis of Advanced H2Production & Delivery Pathways	1.2	10/2016 - 9/2020
DOE	DOE HFCP	Technology Acceleration	In-line Quality Control of PEM Materials	1.15	06/2015 – 08/2018
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	Scalable Elastomeric Membranes for Alkaline Water Electrolysis	>1	10/2017 – 09/2020
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	Proton-Conducting Solid Oxide Electrolysis Cells for Large-scale Hydrogen Production at Intermediate Temperatures	>1	10/2017 - 09/2020
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	Degradation Characterization and Modeling of a New Solid Oxide Electrolysis Cell Utilizing Accelerated Life Testing	>1	09/2017 – 08/2020
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	Thin-Film, Metal-Supported High-Performance and Durable Proton-Solid Oxide Electrolyzer Cell	>1	10/2017– 3/2021
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	High Efficiency PEM Water Electrolysis Enabled by Advanced Catalysts, Membranes and Processes	>1	9/2017 - 8/2020
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	Developing Novel Platinum Group Metal-Free Catalysts for Alkaline Hydrogen and Oxygen Evolution Reactions	>1	10/2017 - 12/2020
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	PGM-free OER Catalysts for PEM Electrolyzer	>1	10/2017 - 09/2020
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	New Approaches to Improved PEM Electrolyzerlon Exchange Membranes	1.0	04/2017 – 04/2019
DOE	DOE HFCP	Hydrogen Fuel R&D / Electrolysis production	High-Performance Ultralow-Cost Non-Precious Metal Catalyst System for AEM Electrolyzer	1.0	10/2017 - 09/2020

Source: JRC 2020, based on publicly available data.

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