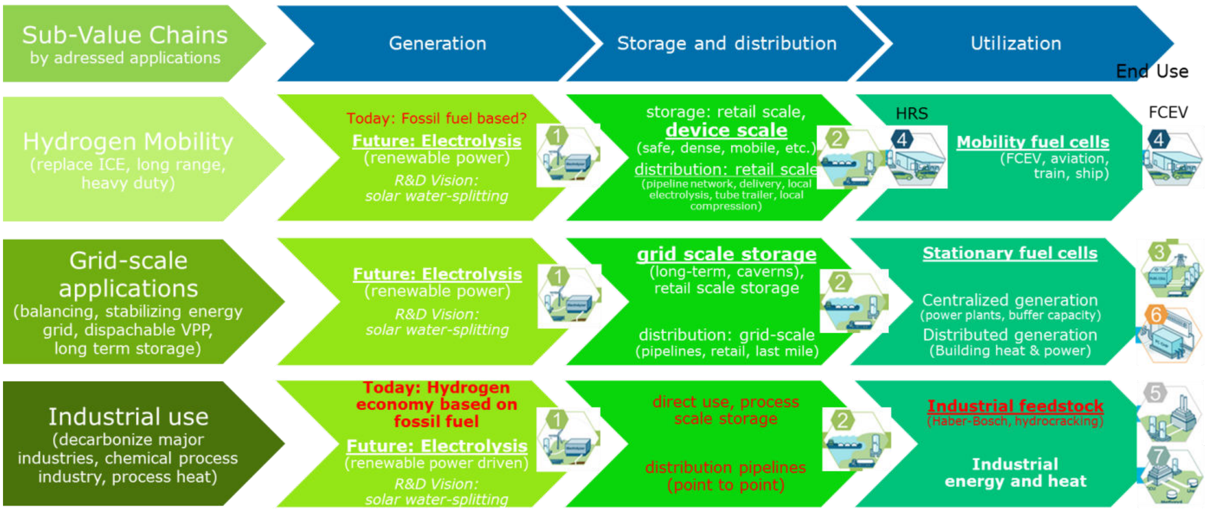
Strategic Value Chain Report<Hydrogen technologies and systems>- second DRAFT (15-03-2019)

1. Description

Today, hydrogen is a well-known commodity in the chemical process industry that is used in oil refining, fertiliser production and to manufacture metals, for instance.[1]However, currently most hydrogen is sourced from fossil-based technologies (e.g. coal gasification, steam reforming), while electrolysis, a key technology for green H2, is still not fully benefiting from the economies of scale larger (future) demand may bring about and thus finds itself confined by prohibitively higher costs compared with incumbent technologies which do not address, inthe particular challenge when drivenof integrating by intermittent renewable sources.With respect to the future, using H2 produced by renewable energies[2], e.g. in industrial applications, for large scale storage or in fuel cell electric mobility (e.g. FCEV, FCEB)[3]is regarded as a promising strategy to decarbonize the economyin general and the gas and liquid fuels' sectors in particular.[4,5] Since it potentially allows for a plenitude of different applications,[6] some of which in sectors hard to decarbonize by electrification alone (e.g. heat, or chemicals production, heavy duty/long haul transportation including road, rail, maritime and air),green hydrogen might be "the missing link in the energy transition"[4].

Figure 1: Value chain and Sub-value chain picture



Decarbonising the power grid is key for the energy transition especially if electrification is spread to sectors which traditionally were not fitted for it. Nevertheless, decarbonisation of the gas and liquid fuels infrastructure is of high relevance too in view of maintaining an overall highly resilient energy system. Hydrogen – a flexible energy carrier that may be produced from green energy sources, can be easily distributed, stored and used with no carbon footprint – at scale, in an ever more

[1] Roads2HyCom consortium (2009) FUEL CELLS AND HYDROGEN IN A SUSTAINABLE ENERGY ECONOMY, https://cordis.europa.eu/docs/publications/1217/121790171-6_en.pdf.

[2] including also alternative pathways such as „blue hydrogen" by combining with a pre-combustion CCS

[3] Fuel Cell Electric Vehicles (FCEV), Fuel Cell Electric Buses (FCEB), Fuel Cell Forklifts, Trucks, etc.

[4] Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

[5] IRENA (2018) Hydrogen from renewable power: Technology outlook for the energy transition, https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf.

[6] Viebahn P, Zelt O, Fischedick M et al. (2018) Technologien für die Energiewende: Politikbericht.

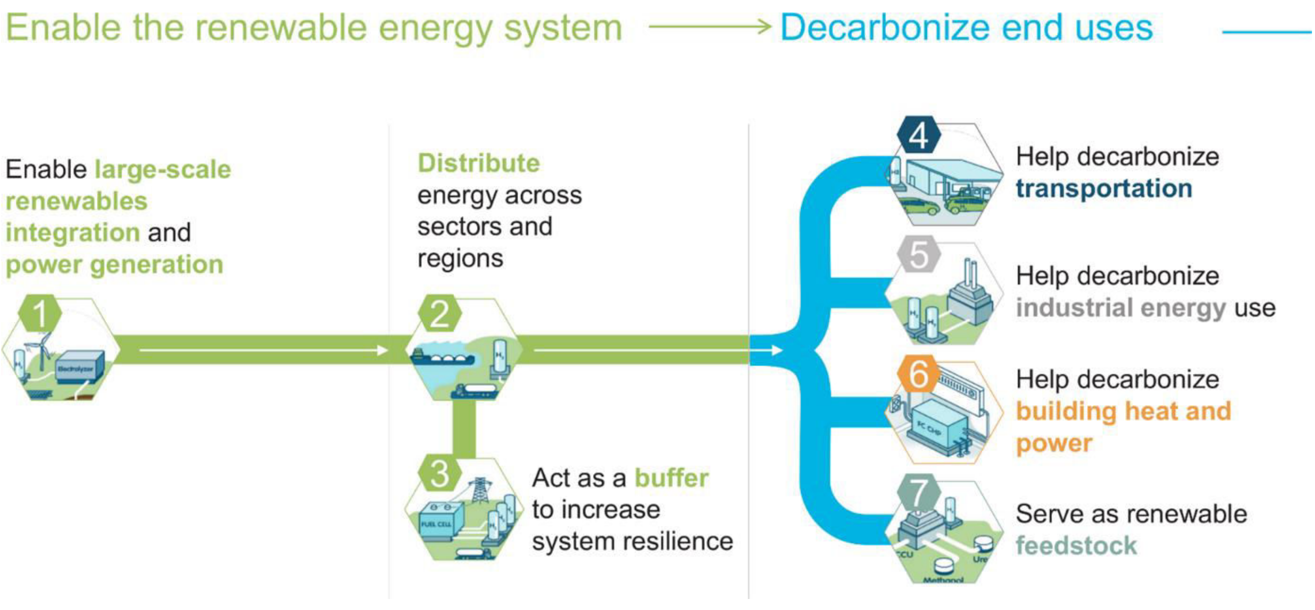
challenging scenario of increased capacity installation and penetration of renewable electricity generation, is a key element to ensure the EU timely meets its carbon neutrality target.

The (renewable or more broadly "low carbon/ carbon free") **hydrogen value chain** consists of the parts of (primary energy production,) *H2 production/generation, H2 storage (including transmission/distribution), and H2 utilization.* [7]

There are potentially/partly different technological solutions, bottlenecks, different relevant time frames, different actors, linkages to other sectors, etc. depending on the applications along the main value chain (hydrogen production, storage to utilization). The representation of the hydrogen economy along these 3 x 3 dimensions allows for a systematic analysis of the Strategic Value Chain (SVC) and sub-value chains (e.g. for SWOT analyses, key players, relevant actions for Europe and recommendations).

The value chain picture (Figure 1) basically follows the stages/ fields relevant for a future hydrogen economy as identified and described in the recent Hydrogen Roadmap Europe (FCH JU with analytical support from McKinsey & Company, January 2019 [8], see Figure 2). For the analytical work of the "analytical SVC Report on Hydrogen Technologies and Systems" we cluster them into main sub value chains (sub-VC). The three stages of the overarching SVC (Generation, Storage & Distribution, Utilization) are briefly explained below.

Figure 2: All over value chain: 7 main fields of the hydrogen value chain[8]



7Frischauf N (2014) Communication/Exploration/Navigation Technologies – Applications, Trade-Offs and possible Transfers between Space and Ground at the Example of MOA², a novel pulsed Plasma Accelerator

8Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

1.1 Hydrogen Generation

Established technology, but significant carbon footprint: Most of the world's hydrogen production today is being produced through a CO2 intensive process called Steam Methane Reforming (SMR) leading to a significant carbon footprint. Hydrogen could also be produced through a process that makes use of renewable electricity, leading to the production of "green" or CO2 neutral hydrogen. In the future, the electrolysis of water should represent the primary renewable production pass way for hydrogen. Biogas could also be used with current SMR technology to produce hydrogen at reduced CO2 footprint but there are some limitations to use such model as main source of hydrogen at scale.[9]

Industrial electrolysis not competitive now (only niches): In general, electrolysis matured decades ago and various alternative electrolysis technologies exist on different technology readiness levels today (e.g. alkaline electrolysis: TRL 8, polymer electrolyte membrane electrolysis: TRL 6, Solid Oxide Electrolysis: TRL 4-5). Also, other hydrolysis concepts of biological, photochemical and thermochemical routes exist at much lower TRL. Two factors limited the market diffusion of commercial electrolysis solution so far: (1) The marginal cost of hydrogen especially derive from the cost of electricity; (2) High capital costs demand continuous operation at maximized output. Although the temporary abundance of electricity from renewables (e.g. peak solar generation) resolves issue 1, it simultaneously increases the weight of issue 2 (due to non-continuous operation of capital-intensive equipment). Yet, the interplay of two different effects may mitigate the both issues in the future. Firstly, reaching economies of scale is hoped to reduce unit cost. Secondly, innovation in electrolysis technology (e.g. high-temperature electrolysis) could increase physical efficiency and thus unlock cost reductions.

*Research vision:*Other renewable hydrogen generation technologies than electrolysis remain at much lower TRL. An example for such technologies is artificial photosynthesis (photo-electrochemical): the term summarizes various concepts that circumvent current collection in photovoltaics by direct electrochemical conversion of excited charge carriers on the very surface of the device. Solar-to-hydrogen conversion efficiency above 16% has been demonstrated[10] and theory predicts about 25% being feasible [11], but economic scalability remains an issue. A second example would be Biomass/photo-biological routes.They may harness natural photosynthesis for both hydrogen and alternative solar fuel production (e.g. by algae). Nonetheless, substantial conversion efficiency remains to be demonstrated.

1.2 Hydrogen Storage (and distribution)

Pressurized gas (existing experience back to town gas, but energy density and safety concerns): Today, rather inexpensive fossil-to-hydrogen conversion and industrial use of hydrogen largely favor on-site and on-demand generation, diminishing incentives for research on storage. However, scale-proven stationary storage technologies are already available (e.g. the use of town gas in the past, storage in salt caverns). Current natural gas infrastructure should be capable of accepting hydrogen feed-in at least at dilute levels [5], providing immediate access to a certain storage capacity. Alternatively, dedicated high-pressure gasholders represent mature buffers at points of generation and/or utilization. Nonetheless, large-scale long-term storage solutions still require further research

9Hydrogen Europe (2017), Hydrogen production: https://hydrogeneurope.eu/hydrogen-production-0.

10 Young JL, Steiner MA, Döscher H et al. (2017) Direct solar-to-hydrogen conversion via inverted metamorphic multi-junction semiconductor architectures. Nat Energy 2(4): 453. doi: 10.1038/nenergy.2017.28

11Döscher H, Geisz JF, Deutsch TG et al. (2014) Sunlight absorption in water – efficiency and design implications for photoelectrochemical devices. Energy Environ. Sci. 7(9): 2951–2956. doi: 10.1039/C4EE01753F and development. As with respect to storage, technologies for a dedicated hydrogen distribution network readily exist, but extensive implementation would require tremendous capital investment.Moreover, small-scale hydrogen-storage for mobility applications still constitutes a bottleneck: *Pressurizing gas* is a mature technique, but complicates refueling, range, and safety.

Liquified hydrogen (better energy density, but requires very low temperature (melting point at −259.14 °C) and adds, excessivefurther conversion losses): Liquefied hydrogen provides higher energy density, yet requires much energy. In addition, technologies based on chemical/ physical reaction with substrates are still at low TRL.

The development of advanced insulation technologies, and high-capacity liquid organic hydrogen carriers (LOHCs) may enable long-distance delivery at high capacities.

Repurposing of existing natural gas infrastructure conceivable (network, storage, etc.) enabling the full decarbonisation of its various end-usages. Full retrofitting of natural gas infrastructure to tolerate 100% hydrogen is feasible and much less expensive than building new dedicated assets from scratch. Furthermore, it prevents natural gas infrastructure to become stranded assets long before their physical obsolescence and thus prevents these costs from being transferred to the economy/society.

1.3 Hydrogen Utilization

Present day: Huge turnover as process chemical (Haber-Bosch, hydrotreating and hydrocracking) - Most of the hydrogen currently produced is used as a feedstock to make other materials due to its chemical rather than energy properties. In the EU, 325 TWh of hydrogen becomes feedstock every year, mostly in the refining and chemical production industries.

Native technology: Fuel cells (various types with varying profiles exist): The specific design of fuel cell technologies depends on the intended application, which may be stationary or in mobile in nature. [12] Meanwhile, a variety of fuel cell designs has emerged, which are classified according to the type of electrolyte employed (e.g. solid oxide, proton exchange membrane).[13]While different technologies are able to reach total energy efficiency of such combined heat and power (CHP) systems running on hydrogen of above 85%, variable energy outputs can be tailored to the energy needs (with electrical efficiency being able to go above 60%).

Drop-in solutions: Mix with or replace natural gas for combustion, heating, co-generation: Despite the apparent interest for fuel cells, renewable hydrogen will initially achieve an immediate and significant impact in the chemical industry as it can directly replace large quantities of fossil-based hydrogen. Beyond the decarbonization of major industrial processes (e.g. Haber Bosch), additional applications may benefit from the superior purity of electrolyzed hydrogen (e.g. fuel cells susceptible to carbon poisoning). Beyond the above, the (partial) conversion of other important industrial processes (e.g. steel making)[14] towards using hydrogen feedstock constitutes on important area of R&D. Likewise, in order to harness the full potential of renewable hydrogen for power-to-X applications, the further development of crucial mature processes and technologies (e.g. Fischer-

12 FuelCellToday (2018) Applications. http://www.fuelcelltoday.com/applications

13FuelCellToday (2018) Technologies. http://www.fuelcelltoday.com/technologies

14Tractebel, Hinicio (2017) Study on early business cases for H2 in energy storage and more broadly power to H2 applications. https://www.fch.europa.eu/sites/default/files/P2H_Full_Study_FCHJU.pdf

Tropsch, methanation) as well as that of novel ones (e.g. direct air capture, carbon capture and storage[15]) is necessary.

15 This technology should produce the CO_2 needed for further processing of H_2 in Fischer-Tropsch and methanation to produce high-value chemicals.

2. Mapping

2.1 Mapping of Global and EU value chain participants: players and their role along the SVC

In order to analyze the global hydrogen value chain paricipants it is the easiest to consider the main networks and associations and their members. The Hydrogen Council (launched at the World Economic Forum 2017, in Davos) is a global initiative of leading energy, transport and industry companies. The composition ofthe members reflect the current global distribution of **leading industries which are spread across Asia (mainly Japan, Korea, China), North America (mainly USA, Canada) and Europe**. Current members of the Hydrogen Council include 24 leading multinationals—3M, Air Liquide, Alstom, Anglo American, Audi, BMW GROUP, China Energy, Daimler, ENGIE, General Motors, Great Wall Motor, Honda, Hyundai Motor, Iwatani, JXTG Nippon Oil & Energy Corporation, Kawasaki, Plastic Omnium, Royal Dutch Shell, Statoil, The Bosch Group, The Linde Group, Total, Toyota and Weichai—as well as 15 dynamic players from across the value chain - Ballard, Faber Industries, Faurecia, First Element Fuel (True Zero), Gore, Hexagon Composites, Hydrogenics, Marubeni, McPhy, Mitsubishi Corporation, Mitsui & Co, Nel Hydrogen, Plug Power, Toyota Tsusho and Royal Vopak.[16]

In much more detail, actors along the Hydrogen value chain can be identified e.g. on the FCH-JU Website for Europe[17] or on the website of H2-International[18] (a map can also be found on Wikipedia).[19]

European value chain participants

The FCH 2 JU is a public-private partnership between the European Commission, European industry and European research organisations, and supports RTD activities in FCH technologies in Europe. Recognising the potential economic and industrial benefits from a strong FCH supply chain in Europe, and the opportunities for initiatives to support new energy supply chains, FCH 2 JU commissioned two recent studies: [20,21]

The Value Chain Study complements the Hydrogen Roadmap for Europe, recently published by the FCH 2 JU. The latter lays out a pathway for the large-scale deployment of hydrogen and fuel cells to 2050 in order to achieve a 2-degree climate scenario. This report also quantified socio-economic and environmental benefits, but with important differences in scope between the two studies.

The Hydrogen Roadmap for Europe looked at the wider energy picture, quantifying the scale of FCH roll-out needed to meet the 2-degree scenario objectives. It assessed the socio-economic impacts of a sector of that scale, looking at the entire FCH value chain. The Value Chain Study is a much narrower (e.g. the only hydrogen pathway assessed was electrolysis) and more detailed bottom-up assessment of the value-added in manufacturing activities and the immediate ecosystem of

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16http://hydrogencouncil.com/; https://global.toyota/en/newsroom/corporate/21497691.html

17https://www.fch.europa.eu/page/FCH-value-chain

18https://www.h2-international.com/companies/

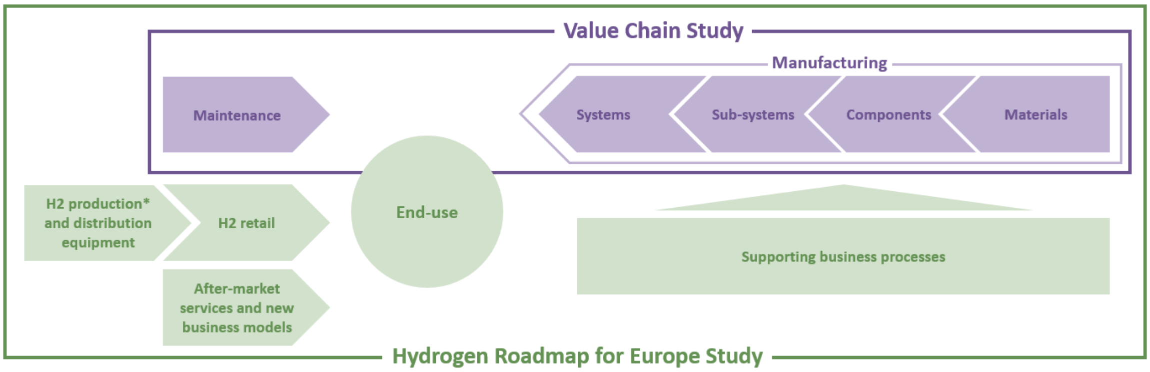
19https://openei.org/wiki/List_of_Companies_in_Hydrogen_Sector

20E4tech, ECORYS and SA-Strategic Analysis (Fuel Cell and Hydrogen Joint Undertaking; publishing waiting final approval by the Governing Board of the Fuel Cells and Hydrogen 2 Joint Undertaking), Value Added of the Hydrogen and Fuel Cell Sector in Europe: supporting European growth and competitiveness. Draft final versions, including the Evidence Report, the Findings Report and the Publishable Summary accessed 15 Mar 2019.

21Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

suppliers that this is likely to create. The scope and boundaries of both studies are illustrated in the figure below. This difference of scope means that the socio-economic impacts estimated in the two studies also differ.

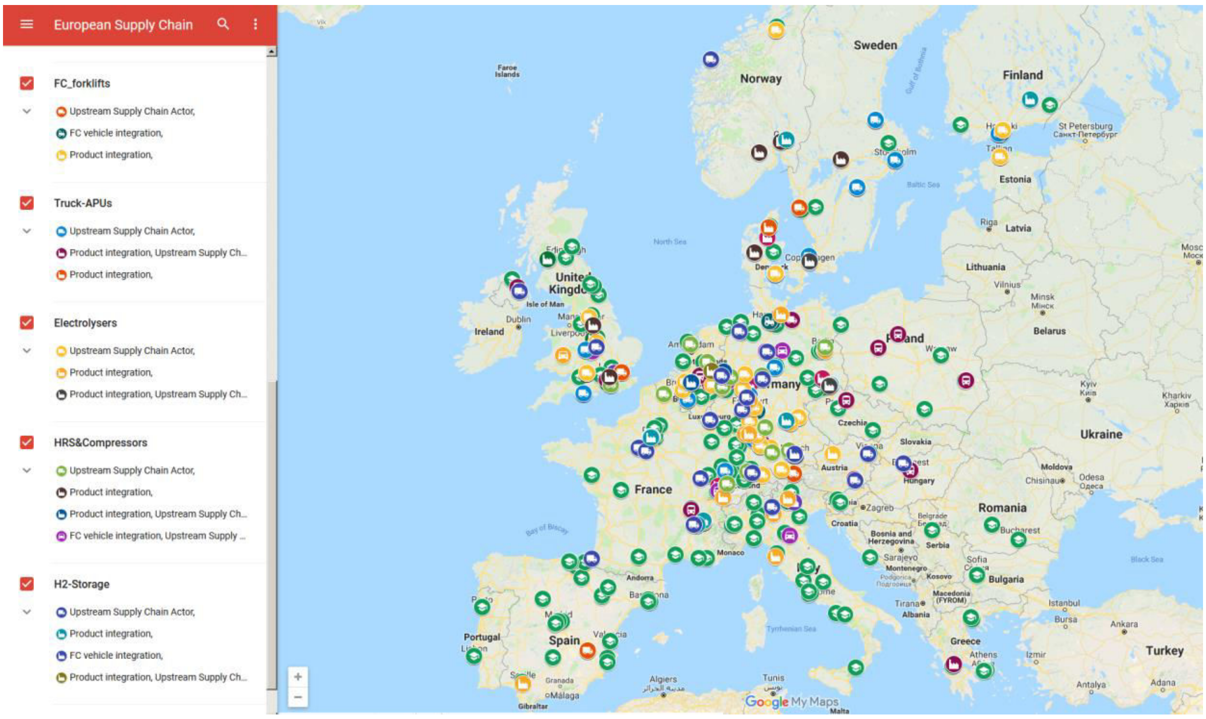
Figure 3: Scope and boundaries of the FCH JU Value Chain and Hydrogen Roadmap for Europe studies



* The Hydrogen Europe Study focused on hydrogen production from steam methane reformation (with and without carbon capture and storage; and both from natural gas and biogas), electrolysis and hydrogen by-product. The value chain study included only electrolysis.

The FCH Value Chain Study gathered data on sector actors and their FCH-related activities, a survey on EU competitiveness in FCH and performed desk-based research to create a detailed database and online map of European FCH supply chain actors.

Figure 4: Map and distribution of leading European players [22]



The actors in the database have also been plotted on an interactive map (a screenshot is shown in Figure 4). Each layer of the map represents one application. There is one layer that includes also all

22https://www.fch.europa.eu/page/FCH-value-chain the knowledge-based actors. Within each layer of companies, the symbol distinguishes between: upstream supply chain actors (lorry symbol), product integrators (factory symbol), vehicle integrators (car, bus and tractor symbols), Knowledge-based actors (academic cap).

Data was gathered on the 13 applications for which detailed supply chain maps and an analysis of EU strengths, weaknesses, opportunities and threats was developed: Transport applications (Passenger cars and LCVs, Buses, HGVs, Trains and light rail, Forklifts, Boats) andEnergy applications (HRS, Electrolysers, Micro-CHP, Commercial CHP / prime power, Large scale CHP / prime power, Back-up power / gensets, Fuel processors / reformers).

Figure 5: Generic PEMFC supply chain structure in both transport and stationary applications. See sections 5.2.X.1 and 5.X.2 of the Evidence Report for such maps per application and with European system integrators. See section 6 of the same Report for such supply chain maps by technology and with European actors in selected critical components.

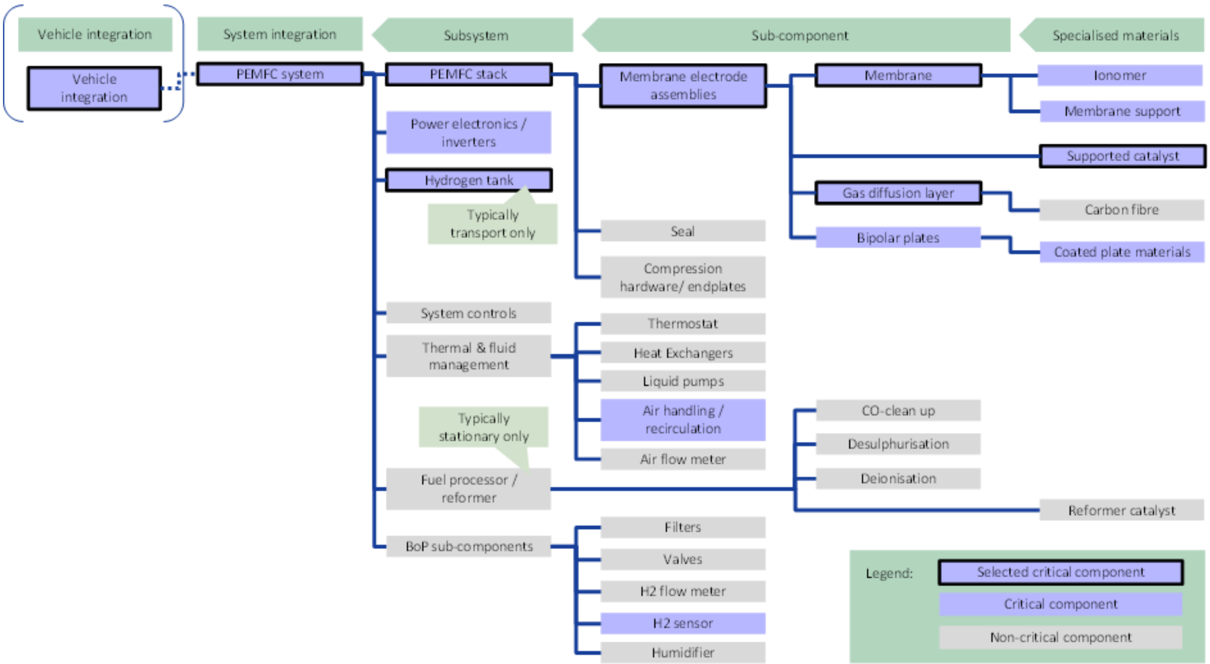
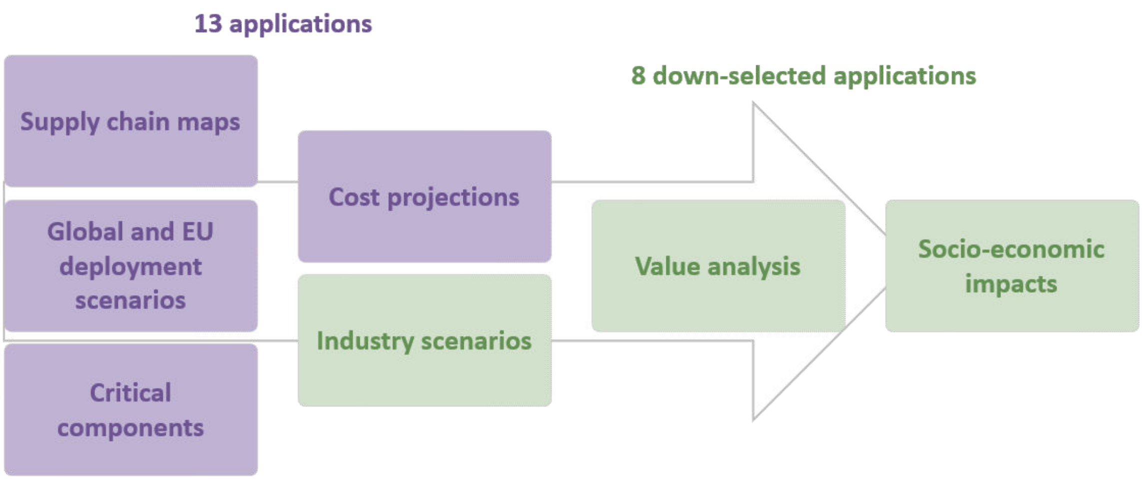


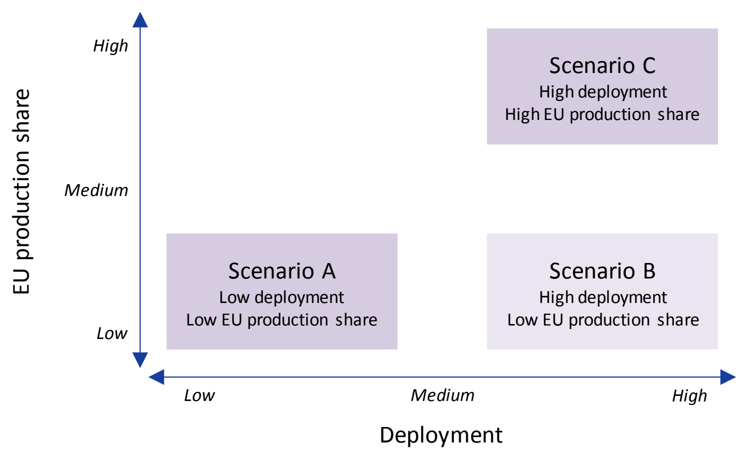
Figure 6: Overall methodology followed in the Value Chain Study



While all 13 hydrogen and fuel cell applications got (1) detailed supply chain maps (per application and per technology, including listing of relevant European players); (2) Global and European deployment scenarios; and (3) system cost breakdowns and global turnover estimations were developed and mapped to the production volumes in the deployment scenarios, only the 8 applications highlighted above were down-selected, on the basis of a set of criteria, for developing industry scenarios. These laid out possible futures of the European FCH value chain, exploring what could happen in the future, and the implications of the possible futures.

Two key parameters were varied in: 1) the extent of deployment of FCH technologies globally (over which the EU has limited control), and 2) the share of FCH production captured by EU actors (over which more control can be exerted). This enabled the impact of different policies and sector approaches to be assessed. Industry narratives were produced to accompany the three scenarios, and validated in a workshop with industry stakeholders. The scenarios are shown graphically in the figure below.

Figure 7: Industry scenarios summary



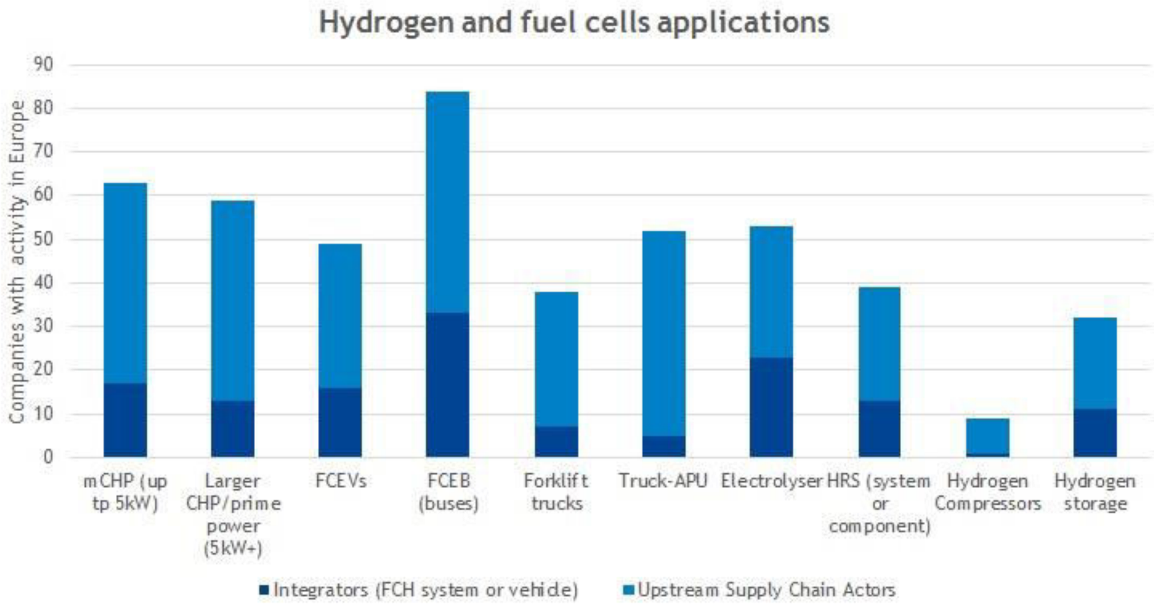
The Value Chain Study undertook a comprehensive analysis of the FCH industry actors in Europe, including the industrial actors (see section 4.1 of the Findings Report) and the knowledge and research based actors (KBAs) (see section 3.1.2 of the Evidence Report).

The analysis depicted by the figure below, taken from the study commissioned by the FCH JU in 2016 on these same matters (and which can be considered the predecessor of the Value Chain Study) was eventually picked up and further developed in the Value Chain Study. It enables a rough perception of the activity of different companies operating in Europe and acting either as integrators or suppliers of certain FCH applications.

Coverage/fragmentation and need to cover VC (Integration of the VC into the global VC(s))

More than half of the actors identified by the FCH JU are research organisations. Out of the ~200 industrial actors, the majority (117) are upstream supply chain actors. There are 76 FCH system integrators (e.g. fuel cell system, electrolyser system, H2 storage system, HRS) and 26 vehicle integrators in the database. Some of the actors play more than one of these roles.

Figure 8: The European Hydrogen and Fuel Cell industry today (2017 status)[23]



It can be seen, that Europe has globally leading companies and research institutes across many hydrogen and fuel cell technologies and applications (see Figure 8).Europe has particular strengths in key components of fuel cell stacks and electrolyzers. Today, many companies sell products worldwide and are well positioned in the fields of fuel cell cars, buses and forklifts but also for other applications such as combined heat and power (CHP) and auxiliary power units (APUs). Together with the (still comparably lower number of) system integrators Europe might create markets and value along the full value chain from hydrogen generation, storage and distribution to the utilization.

With respect to non-EU regions a short comparison of Japan, Korea, China, USA/Canada should provide a quick overview on governmental and industrial most recent activities:

Japanis traditionallystrong in most areas of hydrogen and fuel cell technologies, from R&D to manufacturing and applications. The Japanese fuel cell industry is given strong direction and financial support through national government policy, with hydrogen embedded into the national energy strategy. With the Basic Hydrogen Strategy released on Dec 2017, Japan reiterates its commitment to pioneer the world´s first "Hydrogen Society". Over the past six years Japanese government has dedicated around 1.5 bn $ to R&D and subsidies for achieving low cost and zero emission hydrogen production, developing infrastructure for import and distribution of hydrogen and scaling up hydrogen across sectors such as mobility, residential CHP and power generation.[24]Japan aims to increase the number of FCEVs to 40 ,000 units by 2020, to 200,000 by 2025 and 800,000 by 2030.[25] The number of HRS should be increased to 160 by 2020 and 320 by 2025. The costs for hydrogen generation should be reduced to 17 yen/kWh (~4,6 €/kg,

[23]https://www.fch.europa.eu/page/FCH-value-chain

[24]https://www.ifri.org/sites/default/files/atoms/files/nagashima_japan_hydrogen_2018_.pdf

[25]FCEB should increase to 100 by 2020 and 1200 by 2030; FC forklifts to 500 by 2020 and 10.000 by 2030. Also FC trucks and small ships are to be commerzialised and promoted.

14€cent/kWh) until 2030 (down to ~2 €/kg in the longer term.[26] Power generation should increase to 1 GW (300kt/year) around 2030 and 15-30 GW in the long term.[27]

Korea presenteda new plan by the South Korean government in Jan 2019 to build a hydrogen economy including a massive increase in the number of fuel cell vehicles produced in the country. While only around 2,000 FCEV were built by 2018, the number is expected to rise to 100,000 by 2025 and 6.2 million fuel cell vehicles by 2040, of which 3.3 million vehicles are to be exported. The government wants to achieve this, among other things, by expanding the infrastructure: the number of hydrogen filling stations is to increase from 14 last year to 310 by 2022 and to 1,200 by 2040. In addition, the government plans to reduce the average price of an H2 vehicle to around 27,000 euros through subsidies. Hydrogen costs should be reduced from around 6.25€/kg to 2.34 €/ kg by 2040. The government's long-term goal is to introduce a total of 40,000 hydrogen-powered buses, 80,000 taxis and 30,000 trucks, as well as to promote domestic production of suitable car parts. The government expects the promotion of the hydrogen economy to create nearly 34 billion euros in economic value and 420,000 jobs by 2040.[28], [29]

China's target for FCV development is to deploy one million FCVs by 2030, and zero emission by 2050 through joint development of FCVs and electric vehicles.[30] China will demonstrate 5,000 FCVs by 2020, 50,000 FCVs in service (10,00 commercial, 40,000 as passenger FCEVs) by 2025. HRS are planned to be built up from a few today to over 100 by 2020, over 300 by 2025 and over 1000 by 2030 (with >50% hydrogen production from renewables). Objectives in terms of technologies are to be capable of the design and system integration of fuel cell buses and passenger cars, to establish an entire FCV technology and industry chain, including fuel cell stacks and key materials, fuel cell system and core components, FCVs and critical parts, and hydrogen supply infrastructure and to realize overall development of future clean, low carbon, high-efficient FCV R&D and application system. Targets by 2020 are: FCEV (with low fuel cell power) cost similar to all electric vehicles, by 2025: FCEV (with high fuel cell power) cost similar to hybrid vehicles and hydrogen mainly from renewable resources; by 2030: 100% hydrogen poweredand all five key performance indicators (i.e. auto power, economic, durability, environmental adaptability, and costs) meet commercial requirements and an increasing hydrogen production from decentralized renewable resources.[31]

USA/ Canada: There are highly visible activities in the USA[32] and Canada. The Office of Energy Efficiency and Renewable Energy has spent an average of about $139 million per year (about 0.5% of

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26https://www.ifri.org/sites/default/files/atoms/files/nagashima_japan_hydrogen_2018_.pdf

27https://www.meti.go.jp/english/press/2017/1226_003.html

28Korea presents hydrogen economy plan (Jan 2019), https://www.electrive.com/2019/01/17/korea-presents-hydrogen-economy-plan/

29 Furhter links for Korean Hydrogen Plans:
http://www.edaily.co.kr/news/read?newsId=02427206622358704&mediaCodeNo=257&OutLnkChk=Y
http://www.hani.co.kr/arti/economy/marketing/878752.html
https://www.yna.co.kr/view/AKR20190116160800003?input=1195m
http://news1.kr/photos/view/?3472854
http://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_cd_n=81&cate_n=1&bbs_seq_n=161262
http://www.cte.tv/wp-content/uploads/2016/12/4_Jeon.pdf

30https://www.ieafuelcell.com/documents/FCV%20Tech%20Roadmap%20(Eng)_Final_20180320_Revised.pdf

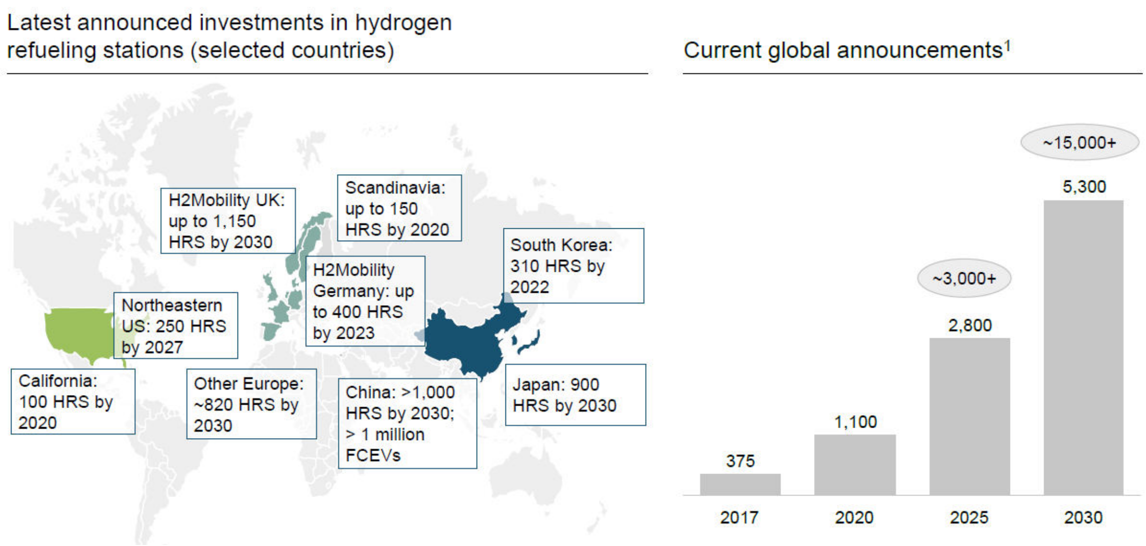
31 see Chinese Roadmap: https://www.ieafuelcell.com/documents/FCV%20Tech%20Roadmap%20(Eng)_Final_20180320_Revised.pdf
http://www.ihfca.org.cn/file/FCV%20Tech%20Roadmap.pdf

32 Program Record #17006, "Historical Fuel Cell and Hydrogen Budgets" (2017), https://www.hydrogen.energy.gov/pdfs/17006_historical_fuel_cell_h2_budgets.pdf
https://www.energy.gov/sites/prod/files/2017/10/f37/fcto_2016_market_report.pdf

the average DOE budget) since 2004 on fuel cell and hydrogen research, development, and demonstration.Some states have local funding, e.g. to increase fuelling infrastructure (California) or support local manufacturing development. Through the high funding level of DOE, there is a strong R&D among national laboratories, universities.

Besides the global R&D activities, plans for hydrogen generation ramp up, and hydrogen deployment plans the example of planned Hydrogen Refuelling Stations (HRS) underpins what are the most active regions globally (namely the above mentioned). Of the 369 hydrogen stations worldwide[33] (thereof 152 hydrogen stations in operation in Europe, 136 in Asia, 78 in North America as of the end of 2018), 273 are publicly accessible and can be used like any conventional retail stations. The others are run for closed user groups supplying e.g. buses or fleet customers. Also, it underpins the important role of the mobility/ transport sector as driver for hydrogen deployment through the need for decarbonisation of the sector.

Figure 9: Globally announced HRS[34]



2.2Level and geographic distribution of industrial base in Europe (cross-border links)

The deploymentof hydrogen will likely start first and grow most steadily in countries that have high seasonal heating demand, extensive existing natural gas networks, and substantial older building stocks.

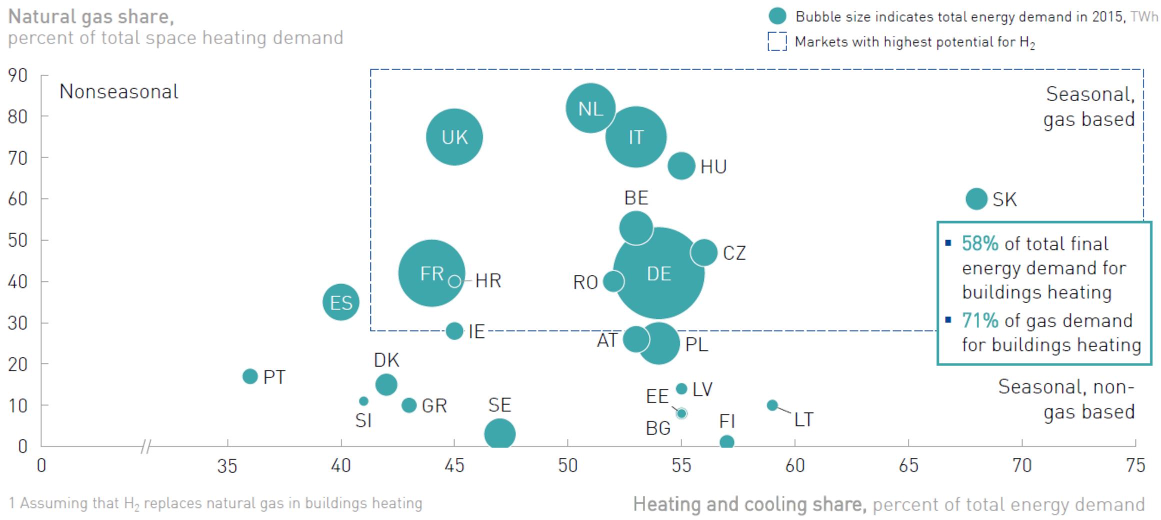
In Europe: Germany, France, the UK, and the Netherlands all fall into this category. The leading countries account for 58% of total final energy and over 71% of gas demand in building heat, thereby creating a huge market for hydrogen (Figure 10).

Indeed these countries are also among the most active along the hydrogen value chain.

33https://www.tuev-sued.de/company/press/news/highest-increase-of-hydrogen-refuelling-stations-in-germany-worldwide-in-2018-again

34 Hydrogen scaling up: Hydrogen Council November 2017.

Figure 10: PRIORITY COUNTRIES FOR HYDROGEN ADOPTION WITHIN THE EU[35]



2.3 Analysis of governance and links at EU and national level

The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) launched an initiative in 2017 to help European regions and cities harness hydrogen and fuel cells to realise their energy transitions. 89 European regions and cities from 22 countries are currently taking part in the initiative, working together to realise major investment projects of around EUR 1.8 billion (Figure 11) that will deploy hydrogen and fuel cell technology across Europe in the next five or so years. For 67% of these planned investments respective regions and cities see a very high likelihood for implementation so that it can be assumed that the large majority of these investments will actually be realised in the next years. In addition, almost half of envisaged projects have already entered into advanced stages of project development, thus underlining the clear ambition of the regions and cities to actually implement envisaged projects. A large number of companies from the FCH industry are actively supporting these efforts and helping regions and cities to realise their plans.

24 participating regions and cities have expressed an ambition to become an "H2 Valley" in the future, with ten regions pursuing concrete plans for implementation in the years ahead. Regions with ambitions to become H2 Valleys are again mainly **in countries which already have substantial experience in FCH deployments, in particular the UK, Belgium, the Netherlands, Germany and France**. A significant number of project participants have expressed their intention to become such H2 Valleys in the future. Typically, these regions have a clear commitment to making hydrogen a cornerstone of their future green energy systems and are pursuing a clear ambition to realise large-scale deployments of the technology. In many cases, these ambitions are documented in existing local H2 strategies or roadmaps that also highlight existing stakeholder support to develop and realise relevant FCH deployment projects.

Figure 11: Geographical overview of envisaged FCH investments[36]

[35]Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

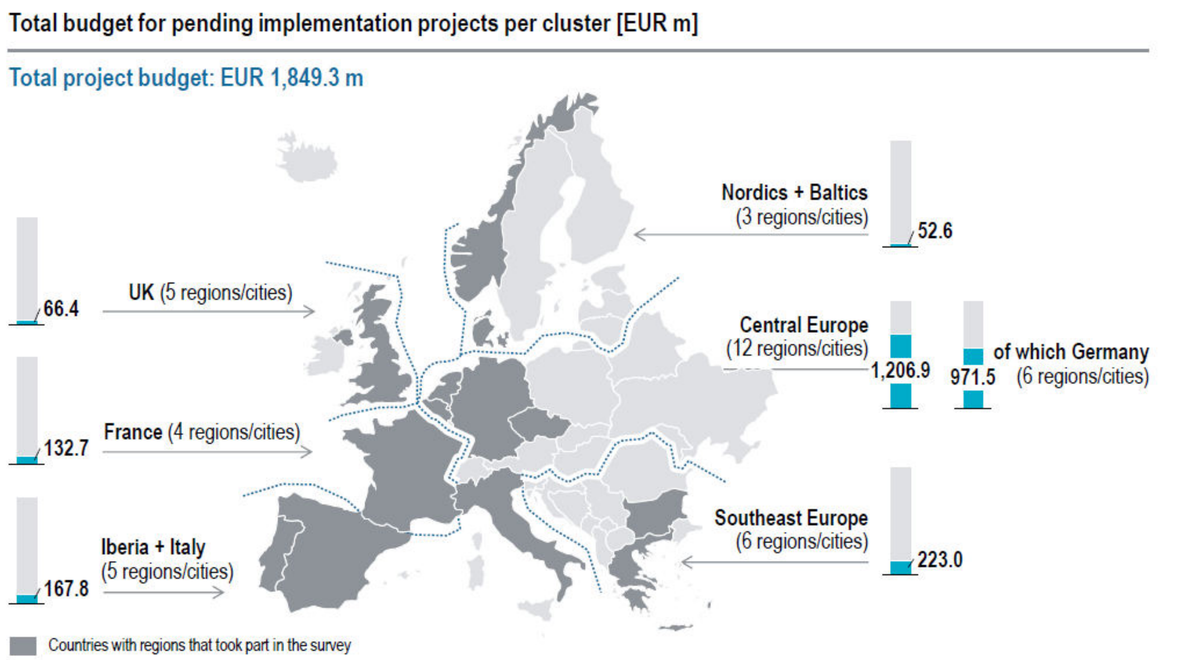
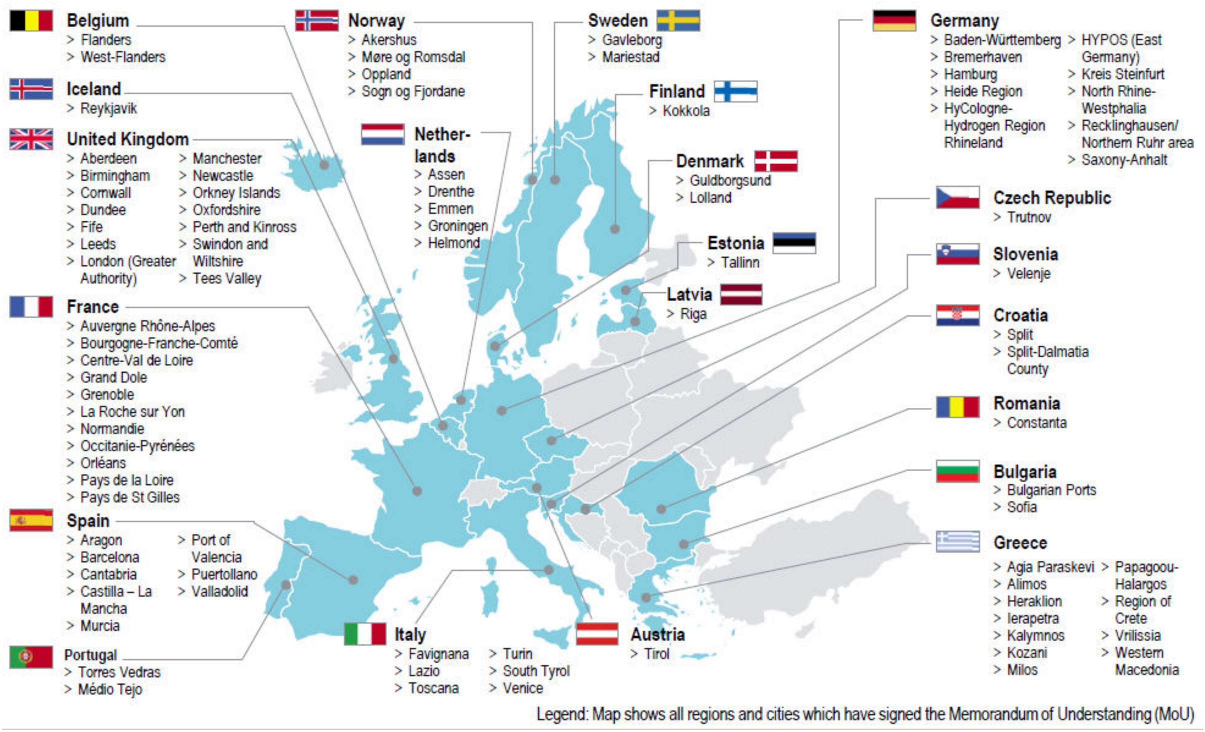


Figure 12: Overview of participating regions and cities as of May 2018[37]



36 05/10/2018 Fuel Cells and Hydrogen for Green Energy in European Cities and Regions; https://www.fch.europa.eu/studies

37 05/10/2018 Fuel Cells and Hydrogen for Green Energy in European Cities and Regions; https://www.fch.europa.eu/studies

3. Assessment and relevance for Europe

Due to the prevalence of on-site and near-site production, the current global position of the EU in terms of hydrogen economy directly correlates with its rank in major H2-consuming industries such as oil refining or fertilizer production. Diffusion throughout general energy supply markets could drive an even stronger localisation (on regional, national, and continental levels). While, global exchange on energy markets only occurs on significant scale for strongly concentrated resources (e.g. crude oil or coal), a renewable (low carbon or carbon free) hydrogen economy could guarantee the EU a certain share of the primary market (equal to its energy demand).

Pioneering stakeholders might earn global leadership in underlying technologies (e.g. scaling of electrolysers). Based on its extensive chemical industry, Europe may leverage its existing knowledge base and infrastructure. For instance, it features the largest hydrogen pipeline network globally.[38]

Nevertheless, with respect to fuel cell deployment, E4tech's 2018 fuel cell industry review claimed that Europe was lagging behind Asia and North America with respect to fuel cell deployment. Nevertheless, 2018 was the second year in a row where Europe was actually catching up in unit shipments (up 70% to 8,600 units compared with the previous year) but still lagging substantially behind in megawatts. In contrast, deployment of larger stationary units has been very limited Europe. This reflects some European strength in micro fuel cell applications on the back of FCH JU European project PACE-EneField and the German KfW433 funding scheme targeting the deployment of such technologies. Transport fuel cell systems in Europe benefited from about 300 OEM car sales, totaling 30 MW. More fuel cell buses also entered service, a trend expected to accelerate further in the near future. Importantly, Europe also saw the world's first passenger fuel cell train begin operation in Germany, with more units to come. Around 100 material handling vehicles were put in service this year, and announcements for the future are also positive. Maritime applications, light- and heavy-duty trucks are starting to show promise, with numbers expected to grow as soon as 2019. In particular, large-scale fuel cells manufacturing primarily exist in North America (e.g. Ballard Power, Plug Power) and commercial FCEV are mostly supplied by Japanese (e.g. Honda, Toyota) and South Korean (e.g. Hyundai) companies. In addition, also China recently has started to engage in hydrogen and fuel cell technology.[39,40]

3.1 Economic, Environmental and societal impact

The deployment and ramp-up of hydrogen has a positive ecological and societal impact for the EU. Currently, most CO2 emissions in the EU occur in the power generation sector (33%), transportation (32%), and industry heating and feedstock (15%). To achieve the 2-degree target, the EU needs to reduce its annual CO2 emissions by about 80% in 2050 compared to today's levels, dropping from approximately 3,500 Mt to approximately 770 Mt per year. According to the Reference Technology Scenario (RTS) of the International Energy Agency, existing energy- and climate-related commitments by European countries should close approximately 60% of the gap (around 1,700 Mt).

38NEW-IG (2011) Fuel Cell and Hydrogen technologies in Europe, https://www.fch.europa.eu/sites/default/files/111026%20FCH%20technologies%20in%20Europe%20-%20Financial%20and%20technology%20outlook%202014%20-%202020_0.pdf

39NOW (2018) Wasserstoff und Brennstoffzellen: Antworten auf wichtige Fragen. https://www.now-gmbh.de/content/service/3-publikationen/1-nip-wasserstoff-und-brennstoffzellentechnologie/180502_dossier-wasserstoff-und-brennstoffzellen_de_web.pdf

40Frost & Sullivan (2018) Fuel Cell Electric Vehicles: Genesis of a New Era or a Myth-Busting in New Energy Vehicle Technology?

However, reducing the remaining 1,100 Mt of CO2 emissions per year will require additional efforts beyond current commitments.

The ambitious scenario seeks to close the gap toward the 2-degree scenario further. In the ambitious scenario, the deployment of hydrogen as shown in the roadmap would reduce annual CO2 emissions by roughly 560 Mt.[41]Consequently, about half of the gap between RTS and the 2-degree scenario would be closed. With efforts in the transportation segment alone, the gap would shrink by more than 20%. Decreasing heavy duty and long-distance transport that generates high CO2 emissions would already lead to a significant reduction. In addition, heating and power for buildings as well as industry feedstock can significantly contribute to decarbonization. In the power generation segment, the direct impact of hydrogen on CO2 emissions is minor. However, in its systemic role for buffering and storage, hydrogen would enable the shift toward power generation from VRE, indirectly contributing to decarbonization.

In the business-as-usual scenario, hydrogen would close only 15% of the gap between the RTS and the 2-degree scenario. Based on our sector-by-sector analysis, abatement would fall short of approximately 400 Mt ofCO2 if hydrogen's role remains limited. As a result, either the 2-degree scenario remains out of reach, or reaching it comes at higher costs. Besides carbon abatement, hydrogen would reduce the need to import fossil fuels and improve energy security as well as trade balances. In end use applications, it would eliminate local emissions such as sulfur oxides, nitrogen oxides, and particulates, all of which contribute to smog formation.

Moreover, hydrogen can play an important role in limiting NOX emissions, which amount to an estimated 7.9 Mt in the EU today. In road transportation, responsible for roughly 40% of current NOX emissions, the substitution of normal vehicles by the projected hydrogen fleet in 2050 could reduce more than 0.5 Mt in NOX emissions.

Widescale hydrogen use has direct implications on many societal factors. For instance, in the EU, approximately twice as many people die because of high air pollution levels compared to road accidents and more than four times as many compared to Alzheimer's disease. Studies show that life expectancies decreaseby seven months when people breath air pollutants above a certain threshold. According to the World Health Organization (WHO), 90% of European cities exceed this threshold, exposing nine out of ten urban citizens to unhealthy levels of air pollutants. Surprisingly, this significant societal risk goes largely unnoticed by the broader public. However, first European cities have begun to recognize the high negative impact of air pollutants. While some European cities like Madrid[42], Paris, or Oslo have announced plans to ban private or diesel cars from their city centers, several cities have also launched initiatives to mitigate the risk Paris, e.g., has declared one day each year "car free," thus cutting NOX emissions by 40% that day. Also, Madrid and Bonn are currently rolling out projects to foster public transportation and its positive effects on traffic, emission, and air pollution reduction.[43] Substituting hydrogen for more conventional fuels would also reduce other nuisances, such as noise pollution in cities and water pollution in lakes, rivers, and ports.

41Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

42The city of Madrid already bans older, more polluting diesel and gasoline vehicles from entering city center.

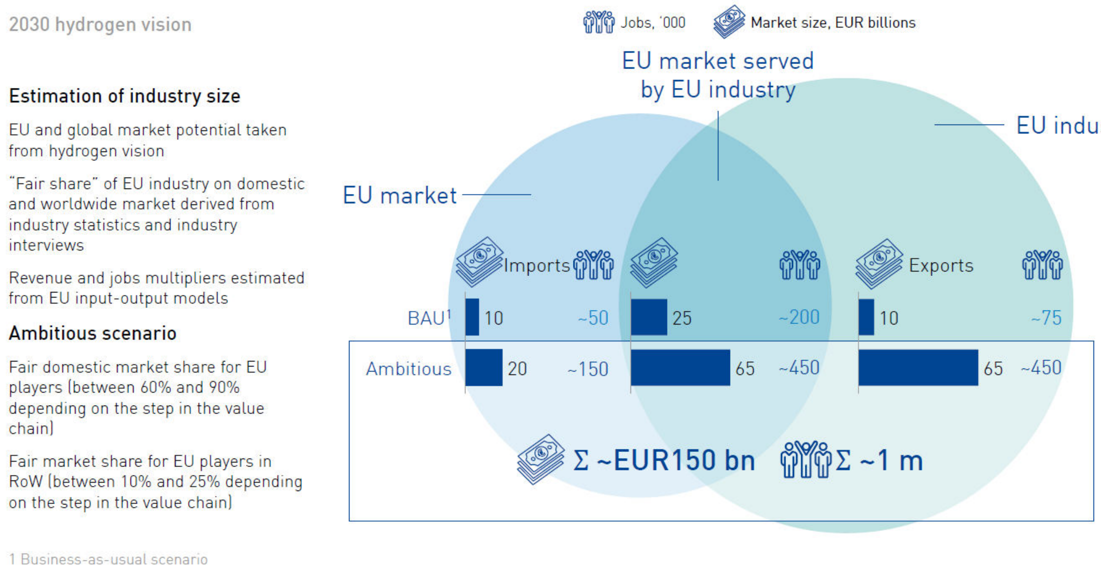
43Spain is developing a pioneering R+D project for the use of hydrogen in port machinery.

3.2Market trends, market size and structure (global size, share in the EU), employment and industrial competitiveness

Besides the ecological and societal impact, the deployment of hydrogen will create additional revenues and jobs for the European market. Moreover, the EU could retain its position as a leader in technology if it focuses on its industries' strengths and capabilities. The energy transition will fundamentally alter value chains in all industries. New skills, capital, and raw materials will be required. While some of these shifts are new economic opportunities, others pose serious threats to the European industrial landscape.

As concerning the expected global market trends, by 2030 hydrogen technologies are expected to probably power up to 1.5 million autonomous taxis, 700,000 autonomous shuttles, 8,000 vertical take-off and landing taxis (VTOLs), 3.6 million delivery trucks and provide up to 1 TWh of backup power for data centres[44,45]. As a vision, by 2050 and deployed at scale, hydrogen could account for almost one-fifth of total final energy, create a $2.5 trillion market for hydrogen and fuel cell equipment, and provide sustainable employment for more than 30 million people.[46]

Figure 13: REVENUES AND EMPLOYMENT IN THE HYDROGEN ECONOMY (in Europe), 2030[47]



In any case what can be seen is that one shift of particular importance is happening in the automotive industry. The automotive industry currently employs around 2.5 million people in Europe directly and 10.8 million people indirectly. As the value creation in automotive shifts away from the powertrain towards energy storage – 30% of a passenger car's value – so do jobs and investments. As Europe lags behind in battery technology, it faces a serious threat to lose a major part of its competitive position in the automotive industry. In hydrogen and fuel cells, the European industry consists of world-class players along the value chain. European companies have strongly invested in research and development, provide leading technology solutions and are renowned for their fuel cells across the world. If Europe remains at the forefront of this development, European players will be able to retain global market shares.

44Hydrogen meets digital, Hydrogen Council, 2018, report prepared for the Global Climate Action Summit

45http://hydrogencouncil.com/global-hydrogen-leaders-forum/

46http://hydrogencouncil.com/hydrogen-scaling-up-new-roadmap-launches-at-cop-23/

47Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

Along with these investments, the industry could also generate significant revenues. Equipment and hydrogen sales in transportation would account for more than 40% to overall customer spending. 40% of spending would also relate to hydrogen sales for new feedstock. Equipment sales for buildings heat and power as well as industry energy, however, would still be in a ramp-up phase. Taking also supplier revenues into account, our roadmap would create a market worth EUR 85 billion in 2030. EU industry is expected to be able to capture about 3/4 of that market, and also participate in the global market, adding another EUR 65 billion in revenues from exports (see Figure 13).

With its engineering know-how and capabilities, the European industry is best qualified to enter the production of hydrogen and distribution equipment. Thus, it should focus on the manufacturing of electrolysis equipment and the corresponding development of distribution infrastructure. Given their strengths, EU players could potentially achieve market shares of 75 to 90% in domestic European revenues. Moreover, EU players would be able to generate significant revenues from exports, reaching for a market share of 25% in markets outside the EU due to their technology leadership in these fields.

Regarding specialized materials and components like fuel cell stacks, the European industry should focus on building up further skills, but also on achieving economies of scale. Components need to drop in costs to enable mass market acceptability of end use applications.

As described, most of the value creation in a hydrogen economy would occur in advanced industries. These industries create more employment and domestic value than the value chains of fossil fuels – directly, indirectly, and through implied effects. To derive potential jobs from the deployment of hydrogen, the study used the number of jobs per euro revenues in industries similar to segments in the hydrogen industry.

For advanced industries such as machinery and equipment, automotive, electricity, and gas supply, roughly ten jobs are created directly and indirectly per EUR 1 million in revenues. For the manufacturing of equipment and end use applications, on average 13 jobs are created per EUR 1 million revenue. In aftermarket services and new business models, EUR 1 million in revenue generates 15 jobs.

Considering this revenue, the European hydrogen industry would employ more than approximately one million people in 2030 (the European hydrogen industry definition of this study is much wider in scope than the one assumed for the FCH Value Chain Study – e.g. the latter is limited to a single hydrogen production pathway, i.e. water electrolysis). About 500,000 jobs would be generated in the manufacturing of hydrogen production and distribution equipment as well as in infrastructure setup for end use applications. Jobs in these fields require mostly highly qualified people, engineering capabilities, and technical know-how. Roughly 350,000 additional jobs would be associated with the value added through fuel cells, specialized components, and end use applications, for instance, in the production of vehicles based on the fuel cell powertrain or in equipment retrofit for industry heat. In addition, by securing a competitive position in FCEVs, the European automotive industry with its infrastructure, production capacities and capabilities will be retained, while a switch to only BEVs risks delocalization of value chains overseas.

Based on its current technology leadership, the European players have the potential to retain their leading positions in technology development and build a strong industry for hydrogen and fuel cell technology, recognized both within and outside the EU.

3.3 PERFORMANCE OF THE SUPPLY CHAIN COMPARED TO MAIN COMPETITORS

Europe is well positioned in almost all aspects of FCH, at least on a par with its peers in most applications and technologies, and ahead in some aspects. A few areas of weakness or limited investment exist.

For example, the leading OEM integrators for **FCEVs** are in Asia, with Hyundai, Toyota and Honda all well advanced. Daimler is currently the only European OEM with a 'commercial' product, in very limited production, though Audi, BMW, Fiat and others have suggested that they may have vehicles around 2020. Europe does however have several entrepreneurial integrators targeting different applications: French company Symbio offers converted Renault Kangoo vehicles with range-extender fuel cells and Renault is now widening this option to other light goods vehicles, German company Streetscooter intends to produce FC range-extender electric vehicles and UK-based Riversimple has designed a car from the ground up. Japan and Korea do use European suppliers when appropriate, though are very focused on developing local alternatives, and specifically support their local supply chain actors. In the near term, Chinese firms are looking for Joint Ventures and technology transfer as they ramp up production, evidenced by the strong relationships held by Ballard, Hydrogenics and other (originally) non-European fuel cell manufacturers in China; the engagement of Impact Coatings of Sweden for a specialist coating line; and initiatives such as the German-based company Fuel Cell Powertrain, which was started using Chinese investment. Other European firms could potentially use this opportunity to develop technology and export markets and also gather valuable in-use performance data.

Europe is well placed in **fuel cell bus** development, having seen the majority of the early roll-out, though China is now deploying more vehicles. European manufacturers have been largely dependent on Canadian technology from Ballard and Hydrogenics for stacks and subsystems, though Europe has suppliers (e.g. Proton Motor) developing these capabilities and who could fill this gap if the technology can be suitably well proven. Costs remain high, in part due to small historical order numbers, though this is changing through larger orders. These larger numbers are typically the result of local, national or international programmes, such as run by the FCH JU. Gaps remain in areas such as integration know-how and capacity, as the small numbers of buses made in Europe thus far have mainly been individually hand-built. In many places a gap also exists in bringing together the right funding to allow local bus operators to take advantage of the technology. More broadly, a gap exists in availability of skilled integration personnel and in financing for public transport authorities to make the transition to these currently expensive buses.

Fuel cell **forklifts** were one of the earliest fuel cell applications to be commercialised, in a market niche which values rapid recharge and zero emissions. They fall under the broader category of material handling equipment, which also includes ground support equipment at airports and seaports. In Europe, H2Logic's activities were taken over by Ballard through Danish subsidiary Dantherm and a collaboration continues with Taiwanese company M-Field. Linde also manufactures FC forklifts. The potential exists in Europe for FC forklifts to be produced and deployed, with an important gap in demand related to the comparatively weak economics of the systems. This may require costs to come down before it can be resolved, if novel or integrated business models are not developed. European developers such as Proton Motor have ceased development activities in forklifts, but indigenous capabilities exist should the market evolve.

To simplify this analysis, **heavy goods vehicles** (HGVs) are those weighing more than 3.5 tonnes, a broader definition than in many instances, including both medium duty and heavy duty trucks. Although some specific component sizes and architecture will differ, enough similarity exists to consider them jointly here. In Europe, a few trucks have been integrated, including Renault Maxity, Scania and MAN vehicles, the latter modified by ESORO. Stacks come from Symbio, from PowerCell and from Hydrogenics. These are conversions by specialist external integrators, and no truck Original Equipment Manufacturer (OEM) is currently building vehicles, though some are showing interest. However, others are more, aggressive evidenced by Hyundai's announcement of 1,000 trucks for Switzerland starting in 2019. Nikola Motor of the USA is designing and developing its own long-haul unit with stacks from PowerCell in Sweden. Suitable hydrogen storage for heavy, very long-distance driving is not yet available however, either in Europe or globally. If liquid hydrogen is chosen, liquefaction capacity could become a bottleneck, but this will take some time to materialise.

In Europe, Germany has taken a global lead in implementation, and regional **trains** powered by hydrogen fuel cells are now in operation. The trains are made by Alstom and fuel cell systems come from Hydrogenics. Ballard has also announced a tie-up with Siemens aimed at the same market. The Alstom and Siemens rail businesses have announced a merger, still in process, which would potentially affect this nascent supply chain. One reason for the merger was to compete better against emerging Chinese competition in rail. In general, rail systems are built around existing architecture designed for bus and heavy-duty uses.

Fuel cells used in **maritime** and inland boats could help make significant reductions in GHG emissions and to mitigate a significant source of smog producing pollutants near port towns. Fuel cells could be applied for both propulsion and hotel loads, but the former is likely only for relatively short journeys (e.g. ferries) in the near term. There have been several shipboard fuel cell power demonstrations, primarily in Europe. PEMFC and SOFC are the primary fuel cell chemistries considered, while MCFC has also been demonstrated but does not appear to be preferred for this application. Maritime propulsion is the focus of this study, and PEMFC is attracting considerable interest for this application. SOFC and MCFC are not examined here, as their on-board use for hotel loads is very similar to conventional stationary applications. Europe is probably marginally stronger than many other regions as this area has been a focus for some time, even though activity has been limited.

Europe has several **Hydrogen Refuelling Stations (HRS)** integrators with a global reputation and reach, including Linde, Air Liquide, Nel (H2 Logic) and ITM Power. Europe is also well positioned across most key components in HRS, and some European actors are working on the development of new components (e.g. the dispenser and hosing). There is still a lack of flow meters that meet the accuracy requirements of weights and measures authorities, but there is relevant development activity by some European actors. Other areas, such as in-line purity assurance remain an area of R&D activity, also by component developers. Europe has several hydrogen compressor suppliers to choose from, including some with novel compression technologies. Europe suffers from the same gaps as other global regions, so is not specifically at a disadvantage, but successful development and commercialisation of higher performing and lower-cost dispensing equipment, hoses, metering equipment and sensors would position Europe well. Other gaps include test capabilities to ensure HRS meet tough standards for refuelling protocols, and a service infrastructure for installed HRS. The availability of reasonably-priced and reliable compressors is a gap here and in other applications.

For m**CHP** Europe has strong heating appliance integrators with varied but increasing degrees of participation in fuel cells. Many have a long history in heating appliances (e.g. boiler manufacturers) and in technology integration, but very few have in-house fuel cell stack development. No European player has the depth of experience that is found in Japan, and European PEM stacks and systems are in the early stages of (subsidised) 'commercial' deployment. Some actors have even stopped in-house activity, preferring to source from and partner with the strongest providers globally, who are typically Japanese players (e.g. Panasonic). Although many systems installed in Europe are hence based on imported technology, these are adapted for European conditions and certified locally, with some components also locally sourced. After Japan, where the Ene-farm programme has led to massive micro-CHP deployment in recent years, Europe, and in particular Germany show the highest activity internationally, both in terms of breadth of technology suppliers as well as efforts to roll out systems into the market.

Europe is well-regarded in **SOFC for mCHP**, with several strong players throughout the supply chain. In addition to its own developments, SOLIDpower acquired an established Australian technology with production in Germany, although some components come from other regions, e.g. China. Ceres Power does not yet have a full commercial product but has important partnerships within and outside Europe, which could result in significant export markets in addition to local sales. Other developers are at different stages of progress, including Viessmann, which is embarking on a new iteration of the SOFC system it already has on the market, Sunfire and Bosch. European actors have strong skills in system modelling, reactor design, catalysts, cell materials and other areas, on a par with other global regions.

There are very few PEM commercial **FC prime power and CHP** integrators either in Europe or globally. The German company RBZ Fuel Cells has developed a small commercial 5kW PEM CHP unit. Nevertheless, this area is considered as potentially a stronger market than micro-CHP: the specific cost of the units can be lower because of balance of plant scale effects; and the business case may be better as more consistent heat and power loads can enable higher utilisation factors.

Alkaline FC (AFC) systems are actively developed in Europe at AFC Energy, targeted at large-scale applications. The units are at an early stage and the supply chain is still evolving, but since very few organisations are developing this chemistry the supply chain is somewhat ad hoc. Israel’s GenCell has commercial units of around 5kW for sale, but no known work is going on elsewhere. Export opportunities for Europe would mainly be around sales of complete systems to other countries, not of components.

European **large PEM** has thus far only been deployed by Nedstack in China, as part of the FCH JU project DEMCOPEM-2MW. It requires some further development and optimisation before it is fully commercial. Whilst CHP is an option for these plants, in practice they are likely to operate in power-only mode unless a suitable local heat requirement exists. This affects the economics both because less of the input energy can be used, but also because the non-CHP system is lower cost.

Europe has limited product development in **large-scale CHP** more broadly. AFC Energy is building final systems, much like Nedstack, but these are at demonstration stage and not yet mass produced. Again, they have an almost completely different materials and component supply chain from other fuel cell types. FuelCell Energy is primarily engineering systems produced in the US, but also has some integration capacity in Europe, and Doosan Babcock uses units from its parent company Doosan, which have largely US and Korean technology, though the catalyst supply is European. Europe has good engineering firms capable of putting these systems together and some deploy outside Europe, but the markets to date have been very small.

Fuel cell systems used for **emergency and off-grid power** are in many cases commercially available, up to a capacity of 10kW. These are often used for telecoms systems and end-uses that require an uninterruptable power supply (UPS). The majority of such systems are PEMFC and DMFC, though AFC plays a small role, and a few specialised SOFC systems are also deployed, though not in Europe or produced by European companies. One industrial actor, SFC Energy, produces DMFC systems for this application, for example for military and recreational customers. They are differentiated from other stationary systems because they run intermittently, requiring different systems configurations, lifetime and durability. Small but growing markets for FC back-up power and gensets exist in North America and Asia in particular, and for specialist systems such as emergency services grid networks in Europe. Countries with particularly unreliable grid connections or areas without grid connection may offer good business cases for back-up or off-grid systems. This favours sales in developing and emerging markets. The market in Europe is not as attractive, partly because of the generally good reliability and coverage of the electricity grid networks in European countries.

Europe is well positioned generally in **electrolysis.** Alkaline electrolysis is commercially proven as a base-load hydrogen generator, and suitable system design makes it viable also for more variable and intermittent operation profiles. Europe is one of the leaders in today's global alkaline electrolysis industry with the two major manufacturers, Nel and Hydrogenics, producing in Norway and Belgium respectively, and with other companies such as McPhy gaining momentum. Major players such as ThyssenKrupp have technologies used for chlor-alkali production which could be used for water electrolysis. China, Japan and the US also have production capacity, but are less active in the global market than the European actors. European companies are positioned well to benefit from market growth.

PEM electrolysis is a much younger technology than alkaline, though it has benefitted from PEM FC research and development. Its commercialisation was pioneered in the US, building on developments for the military. Several North American companies have developed technology or products including Giner, now in partnership with Spanish company H2B2, and Proton OnSite, now owned by Norway's Nel, as well as Hydrogenics in Canada. European developers such as Siemens, Areva, and ITM Power are commercialising their own PEM electrolysers, most of them in view of expected market growth as part of the energy transition. There is little public information on sourcing of components by the system integrators, but many of the supply chain companies currently supplying PEM fuel cell integrators also offer components for PEM electrolysers. This means that Europe is well positioned all along the PEM electrolyser supply chain, however, the electrolyser-specific supply chain is in general less developed than that for PEM fuel cells.

SOEC is globally at the technology demonstration stage, and European actors appear to be leading commercialisation. There is some activity in the US, but Europe is ahead with Sunfire, Sylfen, Haldor Topsoe, and SOLIDpower all engaged, for example. Given the early stage of the technology it is not yet clear what role SOEC will play in the future mix of electrolysis technologies, though in principle it could help to bring down costs and raise (electrical) efficiencies significantly. Similar to SOFC, Europe has a breadth of suppliers and developers with excellent knowledge of the technology and the key stack components, though few of the European suppliers have experience with larger volume manufacturing.

Europe has strong skillsets in a wide range of **hydrogen storage technologies** at many scales, including world-leading science in novel storage technologies. Europe is generally well-positioned, with suppliers or developers in relevant areas, though weaknesses in the supply chain exist. For example, although compressed storage appears to have many players, not all produce tanks in Europe. Hydrogen compressed tank supply has some strong Asian and North American actors, with specialist materials, notably high-grade carbon fibre, coming more from Asia. Valves and regulators are an important area for cost reduction and good opportunities exist for export, though there are few suppliers generally and both the regional and the global supply chain need strengthening. Europe does, however, have a base of high-quality balance of plant component suppliers such as OMB Saleri in Italy and Pressure Tech in the UK, which would be well positioned to supply a growing market. The main gaps in hydrogen storage are related to the availability and cost of tanks and some other components. Carbon fibre availability is a bottleneck and European-based supply could alleviate some concerns about supply risk. Europe's relatively limited industrial supply base is being augmented by new entrants, but these are primarily looking at tank manufacture and supply, and less at materials. Manufacturing scale is also lacking, though it would be comparatively straightforward to increase existing capacity given investment. The broad availability of low-cost reliable components such as regulators would also help advance the industry and support Europe's competitive position.

As interest in large-scale renewable or low-carbon hydrogen grows, methods of storing and transporting it, particularly for long distances, become more important. **Liquid organic hydrogen carriers (LOHC) and ammonia** are increasingly considered, though very few LOHCs are under serious development. Nevertheless, they could form an important part of the future value chain. Europe has conventional industrial strengths in ammonia technologies, plus some smaller-scale developers, and one or two organisations developing LOHC, including Areva and Hydrogenious. LOHC and Ammonia are in the early stages of development as hydrogen carrier technologies. The supply chains are relatively straightforward, and currently somewhat ad-hoc, driven by the product integrator. In a currently very limited application space, Europe is well placed in terms of both industrial actors and knowledge and research based actors (KBAs), including those on reaction chemistry and catalysis.

Performance of other regions including Japan, Korea, China and North America can be found in chapter 4.2 of the FCH Value Chain Study's Findings Report[48].

As per chapter 5 of the above mentioned Findings Report, criticality and cost assessment of a number of FCH components was analysed.

All applications contain a very large number of components, some of which are not unique to FCH, and some of which are already manufactured in large quantities. To identify the most important areas in FCH for Europe, and to render the analysis manageable, it was constrained in several dimensions. Applications with small markets were not analysed in detail; areas with European supply chain strength were prioritised, and only a subset of components was analysed in depth. A short list of 'critical' components was drawn up using a scoring approach described below, and then only a subset of 'selected critical' components within that short list was analysed in detail.

All components are of course vital to the final application, and so this exercise was *not* designed as a ranking of where research funding or other support should be allocated. Alongside this, it is of course impossible to find a perfect definition of 'criticality', or a score that all stakeholders will agree with. However, the selected components are considered representative and suitable for this analysis, in that they span a range of technology areas and supply chain positions and offer transferable insights into the wider potential for the sector. The focus allowed a meaningful depth of analysis for the selected components, and simpler communication of the results and conclusions.

This analysis considers value add for Europe and not only technical performance, socioeconomic and market considerations were included in the six ranking criteria:

- **Performance** –system performance is significantly affected by component or sub-system performance.
- **Cost** –the component or sub-system represents a significant fraction of the system cost.

[48] E4tech, ECORYS and SA-Strategic Analysis (Fuel Cell and Hydrogen Joint Undertaking; publishing waiting final approval by the Governing Board of the Fuel Cells and Hydrogen 2 Joint Undertaking), Value Added of the Hydrogen and Fuel Cell Sector in Europe: supporting European growth and competitiveness. Draft final versions, including the Evidence Report, the Findings Report and the Publishable Summary accessed 15 Mar 2019.

- **Technical Evolution** –the component or sub-system is undergoing or is expected to undergo technological evolution that will lead to significant cost reduction or system performance improvement in the near-term.
- **Supplier Base**–there is a limited supplier base of appropriate quality or the supply base is controlled or concentrated in one global region.
- **New Market** –growth of the fuel cell and hydrogen market would result in a unique new market for the component or sub-system.
- **Socioeconomic Impact** –the component or sub-system represents a unique area of job growth.

For each application, a representative system and list of components was defined, and the components tested against the six critical characteristics above, informed by cost analysis literature, the team's collected knowledge and data sets, and external experts as needed. A score of 1 (meets the definition) or 0 (does not meet the definition) was assigned to each characteristic, and components that scored 4 or above were deemed 'critical'. This subset of components would generally be intuitively familiar to an expert in the field.

The majority of 'selected critical components' score 6, i.e. they meet all of the assessment criteria. In a few cases they have been promoted to help inform the analysis, for example where there is a clear economic interest in Europe. For example, while pressure vessels scored lower than some components, they were selected as critical components given their importance in enabling the spread of multiple applications.

3.4 VC COVERAGE/FRAGMENTATION AND NEED TO COVER VC (INTEGRATION OF THE VALUE CHAIN INTO THE GLOBAL VALUE CHAIN(S)) RELEVANCE AND IMPLICATIONS FOR SMES

Maintaining and increasing the value to Europe largely depends on support and deployment in Europe

Even using a relatively narrow definition of value-added activity, the analysis shows that support within Europe is essential to allow the greatest value capture. If global growth is strong but Europe takes a laissez-faire attitude then Europe exports less overseas, and overseas companies export more into Europe. If global growth is low but Europe has strong internal support, European companies capture a greater share, but of an inevitably smaller market. By supporting both deployment (helping to increase the global market by increasing the European market) and the positioning and growth of companies, Europe has the greatest chance of capturing long-term value. This value is likely to go elsewhere if either is lacking, as other regions will develop more mature capabilities and supply chain clusters.

As an example, analysis of existing conventional supply chains shows that whilst mature supply chains for some products are global, for others (such as cars) supply chains gravitate towards the control of the original equipment manufacturer (OEM), and towards the country or region of deployment. So OEMs tightly control supply chains, which can include design and assembly in-house and partnering with suppliers on design, optimisation and even investment. For high volume production suppliers of appropriate components will co-locate with final assembly plants. So as the fuel cell industry and its supply chain mature, it could become increasingly hard for EU component suppliers to sell to non-EU OEMs, as these OEMs build and strengthen internal and local capabilities. With this in mind, support measures targeted at driving deployment in the EU could serve to activate the supply chain. For instance, the detailed value-added analysis suggests that a significant fraction of the value added can be captured for both FCEVs and HRSs provided the FCEV and HRS system assembly occurs in the EU. A coordinated vehicle and refuelling station deployment programme could (a) help directly capture the value in those applications, and (b) could also support the development of an ecosystem of upstream sub-system and component suppliers. Following standard automotive sector practice, these would likely be local in the longer term. This would also position EU component suppliers to supply both EU and non-EU OEMs located in Europe.

For many other applications, OEMs have less power, and supply chains are likely to be global, so EU suppliers will rely less on EU deployment for sales. Nevertheless, deploying fuel cell and hydrogen applications in the EU will strongly support their development, through providing experience and direct feedback from local markets. It will also enable provision of support services such as installation, maintenance and fuelling, all of which generate significant value and employment, and help inform the activities of the knowledge-based actors.

Many fuel cell and hydrogen applications will also benefit from supply chain support

European companies and researchers are active in most areas of fuel cell and hydrogen supply chains, and are strong in many of them. Gaps do exist though, both in areas where the EU is behind other regions, or where there are no strong players globally. This brings opportunities for European companies to build positions, and different types of support could help them to do this. This would typically fall under existing mechanisms such as accelerated depreciation for capital equipment, simplified or standardised permitting for manufacturing plant, or favourable tax regimes for manufacturers and suppliers.

However, support should be given judiciously. Given that many supply chains will be global, it is neither necessary nor plausible to try to construct a whole supply chain only from EU companies. A better outcome will come from a focus on areas of strength, need, or competitive advantage. For example, European car OEMs are not leading in FCEV, though some have interest and programmes. Nevertheless, the Tier 1s and other actors in the supply chain are strongly engaged and are supplying globally. But even if non-European OEMs deploy vehicles in Europe in response to policy measures, they are likely to use local production capabilities and even European supply chain companies, if these have already built a strong position.

The picture in stationary fuel cell systems is mixed, with the production and supply of large systems currently dominated by US and Asian manufacturers. Some European companies are well positioned in micro-CHP, and looking to enter overseas markets, and the commercial CHP sector (tens to about 100MW) is considered a very promising opportunity, scaling up from already-developed micro-CHP technology. Europe is well positioned in SOFC in particular.

Hydrogen refuelling stations (HRS) stand out as an opportunity of both potentially high total value and of added value, but it is important to note that the figures for HRS in this study include the total cost and value added for installation of the station, and not only production of the systems. Nevertheless, installation benefits may only arise if the supply chain is supported, so that competitive systems can be produced.

Electrolysers are a further area where Europe is well-placed, in part thanks to indigenous technology developed over many years, and in part because European support schemes for both electrolyser-based HRS and for stationary applications such as power to gas have been more consistent than in many other regions, allowing supply chain capacity and expertise to be developed.

The FCH sector offers Europe a chance to benefit economically and environmentally from an emerging industry and strengthen its position in clean technologies generally, but only if it is appropriately supported

The FCH sector contains many large and small players globally, and many applications are on the verge of economic competitiveness after years of investment and development. Major industrial nations such as Japan, Korea and the US are strengthening or developing positions, and China is emerging rapidly. Europe is well positioned to profit from European component and system manufacture, both for European deployment and export. Scenarios developed in this study show likely markets of multiple billions of Euros. Europe will also benefit from deploying overseas technology locally, both through environmental improvements and through local employment, though to a lesser extent.

This study has looked in some detail at hundreds of organisations, multiple FCH components and applications, and a range of different growth scenarios. This breadth means it is not appropriate to make specific recommendations for regions or actors, as they depend strongly on local conditions. However, the analysis allows for general recommendations about areas of the industry and the kind of support that could allow Europe to capitalise on the strong base and high levels of interest in the sector. These include:

- Co-ordination of EU and national visions, to allow companies and other entities to optimise incentives and investment for transport and infrastructure;
- Market activation support, to help crystallise demand and allow supply chains and economic benefits to build around it;
- Supporting FCH in transportation applications, not only in cars but also in heavy-duty applications such as trucks, trains and marine use. This should help both strengthen multiple parts of the component supply chain and ease the roll-out of infrastructure through creating large local demand nodes;
- A continued focus on rapid development of appropriate standards and regulations, to ensure wherever possible that deployment is not held up by either, and that standards across different sectors do not conflict;
- Engagement of the finance sector in providing suitable – and potentially innovative – financing for scale-up and deployment, where capital requirements are high for small companies, or loan guarantees may be needed to overcome risks inherent in an emerging technology;
- Support for companies capable of producing competitive heat and power solutions, whether in the residential, commercial or industrial sectors. Measures here could include scale-up support, or market mechanisms that fairly value all of the benefits that such technologies bring (lower CO_2 emissions, air quality benefits, grid support capability);
- Urgently addressing the skills gap that is emerging in the sector, by ensuring it is communicated as a good opportunity for future employment, plus supporting dedicated training and certification, and early introduction of relevant subjects into curricula;
- Aligning electricity markets and regulations with the stated need for low-carbon hydrogen, by reducing or removing tariffs and levies on electricity that render the hydrogen produced expensive, where these costs are not justified or are double-counted;

- Stimulation of local integration and manufacturing capability for HRS and compressed hydrogen storage; plus support for export if appropriate.

These generic recommendations need to be translated into specific actions to be taken by given actors, and timing assessed. To do this effectively requires a good understanding of local conditions and individual actors. What is right for one company and one country or region will not suit another, and so such specificity is not attempted here. Under all circumstances, some level of co-ordination at EU level will be important, useful and advisable.

The FCH sector is poised to grow, and Europe is still well positioned, but capitalising on Europe's opportunities requires timely action

FCH technologies can act as a strong complement to other 'clean' technologies and help provide a system solution which improves performance across a very wide range of sectors, meeting a range of policy objectives. Multiple indicators suggest that the FCH sector is starting to grow, and poised to grow fast. In fact, this growth must be relatively rapid to create both the size of industry and the mature supply chains required for it to be self-sustaining. The supply chain is currently global and likely to remain so, and Europe's position within it is strong.

To grow – or even maintain – this position will require European actors to invest, both politically and financially, in deploying products locally and in strengthening research, technical and manufacturing capabilities. Letting other regions take the lead will dramatically reduce the chances of Europe profiting – either from an industrial or an environmental perspective – as a smaller proportion of global value will be captured, and fewer products will be deployed locally. If Europe wishes to profit from FCH technology as well as benefit from the environmental improvements it can help to bring, it should act now.

3.5High-risk and capital-intensive nature of investment needs

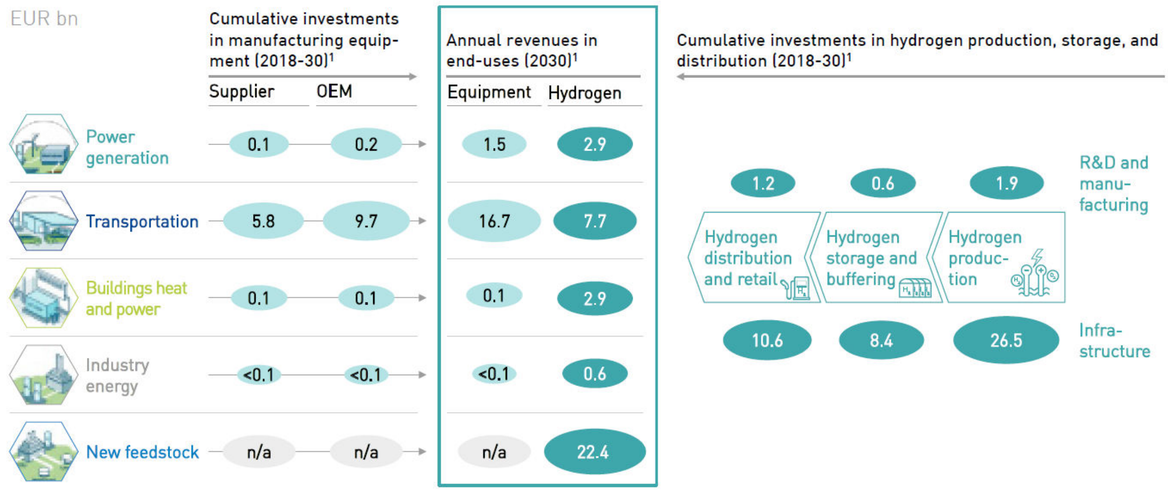
The most-recent hydrogen roadmap for Europe, commissioned by the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU), estimates the amount of required investments to set up an ambitious hydrogen-based economy throughout Europe at about EUR 60 billion by 2030. The main part of this sum, i.e. about 40 %, would be required for setting up infrastructure and equipment for hydrogen production and distribution, mostly for building hydrogen production plants like electrolysers and steam methane reforming plants. The other areas bigger in size would fall into hydrogen distribution and retail in transportation as well as heating for buildings and industry (ca. 25 %), the development of new fuel cell electric vehicles (FCEV) and non-road transportation as well as the respective CAPEX for production lines (ca. 15 %) and into aftermarket services (about 7 %)

Overall, the accessed studies leave the impression, that hydrogen-based mobility is a key aspect of a future hydrogen economy. As an extensive hydrogen economy already exists today and both present and other futures hydrogen utilisation forms will probably expand as well, this observation might be misleading.[49]However, broad diffusion of hydrogen technology in the transportation sector might represent the single most significant driver to expansion and decentralisation of hydrogen generation. Certainly, it will necessitate the build-up of an extensive distribution and retail infrastructure, which does barely exist so far.

[49]Ball M, Weeda M (2015) The hydrogen economy – Vision or reality?: 1 1This paper is also published as Chapter 11 'The hydrogen economy – vision or reality?' in Compendium of Hydrogen Energy Volume 4: Hydrogen Use, Safety and the Hydrogen Economy, Edited by Michael Ball, Angelo Basile and T. Nejat Veziroglu, published by Elsevier in 2015, ISBN: 978-1-78242-364-5. For further details see: http://www.elsevier.com/books/compendium-of-hydrogen-energy/ball/978-1-78242-364-5. International Journal of Hydrogen Energy 40(25): 7903–7919. doi: 10.1016/j.ijhydene.2015.04.032

Another challenge to a possible future hydrogen mobility scenario lurks in recent boost in public interest in battery technology and battery electric vehicles. Currently fuel cell technology is lagging behind the speed of battery technology development and deployment, and thus in the risk a being left behind. On the other hand, there seems to be potential for synergies, as both technologies could complement each other:[50] While hydrogen-fuelled vehicles seem preferable for heavy load or long distance applications (e.g. busses, trains, ships), battery electric vehicles seem superior in low to medium-range applications.

Figure 14: INVESTMENTS OF EUR 65 BILLION REQUIRED UNTIL 2030 ALONG THE VALUE CHAIN[51]



1 Including investments/revenues in aftermarket services and new business models (assumption: 8% of investment/revenue)

Beyond the rather specific issues of hydrogen mobility, the European Commission points out the special techno-economic challenges, which the FCH lists as its objectives:[52]

1. Reducing the production cost of fuel cell systems to be used in transport applications, while increasing their lifetime to levels competitive with conventional technologies,

2. Increasing the electrical efficiency and the durability of the different fuel cells used for power production, while reducing costs, to levels competitive with conventional technologies,

3. Increasing the energy efficiency of production of hydrogen mainly from water electrolysis and renewable sources while reducing operating and capital costs, so that the combined system of the hydrogen production and the conversion using the fuel cell system is competitive with the alternatives available in the marketplace,

4. Demonstrating on a large scale the feasibility of using hydrogen to support integration of renewable energy sources into the energy systems, including through its use as a competitive energy storage medium for electricity produced from renewable energy sources and

50Robinius M, Linßen J, Grube T et al. (2018), Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles

51Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

52Fuel Cells an Hydrogen Joint Undertaking (2018), Vision & Objectives. Accessed 14 Dec 2018

5. Reducing the use of the EU defined "Critical raw materials", for instance via low or platinum[53] free resources and through recycling or reducing or avoiding the use of rare earth elements.

Considering public financial support, the IEA advises to tailor policy support to the specific phase of the innovation/deployment cycle and to technology maturity/market uptake: technology push mechanisms for less-developed innovation (e.g. high temperature fuel cells and electrolysers), long-term R&D funding technologies to scale-up and the mobilization of private investment for post-commercialization deployment.[54] Similarly, in its "Roadmap for financing hydrogen refuelling networks", Roland Berger lays out the need for initial public investments, which should make way for private investments in later phases. In addition, the authors provide an array of different financing options.[55] The most-recent Hydrogen2 roadmap for Europe proposes the implementation of "a regulatory framework that provides clear, realistic and binding long-term targets for zero-emission products and processes" to enable investments.[56] Hydrogen Europe suggests that an IPCEI on the production, logistics and use of H2 in the Benelux countries, France, Germany, Austria and Switzerland could prove a catalyst for developing a European hydrogen economy. Moreover, it points out that the investments on a possible IPCEI project would roughly cover 1/5 of the required investments as specified by the before-mentioned hydrogen road map.[57]

3.6Use of advanced technologies – R&D status: TRL/maturity, R&D needs, technology barriers/challenges, producability, time to market, disruptive potential

Chemical storage has shown rapid development in Europe in recent years. Considerable funding from both the EU and its Member States has created a vibrant research community in the production, storage, and conversion of hydrogen, which can be re-electrified via fuel cells. As with batteries, new innovative materials and devices have created a range of technological options for exploitation for industry. Many projects in Power-to-Gas are emerging in Germany and other European countries. Indeed, the majority of hydrogen storage projects worldwide are currently installed in Europe. Most demonstration projects envisage the use of hydrogen for mobility purposes or wholesale via gas grid, but only a few of them include large-scale storage and electrification in their scope.[58]

Electrolyser technology uses electricity to split water (H2O) into hydrogen (H2) and oxygen (O2). Alkaline electrolyser technology is well known and has been utilised for about a century. Higher power density and efficiency is obtained with proton exchange membrane (PEM) cells. Recent developments include high temperature ceramic electrolysers based on solid oxide technology, which can make use of CO2 and produce syngas or synfuels. In addition, plasmachemical conversion or plasmolysis to split CO2 or water through vibrational excitation of the molecules in thermal non-equilibrium has been shown to be possible. Another development is photo-electrolysers that can direct H2 production from sunlight.

[53]or also iridium which is a main component in PEM and one of the most rare materials on earth

[54]IEA (ed) (2015), Technology Roadmap Hydrogen and Fuel Cells

[55]Roland Berger (2013), A roadmap for financing hydrogen refueling networks – Creating prerequisites for H2-based mobility

[56]Hydrogen Roadmap Europe (2019): Fuel Cell and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe: A sustainable pathway for the European Energy Transition, January 2019. https://www.fch.europa.eu/studies.

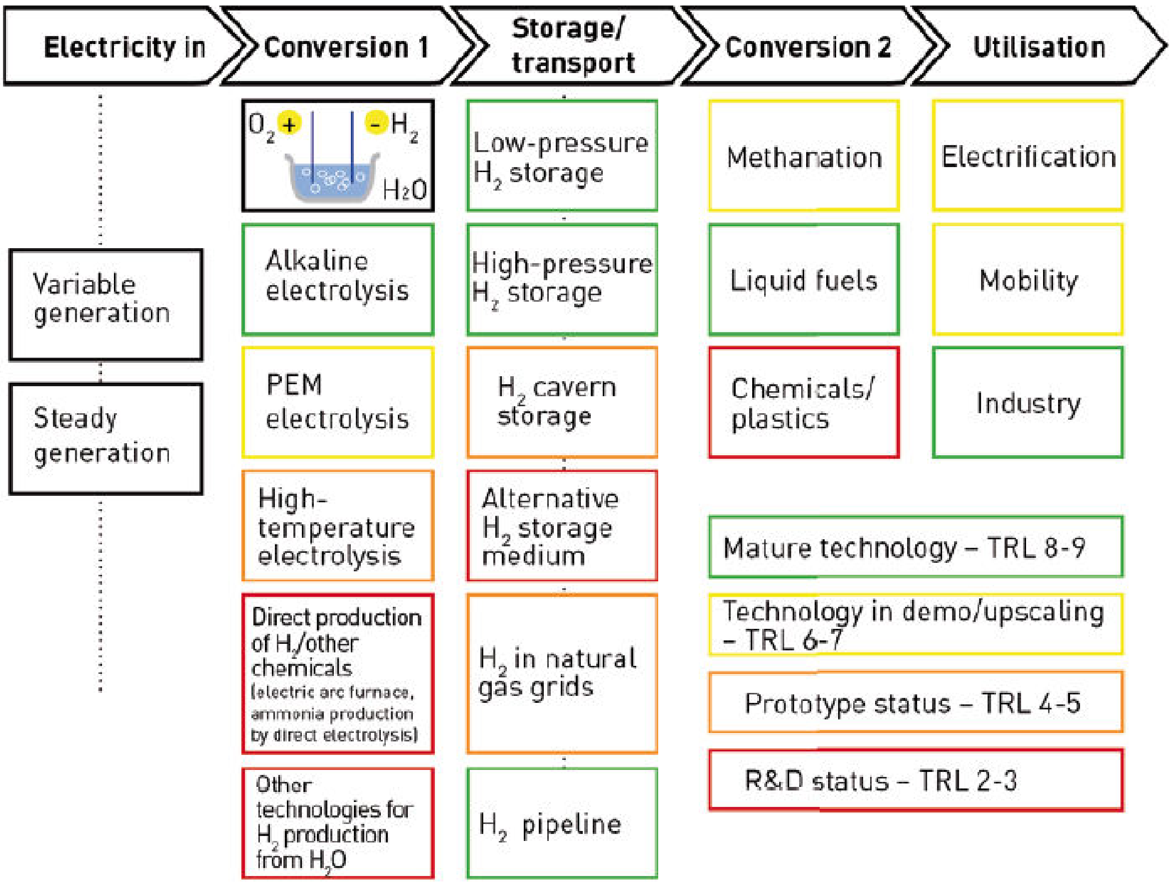
[57]Hydrogen Europe (2018), Strategic Value Chain on a Hydrogen Based Economy

[58]EASE/EERA, EUROPEAN ENERGY STORAGE TECHNOLOGY DEVELOPMENT ROADMAP 2017 UPDATE

Hydrogen plays a central role in chemical **energy storage**. However, its low volumetric energy density requires compression of usually between 200 and 700 bar or liquefaction.

Hydrogen has an extended **versatility of use**: it can be reconverted to electrical energy for stationary applications (power and heat generation, internal combustion engines and turbines, direct steam generation, catalytic combustion, and fuel cells) or mobile applications (transport) giving only water vapour as a reaction product, transmitted in dedicated pipelines to connect production sites with consumer sites, admixed into the existing natural gas grid to a certain limit, converted to others fuels (methane, methanol) or used in the chemical industry. Moreover, it is one of the very few options to store energy over days and weeks, e.g. in solution-mined salt caverns, which has been tested in the US for decades and is considered as a safe and cost-effective solution for large-scale storage of H2.

Hydrogen technologies and systems and TRL levels:



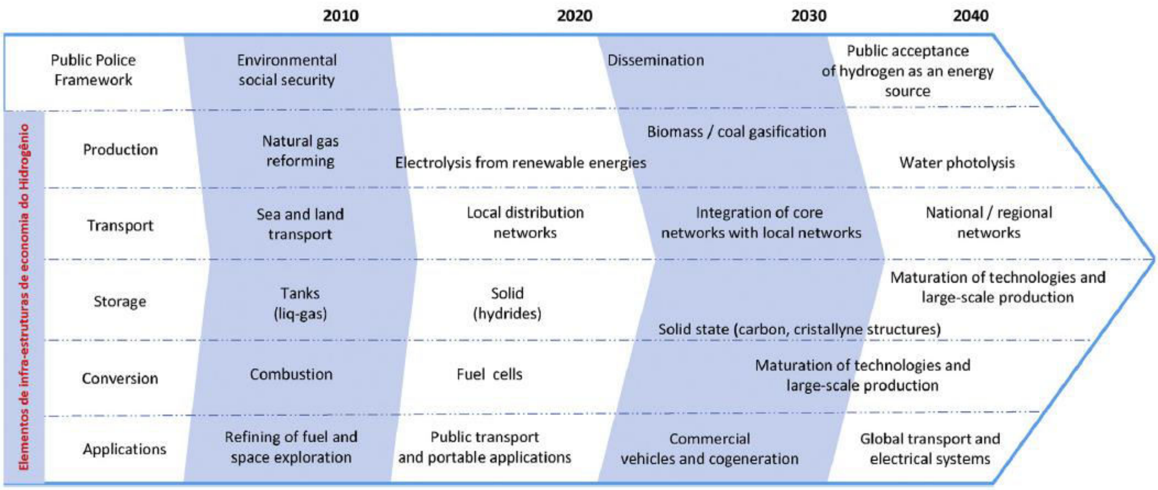
According to the SET PLAN Targets for Electrolysis and Hydrogen Storage Technologies for 2030 and beyond[59], the durability, operating performance should be further improved while production capacity should increase by a factor of 10 (e.g. for alkaline and PEM technologies and more for solid oxide electrolysers). The hydrogen generation costs should reduce to 2 €/kg (2030) and even 1 €/kg as ultimate goal (non-energy cost).

This example shows, that the major challenges for the chemical energy storage technology are related to costs (and upscaling), but many technical aspects need to be further developed to meet the SET Plan targets. The investment costs (EUR/kW) need to be reduced to expand application

59Joint EASE/EERA recommendations for a: EUROPEAN ENERGY STORAGE TECHNOLOGY DEVELOPMENT ROADMAP 2017 UPDATE areas for chemical energy storage, mainly with an up-scaling of the technology, more product standardisation, mass production and supply chain optimisation. On the technical side, higher efficiency, higher pressure, higher power density, and higher durability are the key challenges for all hydrogen technologies.

When overcoming these challenges the following technological developments, deployment and utilization of hydrogen could be expected in the next decades (general overview).

Expected technological developments to transition to a hydrogen economy[60]



3.7Systemic importance: spill-over effects, sectoral interlinkages (other SVCs) and Relevance of the SVC to EU objectives

Europe's transition to a decarbonized energy system is underway. The 28 Member States of the EU have signed and ratified the Conference of the Parties (COP21) Paris agreement to keep global warming "well below2 degrees Celsius above preindustrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius." This transition will radically transform how the EU generates, distributes, stores, and consumes energy. It will require virtually carbon-free power generation, increased energy efficiency, and the deep decarbonization of transport, buildings, and industry. A future hydrogen economy and related scale up of technologies and systems is relevant and linking to the above mentioned sectors and EU objectives. It is expected to be an (or the) important link for the decarbonisation goals.

3.8Major Initiatives taken at EU and national level; Programmes, networks, trans-national or trans-regional initiatives, etc.

The EU features various initiatives, which relate to the hydrogen economy:

- Energy Union strategy: focused on boosting energy security, creating a fully integrated internal energy market, improving energy efficiency, decarbonising the economy (not least by using more renewable energy), and supporting research, innovation and competitiveness

60 Hydrogen: Trends, production and characterization of the main process worldwide (2016), Tatiane da Silva Veras, Thiago Simonato Mozer 1,Danielle da Costa Rubim Messeder dos Santos 1, Aldara da Silva Cesar*; i n t e r n a t i o n a l j o u r n a l o f h y d r o g e n e n e r g y 4 2 (2 0 1 7) 2 0 1 8e2 0 3 3.

- Energy Security Strategy: short and long-term measures to shore up the EU's security of energy supply
- 'Clean Energy for All Europeans' package: has three main objectives: putting energy efficiency first, achieving global leadership in renewable energies, and providing a fair deal for consumers
- EU funding and other support is helping to build a modern, interconnected energy grid across Europe
- Energy Roadmap for 2050, in order to achieve its goal of reducing greenhouse gas emissions by 80-95%, when compared to 1990 levels, by 2050[61]
- Fuel Cells and Hydrogen Joint Undertaking: public private partnership supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe[62]

Fuel Cells and Hydrogen Joint Undertaking (FCH JU): The FCH JU provides the only funding programme at the EU level that is dedicated to hydrogen and fuel cell technology alone. With a total budget of approximately EUR 1.3 billion through 2020, it mainly supports research and innovation activities in the FCH sector and issues annual calls for proposals on selected topics. As an industry-led public-private partnership, the FCH JU will only be able to support FCH projects envisaged by coalition participants to a limited extent. Theorganisation also provides dedicated support regarding the funding and financing of FCH projects.[63]

Besides the EU, individual member states enacted own initiatives with respect to the hydrogen economy on different scales (national, regional, see also chapter 2.3). Examples are

- France: Hydrogen Deployment Plan for Energy Transition[64]
- Germany: National Innovation Programme Hydrogen and Fuel Cell Technology,[65] Hydrogen Power Storage & Solutions East Germany [66], State Agency for New Mobility Solutions and Automotive Baden-Württemberg[67]
- Great Britain: The UK H2Mobility coalition[68]
- Spain: National Policy Framework to support the deployment of hydrogen in transport. [69]
- ...

61European Commission (2018) Energy Strategy and Energy Union. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union.

62 Fuel Cells an Hydrogen Joint Undertaking (2019) Who we are. https://fch.europa.eu/page/who-we-are.

6305/10/2018 Fuel Cells and Hydrogen for Green Energy in European Cities and Regions; https://www.fch.europa.eu/studies

64Gouvernement.fr Hydrogen Plan: "making our country a world leader in this technology". https://www.gouvernement.fr/en/hydrogen-plan-making-our-country-a-world-leader-in-this-technology-0

65NOW (2019) National Innovation Programme Hydrogen and Fuel Cell Technology (NIP). https://www.now-gmbh.de/en/national-innovation-programme

66HYPOS (2017): landing page. http://www.hypos-eastgermany.de/de/

67e-mobilBW (2019) Welcome to e-mobil BW. https://www.e-mobilbw.de/en/

68UKH2Mobility (2019) About. http://www.ukh2mobility.co.uk/about/.

69https://industria.gob.es/es-ES/Servicios/Documents/marco-energias-alternativas.pdf

National funding programmes: Several European countries have national funding programmes in place that are either devoted specifically to FCH investments (such as e.g. the NIP 2.0 in Germany) or have a broader scope that also covers FCH projects (e.g. funding programme for zero-emission vehicles of the Office for Low Emission Vehicles in the UK and the National Energy Efficiency Fund in Spain). Depending on individual conditions and available budgets, these national programmes are important to provide co-funding alongside EU funds, or can even fund FCH projects without the need to rely primarily on EU funding. Information on such funding opportunities can usually be obtained from the relevant national ministries or agencies.[70]

4. SWOT analysis

A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysishas been made in the most recent reports commissioned by the FCH2 JU.[71] In these reportsSWOT analyses for applications and critical components have been prepared. In view of the need to keep the FCH JU input on this IPCEI as objective as possible, we here pick-up on the SWOT analysis made at the sub-value chain level of these reports to create an own general and wider SWOT analysis. This SWOT analysis will be aligned along the major value chain as presented in Figure 1 of this report and encompasses SWOT analyses on:

- Hydrogen production
- Hydrogen generation and distribution
- Hydrogen utilization (in mobile, stationary and industrial applications)

Under Strengths we answer the question: What is the EU good at? We consider the advantages the EU has, what the EU can do better than other regions, what are the unique or low-cost resources that the EU has and what factors make the EU successful. Under Weaknesses we answer the question: What is the EU not good at? We consider the disadvantages the EU has but also the main challenges and bottlenecks that are present. Under Opportunities we answer the question: What are the favourable external factors that could benefit the EU? We look at the opportunities that are there and trends that could be of interest. Under Threats we answer the question: What are unfavourable external factors that could harm the EU. We look at the obstacles in the EU, what is going well for the EU's competitors and trends that have the potential the hurt the EU.

Work in progress and still content and allocation to 4.1, 4.2, 4.3 to be done.

E.g. also create an all over SWOT analysis (all over hydrogen economy)

70 05/10/2018 Fuel Cells and Hydrogen for Green Energy in European Cities and Regions; https://www.fch.europa.eu/studies

71 E4tech, ECORYS and SA-Strategic Analysis (Fuel Cell and Hydrogen Joint Undertaking; publishing waiting final approval by the Governing Board of the Fuel Cells and Hydrogen 2 Joint Undertaking), Value Added of the Hydrogen and Fuel Cell Sector in Europe: supporting European growth and competitiveness. Draft final versions, including the Evidence Report, the Findings Report and the Publishable Summary accessed 15 Mar 2019.

4.1 SWOT analysis for Hydrogen generation (e.g. electrolyzers)

Strengths (to build on in the EU)	**Weaknesses (key challenges, bottlenecks)**
➢ Mature electrolyser technology ➢ strong electrolyser manufacturers (Alkaline, PEM, SOEC + materials) in Europe ➢ strong research base in electrolyser technology and science	➢ electrolysis requires very cheap and abundant low carbon electricity ➢ other routes of producing Hydrogen are still at low TRL ➢ R&D in solid electrolytes, gas diffusion layers, stack sealing materials (reliability) needed ➢ small and fragmented industry ➢ Little supply chain optimisation ➢ Potential lack of economic competitiveness compared to other means of hydrogen production, e.g. SMR ➢ The range of technologies being developed leads to some duplication of effort and fragmentation of approach, given the currently small market with companies still building profitability ➢ Market is dependent on policy for electricity, and renewables in particular ➢ Electricity and gas sector coupling still under discussion, role of existing players to be clarified for power-to-gas (gas-to-power fully operational)
Opportunities (potentials, employment, external factors that could benefit the EU)	**Threats (What are unfavourable external factors that could harm the EU?)**
➢ Some "no regrets" option should be identified (and development of large scale (>100MW) electrolyser plant should belong to these no regrets option) ➢ Power-to-X gaining traction ➢ Latest Renewable Energy Directive is likely to support a wide range of renewable hydrogen-based fuels ➢ Remote hydrogen production in conjunction with renewables could offer local benefits ➢ Solid oxide electrolysers offer promise for operating cost reduction ➢ Supply chain crossover with FC could help lower costs	➢ Before 2050, limiting the production of clean hydrogen to electrolysis is not compatible with the volumes needed at the European level. All production modes need to be included, such as using biomethane instead of natural gas in the reformers, and CCUS (cf definition in project Européen CertifHy). ➢ Dominance of non-European competitors ➢ Industrialisation may take place outside the EU or not bring costs down as far as anticipated ➢ Faster experimentation capabilities in non-EU country on gas and electricity sector coupling (China & US)

4.2 SWOT analysis for Hydrogen storage and distribution

Strengths (What is the EU good at?)	**Weaknesses (What is the EU not good at?)**
Storage ➢ Good EU capabilities in compressed and liquid storage tank manufacture, some hydrides and other carriers ➢ Wide ecosystem around producers, including safety and standards ➢ Capabilities to develop tanks, and several major new entrants ➢ Strong science base **Distribution** ➢ Operating EU electricity and gas market with strong players and efficient regulation ➢ EU Wide gas infrastructures with high transmission and storage capacities	**Storage** ➢ safety of high pressure storage and highly flammable ➢ need to develop and demonstrate industrial feasibility of liquid hydrogen carriers to reach high density storage ➢ urgent need to know LC(C)A on decarbonizing fossil fuel and using hydrogen for heating versus fossil fuel heating combined with CCS (essentially industrial) ➢ Some primary materials come from outside EU ➢ currently small market and high costs ➢ Standards missing ➢ Few suppliers ➢ High density storage and transport still challenging technically and cost-wise Distribution ➢ complicated cross-border regulatory barriers (on production, storage, distribution) ➢ distribution of H2 might require a new network ➢ Lack of Transportation of hydrogen by pipeline
Opportunities (What are the favourable external factors that could benefit the EU?) **Storage** ➢ x ➢ Distribution ➢ opportunity to reuse existing transmission/distribution infrastructure ➢ xx	**Threats (What are unfavourable external factors that could harm the EU?)** Storage ➢ Acceptance in case of accidents ➢ Technology alternatives are developed earlier ➢ markets outside EU Distribution ➢ Are existing natural gas pipelines compatible with hydrogen? ➢ Acceptance: in case of major accidents ➢

4.3 SWOT analysis on Hydrogen utilization (mobile, stationary, industrial use)

Strengths (What is the EU good at?)	**Weaknesses (What is the EU not good at?)**
➢ Hydrogen economy enables 0 tailpipe emission mobility with high autonomy ➢ High & growing share of low emission power (renewable & nuclear) ➢ carbon-free energy vector for transport and heat that allows to using similar or slightly adapted vehicles or heating equipment to operate as before ➢ EU has the skills to setup a world-class industry: leading research centers, leading groups, (energy, industrial gases, sustainable mobility), SMEs, start-ups, dynamic competitiveness clusters and regions committed to energy and hydrogen mobility. ➢ EU has key technologies (SMEs and start-ups that are behind major innovations) ➢ Strong emphasis on demonstration projects	➢ high investment cost in a new infrastructure ➢ power generation mix differ widely from member state to member state. Lack of coordinated energy policy ➢ Strong opposition from individual member states (and invidual stakeholders) to technologies that can potentially have a strong impact on hydrogen: nuclear power & CCS ➢ Efficiency of hydrogen supply chain ➢ Incomplete/immature hydrogen infrastructure ➢ insufficient awareness of stationary fuel cells among the public ➢ Low- or non-platinum catalysts and catalytic mechanism ➢
Opportunities (What are the favourable external factors that could benefit the EU?)	**Threats (What are unfavourable external factors that could harm the EU?)**
➢ Decarbonisation ➢ Increased use of RES ➢ reduced noise levels in transport/traffic ➢ new Jobs, attracting skilled work force, new businesses ➢ Increasing public awareness on air quality ➢ Valorization of growing renewable electricity surplus => avoid curtailment ➢ Conversion of existing EU natural gas infrastructures (transmission, distribution and underground storage) and uses to renewable energy => => optimization of existing assets ➢ Emission reduction (not only CO2) ➢ Energy independency (or at least reduction of energy dependency) ➢ Job & growth creation ➢ Taking full advantage of the current finacial effort to develop low emission generation capacities ➢ Developement of new businesses and competencies	➢ Safety concerns, acceptance (How to avoid accidents?Damage prediction for accidents. Costs for safety in hydrogen technology systems.) ➢ Standardisation ➢ Regulation etc tariffs, dedicated power production for electrolysis, etc (How to make incentives for green hydrogen.) ➢ Technology to be developped and deployed outiside EU ➢ chicken and egg problem ➢ High cost of fuell cell vehicle, hydrogen refueling station, …. ➢ unsufficient level of de-risking to make projects viable. ➢ Education: safety concerns among consumers ➢ On LCV, technology is lagging behind BEV - need to identify enough use cases for a significant market uptake ➢ Technology to be developped and deployed outiside EU. In particular FC mobility

➢ High potentiel of subcontractors but they need to adapt their skills to the specificities of hydrogen and fuel cells ➢ European (FCHJU, H2020) and national/regional supports & promotions (eg France: national hydrogen plan) ➢ growing interest for RE hydrogen through electrolysis fuelled by wind/solar to produce methane or ammonia. ➢ Major European cities, whose stakes in air quality are fundamental: interesting perspectives for the hydrogen players. Local authorities have a fundamental role to play. ➢ Identify use cases: e.g. train sector, logistics, ... ➢	➢ FC vehicles are being developped outside europe - dependency on success and desire to deploy by others ➢ competition between battery-EV and FCEV: if disruption in battery, FCEV might become obsolet