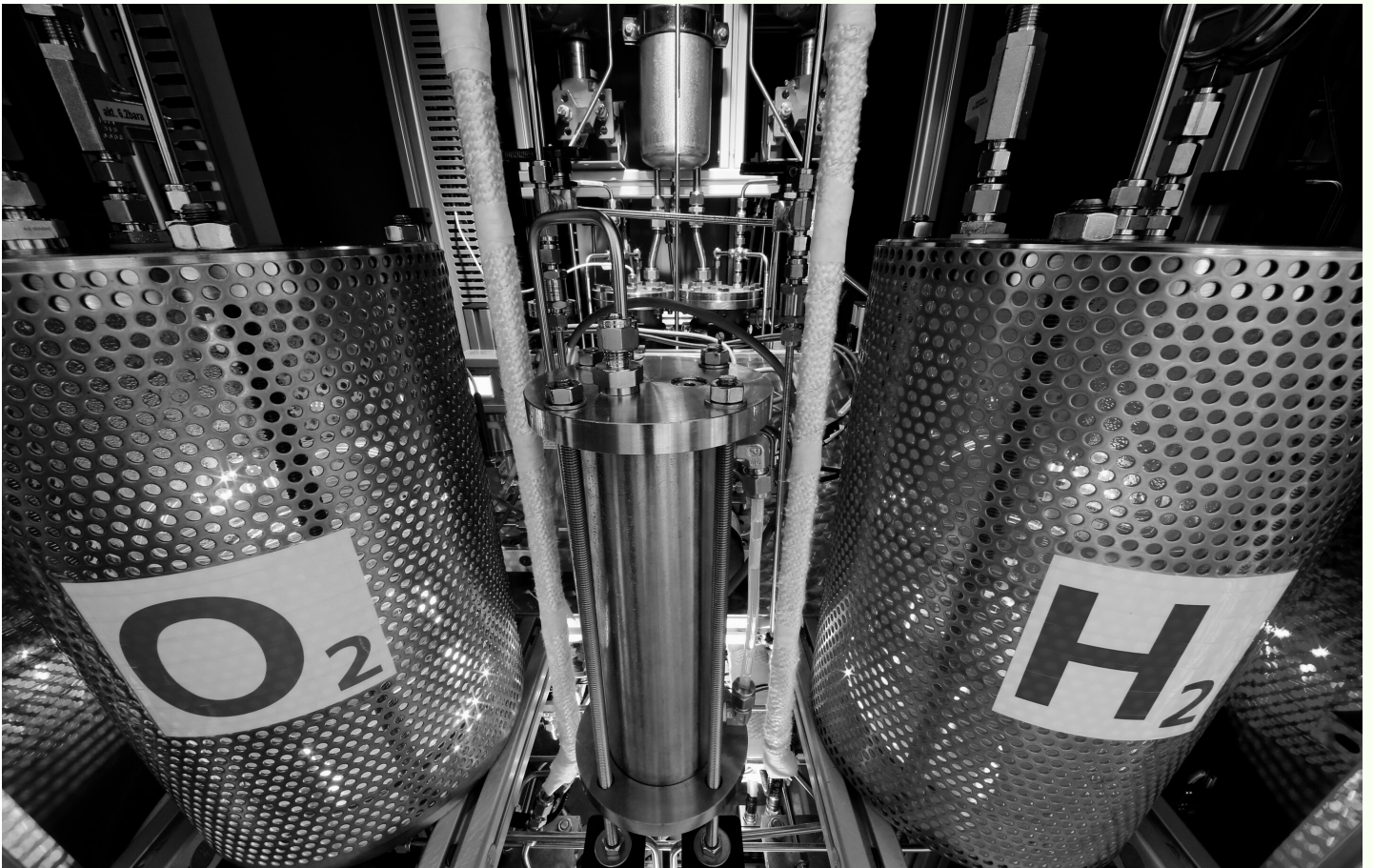


Green Hydrogen Investment and Support Report

Hydrogen Europe's input for a
post COVID-19 recovery plan



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01 EXECUTIVE SUMMARY

Hydrogen will play a pivotal role in achieving an affordable, clean and prosperous economy. To recover from the economic recession caused by the COVID-19 virus, **investments in building a hydrogen economy can contribute to a clean and affordable energy system, but above all can scale up an innovative new hydrogen manufacturing industry, creating new green jobs and economic growth.**

To get insight into building such a hydrogen system, consisting of production, infrastructure and storage, and hydrogen applications, **an estimate of the necessary investments and required support has been made.** These investments create new markets for hydrogen products, equipment and applications, such as electrolyzers and fuel cells. Based on these data, European Member States together with the European Union could design policies and support schemes, especially for a post COVID-19 economic recovery plan.

In this document, to estimate the total investments for building a hydrogen system up to 2030 the FCH JU study Hydrogen Roadmap Europe has been used for the hydrogen demand assumptions in 2030 and Hydrogen Europe's paper 2x40 GW Green Hydrogen Initiative has been used for green hydrogen production assumptions in 2030. Overall, **the total investments up to 2030 are estimated to be 430 billion Euro, with an estimated necessary support of 145 billion Euro.**



Building the hydrogen system	Investments	Support (grants/subsidies)
Investments and Support	up to 2030	up to 2030
Hydrogen Production	220 billion Euro	95 billion Euro
Among which renewables	160 Billion Euro	
Hydrogen Infrastructure & Storage	120 billion Euro	15 billion Euro
Hydrogen Applications	90 billion Euro	35 billion Euro
TOTAL	430 billion Euro	145 billion Euro

Table 1

Starting from these investments, an innovative and competitive hydrogen manufacturing industry can start up, build up and scale-up. The EU and Member States could support the construction of this industry, by providing – amongst others – loans, mezzanine financing and even equity. However, many companies mention that the most important factor for them in order to decide if expanding or not their manufacturing capacity is that they can be sure that targets for the market, such as the 2x40 GW electrolyser capacity in 2030 and hydrogen demand increase, are secured and guaranteed by governments.

02 INTRODUCTION

To build a hydrogen system and help the economy recover from the recession caused by the COVID-19 virus, with an increasing demand for clean hydrogen applications together with scaling up hydrogen production and building up hydrogen infrastructure, large scale investments are necessary. These investments need to be initiated and stimulated through EU and governments policies and support. However, these hydrogen investments can create a market to scale up, start-up and grow a competitive and innovative European hydrogen manufacturing industry. **If Europe is at the forefront of these hydrogen developments, it can create a world class manufacturing industry**, especially in electrolyser, fuel cell and other hydrogen equipment and manufacturing applications.

In this report we estimate the total needed investments in building a hydrogen system up to 2030. Investments in renewable energy and hydrogen production, in hydrogen infrastructure and storage and in hydrogen applications are estimated, together with an indication of the financial support that is needed in this first phase of building a hydrogen system. These investments give insight into the markets for specific hydrogen products, equipment and applications. Based on these insights policies and support schemes could be designed, especially for a COVID-19 economic recovery plan.

The starting points and assumptions to estimate total investments for hydrogen up to 2030 are from Hydrogen Europe's paper "Green Hydrogen for a European Green Deal - A 2x40 GW Initiative" (2x40 GW Green Hydrogen Initiative)[1] and the FCH JU report "Hydrogen Roadmap Europe - A sustainable pathway for the European Energy Transition" (Hydrogen Roadmap Europe)[2].

The hydrogen demand, according to the Hydrogen Roadmap Europe ambitious scenario in 2030, will be 665 TWh or 16,9 million tonnes. This hydrogen demand needs to be produced in the EU or needs to be imported. According to the 2x40 GW Green Hydrogen Initiative, 7,4 million tonnes of hydrogen is supplied by green hydrogen, 4,4 million tonnes is produced in the EU, while 3 million tonnes is imported from North-Africa and Ukraine. This implies that 9,5 million tonnes of hydrogen need to be produced additionally, with the lowest carbon content as possible. It is assumed that the present amount of hydrogen can be produced through electrolysis, benefitting from other low-carbon electricity sources in Europe, and also from natural gas with Carbon Capture and Storage (CCS), producing altogether 8,2 million tonnes low carbon hydrogen. The remaining new low carbon hydrogen production, 1,3 million tonnes, will be from coal gasification with CCS.

[1] Hydrogen Europe, Green Hydrogen for a European Green Deal - A 2x40 GW initiative, April 2020

[2] FCH JU (Fuel Cells and Hydrogen Joint Undertaking), Hydrogen Roadmap Europe - A sustainable pathway for the European energy transition, January 2019

DEMAND				PRODUCTION		
<i>FCH JU Hydrogen roadmap Europe</i>	TWh H ₂	Mt H ₂	Pure H ₂ or blended in Natural Gas	<i>Hydrogen Europe 2x40 GW Green Hydrogen Initiative</i>	TWh H ₂	Mt H ₂
Feedstock Existing	359	9,1	Pure H ₂	EU production green H ₂	173	4,4
Feedstock new Steel, Kerosene	98	2,5	Pure H ₂	Import green H ₂	118	3,0
Industry heat + space heating	79	2,0	Pure H ₂ and/or blended	<i>Assumptions Low Carbon H₂</i>		
Transport	71	1,8	Pure H ₂	Existing H ₂ use now grey to low carbon H ₂ gas SMR/ATR with CCS/CCU, 90% CO ₂ emission reduction and low-carbon electrolysis	324	8,2
Power balancing	58	1,5	Pure H ₂ and/or blended	New low carbon H ₂ Coal gasification with CCS/CCU, nearly 100% CO ₂ emission reduction	50	1,3
TOTAL	665	16,9			665	16,9

Table 2: Hydrogen demand 2030 according to FCH JU Hydrogen Roadmap Europe and hydrogen production according to Hydrogen Europe 2x40 GW Green Hydrogen Initiative and low carbon hydrogen production assumptions.

03 HYDROGEN PRODUCTION

Hydrogen demand in the EU in 2030 according to the FCH JU's Hydrogen Roadmap Europe is 665 TWh or about 16,9 million ton. This amount of hydrogen will be supplied as follows:

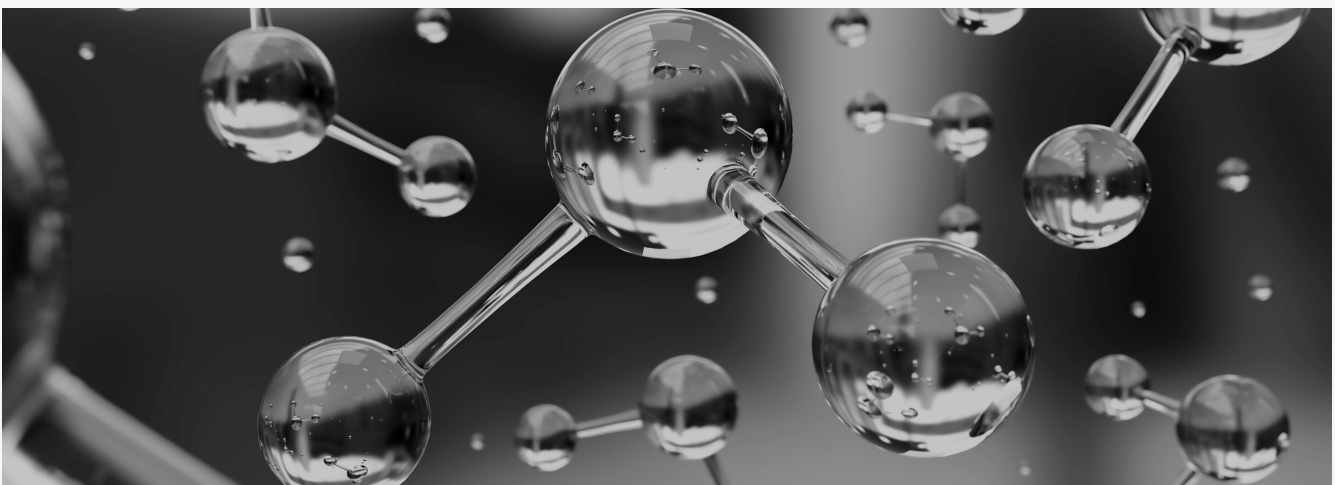
- According to the 2x40 GW Green Hydrogen Initiative, 173 TWh or 4,4 million tonnes green hydrogen will be produced in the EU and 118 TWh or 3 million tonnes green hydrogen will be imported from North Africa and Ukraine.
- It is assumed that the other part of the hydrogen supply in 2030, 9,5 million tonnes, will be low carbon hydrogen:
 - 324 TWh or 8,2 million tonnes (the present grey hydrogen production) will be produced from natural gas by SMR (Steam Methane Reforming) with CCS, realising a 90% CO₂ emission reduction, and from electrolysis from decarbonised electricity sources.
 - 50 TWh or 1,3 tonnes low carbon hydrogen is assumed to be produced from new coal by gasification with CCS/CCU whereby nearly 100% CO₂ emission reduction can be realised. These coal gasification plants will be pre-dominantly realised in Poland, Bulgaria, Romania and Hungary.

4,4 MILLION TONNES GREEN HYDROGEN PRODUCTION IN THE EU

The realization of 40 GW electrolyser capacity in the EU, producing 4,4 million tonnes of clean hydrogen, requires the realization of up to 80 GW of additional renewable electricity production, wind offshore, wind onshore and solar PV. Total investments are up to 80 and 90 billion Euro, see table 3. These could be lowered by maximising the use of already existing carbon free electricity available in Europe.

The realization of the 6 GW captive electrolyser capacity, whereby the electrolyser is located at the hydrogen demand and connected to the electricity grid, does not need a hydrogen infrastructure or storage capacity. The only restriction to this is the electricity grid capacity and, therefore, these electrolyser installations will be in the 100 MW to 1 GW range. A load factor of 8.000 could be realised through electrolysers being connected to the grid, benefiting from stable electricity supply, together with a strong Guaranties of Origin system and traceability system, whereby the electricity could come from renewable and low carbon electricity sources This approach could yield synergies and benefit from sector coupling: additional flexibility for the electricity system and additional revenues for electrolysers. However, realizing a load factor of 8.000 hours means that the electricity cost that needs to be paid will be higher than the electricity production cost by the renewables due to grid fees, storage and flexible costs in the electricity system.

The realization of the 34 GW hydrogen production plants, whereby the electrolyser is located near the resource requires hydrogen infrastructure and storage. The load factor will be restricted by the renewable resource. To realize 5.000 hours load factor, especially in the south of Europe, a smart combination of solar PV with wind that needs to be connected at location to the electrolyser capacity is required. Lower load factors, for example by connecting solar PV capacity one to one to the electrolyser capacity, would mean also a lower load factor for the pipeline and will need much more hydrogen storage capacity. Meaning, in the end, a higher system cost.



EU 40 GW	Electrolyser Capacity MW	Hydrogen Production Mt H ₂	Needed Total Electricity Production	Elec Prod Offshore Wind	Elec Prod Onshore wind	Elec Prod Solar
Captive market , hydrogen production near the demand at chemical, steel, refineries, glass, ceramics and hydrogen refuelling stations Electrolysers connected to the electricity grid Load factor electrolysers 8.000 hours Grid fee, flexibility and storage cost 20-40 Euro per MWh				Electricity production by renewable resources connected to the electricity grid Load factor offshore wind 5.000 hr Load factor onshore wind 3.000 hr Load factor solar PV South EU 1.800 hr		
TOTAL captive market	6.000	0,96	48 TWh	32 TWh 6.400 MW	16 TWh 5.400 MW	0 TWh 0 MW
Hydrogen market , hydrogen production near the resource at offshore wind or combined onshore wind + solar Electrolysers connected to a hydrogen pipeline, only marginally to an electricity grid. Load factor electrolysers 5.000 hours				Electricity production by renewable resources connected to the electrolysers Load factor offshore wind 5.000 hr Load factor onshore wind 3.000 hr Load factor solar PV South EU 1.800 hr		
TOTAL Hydrogen market	34.000	3,4	170 TWh	42,5 TWh 8.500 MW	42,5 TWh 14.200 MW	85 TWh 47.200 MW
INVESTMENTS EU; 40 GW electrolyser capacity with 81.7 GW renewable electricity capacity						
	Meuro/MW	Captive market MW	Captive Market Billion Euro	Hydrogen Market MW	Hydrogen Market Billion Euro	Total Investments Billion Euro
Electrolysers	0,25-0,50	6.000	2,1	34.000	10,6	12,7
Offshore Wind	3,0	6.400	19,2	8.500	25,5	44,7
Onshore Wind	1,2	5.400	6,4	14.200	17,0	23,4
Solar PV	0,3	0		47.200	14,2	14,2
TOTAL			27,7		67,3	95,0

Table 3: Investments in solar, wind and electrolyser capacity to produce 4.4 million ton green hydrogen in the EU.

IMPORT 3.0 MILLION TONNES HYDROGEN FROM NORTH AFRICA AND UKRAINE

The realization of 40 GW electrolyser capacity in North Africa (30 GW) and Ukraine (10 GW), producing 4 million tonnes of green hydrogen, requires the realization of about 77 GW of additional renewable electricity production, wind onshore, solar PV and solar CSP. The total investments for renewable energy and electrolyser plants are about 92 billion Euro, see table 4.

The realization of the 30 GW hydrogen production plants in North Africa and 10 GW hydrogen production plants in Ukraine, whereby the electrolyser is located near the resource requires a hydrogen infrastructure and storage or a direct connection to an ammonia plant. The load factor will be restricted by the renewable resource. To realize 5.000 hours load factor in North Africa, a smart combination of solar with onshore wind or a smart combination of solar PV with solar CSP, that needs to be connected at location to the electrolyser capacity is required. To realize 5.000 hours load factor in Ukraine, a smart combination of solar PV with onshore wind, that needs to be connected at location to the electrolyser capacity is required. Lower load factors, for example by connecting solar PV capacity one to one to the electrolyser capacity, would mean also a lower load factor for the pipeline and it will need much more hydrogen storage capacity and therefore higher hydrogen cost for the consumer.



Ukraine + North Africa 40 GW	Electrolyser Capacity MW	Hydrogen Production Mt H ₂	Needed Total Electricity Production	Elec Prod Solar CSP	Elec Prod Onshore wind	Elec Prod Solar PV
Ukraine , hydrogen production near the resource at combined onshore wind + solar Electrolysers connected to ammonia plants and/or hydrogen pipeline Load factor electrolysers 5.000 hours				Electricity production by renewable resources connected to the electrolysers Load factor onshore wind 3.000 hr Load factor solar PV Ukraine 1.500 hr		
TOTAL Ukraine	10.000	1,0	50 TWh 22.200 MW	0 TWh 0 MW	33,3 TWh 11.100 MW	16,7 TWh 11.100 MW
North Africa , hydrogen production near the resource at combined onshore wind + solar PV or combined solar PV and solar CSP Electrolysers connected to ammonia plants and/or hydrogen pipeline Load factor electrolysers 5.000 hours				Electricity production by renewable resources connected to the electrolysers Load factor Solar CSP 4.000 hr Load factor onshore wind 4.000 hr Load factor solar PV North Africa 2.100 hr		
TOTAL North Africa	30.000	3,0	150 TWh 54.500 MW	37,5 TWh 9.400 MW	37,5 TWh 9.400 MW	75 TWh 35.700 MW
INVESTMENTS Ukraine + North Africa; 40 GW electrolyser capacity with 76.7 GW renewable electricity capacity						
	Meuro/MW	Ukraine MW	Ukraine Billion Euro	North Africa MW	North Africa Billion Euro	Total Investments Billion Euro
Electrolysers	0,25-0,5	10.000	3,5	30.000	10,0	13,5
Solar CSP	4,2	0	0	9.400	39,4	39,4
Onshore Wind	1,2	11.100	13,3	9.400	11,3	24,6
Solar PV	0,3	11.100	3,3	35.700	10,7	14,0
TOTAL			20,1		71,4	91,5

Table 4: Investments in solar, wind and electrolyser capacity to produce 4 million ton green hydrogen in North Africa and Ukraine.

TENDERING RENEWABLE ENERGY WITH ELECTROLYSER CAPACITY FOR HYDROGEN PRODUCTION

A tender procedure for the production of green hydrogen needs to be an integrated one for both green electricity production and the conversion of electricity into hydrogen by electrolysis. In such a tender procedure, a price is offered per kg of hydrogen produced. The one with the lowest bid wins the tender. When the production costs are higher than the market price, the idea is that governments subsidise the difference.

However, that requires a 15-20 year relation, with yearly payments by governments. As part of an economic recovery program, it is maybe interesting to capitalize the total amount of subsidies that will be paid over a 15-20 year period to an investment subsidy upfront when realizing the project. This will reduce investment cost, making it easier and cheaper to finance these projects.

Tendering captive hydrogen production. Hydrogen production is at the demand, while renewable electricity production is at another place, transported via the electricity grid to the electrolyser. The electrolyser can produce at base load 8000 hours but needs the electricity system for transport, storage and flexibility. Because of grid capacity constraints, the electrolyser capacity will be restricted to a couple of 100 MW. So, in this case the electricity costs at the electrolyser include the electricity production cost plus grid fees for transport, storage and flexibility cost. Grid fees of 20-40 Euro/MWh are assumed. These costs could be waived by regulation or compensated by an extra subsidy of 1-2 Euro per kg of hydrogen. This needs to be arranged separately from the tender.

The tender will be based on the production cost for hydrogen (renewable/carbon free electricity plus electrolyser cost included). Let's assume that on average there is a difference between production cost and market price for hydrogen of 1 Euro per kg. That would mean a subsidy of 1 billion Euro per year for the 6 GW captive electrolyser capacity installed in the EU that produces about 1 million tonnes hydrogen. If we capitalize this over a period of 15 years it is roughly 10 billion Euro. The total investments were estimated to be 29 billion Euro. So, this tender based investment subsidy percentage will be between 30% and 40%.

Tendering integrated renewable hydrogen production plants. Hydrogen is produced by electrolyzers that are directly coupled to the renewable electricity production. Because the electrolyzers are directly connected to these intermittent resources, these electrolyzers do not produce in base load. We assume that by a clever combination of solar and wind, solar PV and solar CSP or by offshore wind alone a load factor of 5.000 hours can be realised. Although lower load factors for the electrolyser, it is assumed that hydrogen production costs for these integrated renewable hydrogen production plants can be the same or lower than captive hydrogen production, because of better resource conditions, larger multi GW scale and integrated renewable energy/electrolyser system optimization.

The problem in this case is that the hydrogen infrastructure, hydrogen pipelines and/or ships plus salt cavern storage availabilities are limited according to geography. Therefore, transport and storage costs at the beginning will be much higher and/or hydrogen will need to be blended in the natural gas grid which reduces its value. Therefore, it is necessary to compensated this by an extra subsidy, most probably 1-2 Euro per kg of hydrogen. However, this will take place only for a couple of years, when the hydrogen infrastructure is ready this can be reduced and eventually will not be needed.

The tender will be based on the production cost for hydrogen (renewable electricity plus electrolyser cost included). Let us assume that on average there is a difference between production cost and market price for hydrogen of 1 Euro per kg, the same as for captive hydrogen production, although it is expected to be lower.

For the 34 GW integrated renewable hydrogen plants in the EU, producing 3.4 million tonnes hydrogen, the subsidy will be 3,4 billion Euro per year. Or, by capitalizing this amount, it is roughly 35 billion Euro. The investment is about 67 billion Euro, so about a 50% tender based investment subsidy. For the 10 GW integrated renewable hydrogen plants in Ukraine, producing 1 million tonnes hydrogen, the subsidy will be of 1 billion Euro per year. Capitalized about 10 billion Euro, which is about 50% of total investments.

For the 10 GW integrated renewable hydrogen plants in the North Africa, producing 1 million tonnes of hydrogen, the subsidy will be 3 billion Euro per year. Capitalized about 30 billion Euro, which is about 40-50% of total investments.

	GW Electrolyser	Mt H ₂	Renewable electrolyser Investment Billion Euro	+ Tender based investment subsidy	Additional support
Captive market EU	6	1,0	27,7	30%-40%	Compensation grid fees always
Hydrogen plant EU	34	3,4	67,3	40%-50%	Compensation high transport cost first years
Hydrogen plant Ukraine	10	1,0	20,1	40%-50%	Compensation high transport cost first years
Hydrogen plant North Africa	30	3,0	71,4	40%-50%	Compensation high transport cost first years
TOTAL	80	8,4	186,5	72-91 billion Euro	

Table 5: Investments and tender based capitalized investment subsidies in renewable energy and electrolyser capacity according 2x40 GW green hydrogen initiative

8,2 MILLION TONNES LOW CARBON HYDROGEN PRODUCTION BY SMR WITH CCS AND LOW-CARBON ELECTROLYSIS

The existing hydrogen production in the EU is predominantly from natural gas by Steam Methane Reforming (SMR). In a study by the IEA[1], five different CO₂ capture technologies added to a SMR Plant that produces 75.000 tonnes hydrogen per year have been investigated with respect to the CO₂ capture rates and the required investments. CO₂ capture rates of these 5 capture technologies varies between 55% (5,5 kg CO₂/kg H₂) and 90% (9 kg CO₂/kg H₂) of CO₂ emissions. Additional investment cost range between 40 and 176 million Euro, increasing hydrogen cost between 0,23 and 0,57 Euro/kg H₂.

Today around 8.2 million tons of grey hydrogen are produced in the EU – most of it by SMR from natural gas. When we assume that 90% of the CO₂ emissions need to be abated, the total additional investments are 19,2 billion Euro. Subordinated loans could help to realize the carbon capture installations. Not included in these investments are the CO₂ transport and storage costs.

Low-carbon hydrogen with available clean electricity will also contribute to these amounts as it is unlikely that all the current SMR capacity can be retrofitted with CCS, given space and CO₂ storage constraints.

[1] IEAGHG Techno Economic Evaluation of SMR Based Standalone (merchant) Plant with CCS, 2017/02, February 2017

1,3 MILLION TONNES LOW CARBON HYDROGEN PRODUCTION BY COAL GASIFICATION WITH CCS

The future demand for hydrogen in 2030 is higher than the existing fossil fuel-based hydrogen production and the projected hydrogen production by the 2x40 GW Green Hydrogen Initiative. Therefore, new low carbon hydrogen needs to be produced from fossil fuels with capturing and storing the CO₂, or by relying in a more extensive way on the production of low carbon hydrogen with carbon free and low carbon electricity from the grid. The EU does not have a lot of own gas and oil production, it needs to import gas mainly from Russia, Norway and Algeria by pipeline and oil from many different countries by ship. The domestic fossil energy resource available in the EU is coal, especially in Poland, Bulgaria, Romania, Hungary and Germany. It could be interesting to produce low carbon hydrogen from coal gasification, capturing and storing the CO₂ as a start and expanding to green hydrogen production from biomass gasification.

In Australia, Kawasaki Heavy Industries is building a coal gasification plant with carbon capture and storage together with a hydrogen liquefaction plant and shipping the hydrogen to Japan. A coal gasification plant producing 225.500 tonnes of hydrogen per year is built with nearly 100% carbon capture and storage. The investments are of 2 billion Euro. If we assume similar investment costs in Europe to develop coal gasification plants, then a total investment of 11,5 billion Euro is required. If indeed nearly 100% CO₂ emissions could be captured and stored, an investment grant of 25% with additional subordinated loans could stimulate realization[1].



[1] Study on Introduction of CO₂ free energy to Japan with Liquid Hydrogen, Shoyi Kamiya, Motohiko Nishimura, Eichi Harada, Physics Procedia 67(2015)11-19

OVERVIEW HYDROGEN PRODUCTION INVESTMENTS

Hydrogen Production	Total Investments up to 2030 (Euro)	Total Support up to 2030 (Euro)
Green Hydrogen production EU, 40 GW electrolyser with new solar + wind	95 billion	45 billion grants 51 billion subordinated loans
Green Hydrogen production Ukraine, 10GW electrolyser with new solar + wind	20 billion	10 billion grants 10 billion subordinated loans
Green Hydrogen production North-Africa, 30 GW electrolyser with new solar + wind	72 billion	36 billion grants 36 billion subordinated loans
Existing hydrogen production, Gas SMR adding Carbon Capturing with 90% CO ₂ emission reduction	20 billion	No grants 20 billion subordinated loans
New hydrogen production with coal gasification with nearly 100% CCS in Poland, Bulgaria, Romania and Hungary	12 billion	4 billion grants 8 billion subordinated loans
	220 billion	95 billion grants/subsidies

Table 6: Investments in hydrogen production

04 HYDROGEN INFRASTRUCTURE AND STORAGE

HYDROGEN TRANSPORT PIPELINE BACKBONE THROUGHOUT EUROPE CONNECTED TO AFRICA

According to the hydrogen backbone infrastructure map in the 2x40 GW Green Hydrogen Initiative, the main part of the hydrogen backbone is converting existing natural gas pipelines into hydrogen pipelines. An estimated 50.000 km natural gas pipeline infrastructure needs to be converted to a hydrogen pipeline infrastructure. Next to this, about 5.000 km of new hydrogen pipelines to Africa, Greece-Black Sea to Italy, Portugal-Spain, is needed. The specific investment cost in new transport pipeline capacity is 1 million Euro per 10 GW capacity per km[1]. A new pipeline from Africa to Greece and Italy, 2.500 km with capacity of 20 GW, will therefore cost 5 billion Euro[2].

The German gas transport grid operators have proposed to realise a hydrogen backbone in Germany that connects large scale hydrogen production with the hydrogen demand in large chemical, petrochemical and steel plant sites and with hydrogen salt cavern storage. The hydrogen backbone will be realised to a large extent by converting natural gas pipelines and with some new hydrogen pipelines to make the proper connections. A total length of 5.900 km hydrogen backbone is proposed in Germany. A similar hydrogen backbone plan is proposed in the Netherlands, for the period 2023-2027. In the Netherlands the retrofit and partial new hydrogen pipeline cost will be about 1,5 billion Euro. A fully new built hydrogen backbone (so not by converting the natural gas pipelines into a hydrogen pipelines) would have cost about 5-6 billion Euro. So the cost to re-use and convert natural gas pipelines for hydrogen are about 25% of the cost to build a fully new hydrogen pipeline Backbone.

The estimated investment costs for a European-North Africa-Ukraine hydrogen backbone, with 50.000 km converted natural gas pipelines and 5.000 km new hydrogen pipelines with a capacity of 20 GW, will be

- 50.000 km* 2 million Euro/km *0,25 = 25 billion Euro for converting natural gas pipelines,
- 5.000 km * 2 million Euro/km = 10 billion for new hydrogen pipelines.

[1] Ad van Wijk, Frank Wouters, Hydrogen, the bridge between Africa and Europe, to be published in Shaping an inclusive Energy Transition, Springer, 2020

[2] Analysis of advanced H2 production & delivery pathways, Strategic Analysis, June 2018

Converting pipelines could be stimulated with subordinated loans. However, new hydrogen pipelines initiated by the European Union, North African countries and Ukraine, jointly owned by gas transmission system operators of the countries involved, need about 50% grants/subsidies together with 50% subordinated loans.

3.700 HYDROGEN REFUELLING STATIONS (HRS), BUNKERING AND OTHER FUELLING POINTS

The FCH JU hydrogen roadmap Europe estimates that 3.740 HRS in 2030 needs to be installed, requiring 8,2 billion Euro total investments. Next to this there is a need for hydrogen bunkering stations for ships along rivers Rhine, Danube, Po and others. Bunkering stations for sea ships in harbours. Fuelling stations for drone-tubes, etc. In total an investment needs of about 10 billion Euro up to 2030 is estimated.

50% subsidy/grant (like in Germany) plus 50% subordinated loans

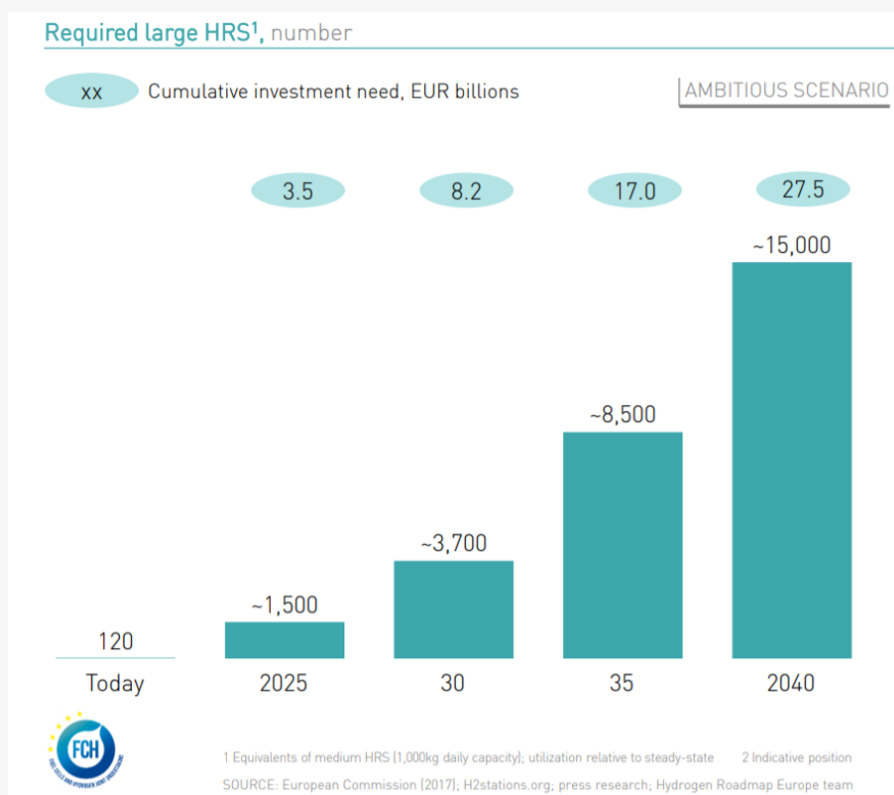


Figure 1. Development Hydrogen Re-fuelling Station in the EU, source FCH JU

HYDROGEN PORT FACILITIES

Port facilities are needed to import and export hydrogen by ship and transport the hydrogen to the hinterland of these ports. Port facilities include, amongst others, liquid hydrogen terminals, liquid hydrogen storage tanks, liquid hydrogen truck loading, evaporation units, Liquid Organic Hydrogen Carrier (LOHC) terminals, storage tanks, dehydrogenation plants, ammonia terminals, storage tanks, ammonia cracking installations, etc.

Estimated investments that need to be done in a port, are:

- Liquid hydrogen terminal and storage, Capex about 1 billion Euro
- Ammonia terminal, storage and ammonia cracking installation, Capex about 300 million Euro
- LOHC terminal, storage and dehydrogenation plant, Capex - especially dehydrogenation - plant 200 million Euro
- Port pipeline infrastructure for hydrogen, ammonia, bunkering facilities and multi modal logistic centres, Capex 1 billion Euro.

In total an investment of about 2,5 billion Euro in port facilities is needed. An estimated total of 8 ports in Europe needs to realize these port facilities, which is a total investment of 20 billion Euro.

3 MILLION TONNES HYDROGEN STORAGE CAPACITY IN SALT CAVERNS

At least, roughly estimated, 1/3 of green hydrogen needs to be stored before use, due to the intermittency of solar and wind resources and the base load demand for hydrogen in industry and mobility. This is an amount of 2 million tonnes hydrogen. Next to this, about 20% of low carbon hydrogen needs to be stored before use. This 20% is the same percentage as for natural gas storage due to seasonal variation in demand. This equals to about 1 million tonne hydrogen storage. This gives a rough estimate of a total 3 million tonnes of hydrogen storage capacity needs.

Each salt cavern can store on average 6.000 tonnes hydrogen, so 500 salt caverns are needed. The average cost for one salt cavern is about 100 million Euro. A total 50 billion Euro investments is needed in hydrogen storage. A salt cavern needs to be filled up with cushion gas first, before the storage facility can be operational. About 3 million tonnes hydrogen is needed as cushion gas. Therefore, upfront investments are needed for about 3 million tonnes hydrogen, times 1,5 Euro/kg means 5 billion Euro for cushion gas.

The total investments in salt cavern hydrogen storage are 55 billion Euro, 50 billion Euro Capex investments and 5 billion Euro for cushion gas.

OVERVIEW HYDROGEN INFRASTRUCTURE AND STORAGE INVESTMENTS

Hydrogen Infrastructure and Storage	Total Investments up to 2030 (Euro)	Total Support up to 2030 (Euro)
Hydrogen pipeline backbone EU-North Africa Ukraine	35 billion	5 billion grants 20 billion subordinated loans
Hydrogen re-fuelling stations, bunkering and other fuelling points	10 billion	5 billion grants 5 billion subordinated loans
Hydrogen port facilities	20 billion	20 billion subordinated loans
Hydrogen salt cavern storage <ul style="list-style-type: none"> • Capex cost • Cushion gas 	50 billion 5 billion	50 billion subordinated loans 5 billion cushion gas subsidized
	120 billion	15 billion grants/subsidies

Table 7: Investments in hydrogen infrastructure and storage

05 HYDROGEN APPLICATIONS

In the ambitious scenario of the FCH JU Hydrogen Roadmap Europe, the hydrogen demand in 2030 is 665 TWhHHV or about 16,9 million tonnes as a starting point. We have made some small adjustments for the hydrogen demand for feedstock and for heating, compared to the roadmap.

9,1 MILLION TONNES HYDROGEN FOR THE TRADITIONAL INDUSTRY FEEDSTOCK

The traditional use of hydrogen, as feedstock in chemical and refineries (9,1 million tonnes in 2030), does not need additional or new investments in equipment. The cost of decarbonising the production of this hydrogen is already included in the section “production” and “infrastructure and storage” For the other hydrogen applications, new feedstock, hydrogen heating, mobility and electricity balancing, the investment in new hydrogen equipment, appliances, etc. is necessary and estimated in the next chapters.

2,5 MILLION TONNES HYDROGEN FOR NEW INDUSTRY FEEDSTOCK

1 million tonnes hydrogen for 20 million tonnes steel production

In Sweden Hybrit, a joint venture between SSAB, LKAB and Vattenfall, is developing since 2016 a process where hydrogen is used for direct reduction of iron ore, called DRI (Direct Reduction of Iron). With the DRI process about 45-55 kilo hydrogen is needed to produce 1 tonnes of crude steel[1]. 1 million tonnes hydrogen is therefore needed to produce about 20 million tonnes steel. The total steel production in the EU was about 160 million tonnes in 2019, assumed that it will increase to 200 million tonnes, then the crude steel production with hydrogen as feedstock can cover 10% of steel production in the EU.

According to Hybrit, the production cost for crude steel with the DRI process will be 20-30% higher, this is partly caused by higher fuel cost and extra investment cost for retrofitting and installing new furnaces, ovens and other equipment in steel plants.

[1] Hybrit. Fossil free Steel, summary of findings from HYBRIT pre-feasibility study 2016-2017

Assessment of hydrogen direct reduction for fossil-free steelmaking, Valentin Vogl, Max Åhman, Lars J. Nilsson Journal of Cleaner Production 203 (2018) 736-745

The production costs for 1 tonne of steel are about 300 Euro/tonne. If you want to fully compensate this price difference, about 75 Euro per tonne crude steel needs to be supported, which means about 1 billion Euro per year.

However, Hybrit has assumed higher hydrogen production costs than via the 2x40 GW Green Hydrogen Initiative, even when transport and storage costs are included. Therefore, it seems logical to stimulate realizing DRI steel plants, by giving an investment grant and/or subordinated loans with low interest rates. The Capex cost of a DRI steel plant is estimated at about 350-450 Euro per ton of produced steel. So total investment to produce 20 million ton steel is about 8 billion Euro. A 25% investment grant could be considered.

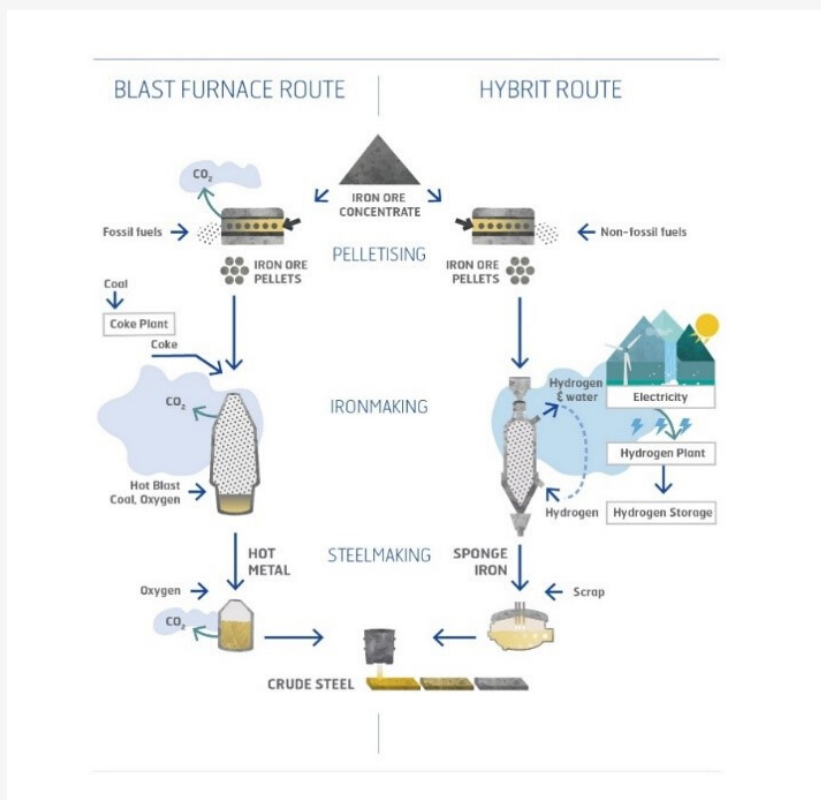


Figure 2. schematic overview steel production via blast furnace and via DRI process, source Hybrit

1,5 million tonnes hydrogen for 3 million tonnes synthetic kerosene and 2 million tonnes synthetic diesel

The kerosene demand in the EU in 2018 was 62,8 M tonnes. Kerosene is one of the products produced from oil by a refinery. On average 7,5% of the refinery output is kerosene.

[1] Ad van Wijk, Frank Wouters, Hydrogen, the bridge between Africa and Europe, to be published in Shaping an inclusive Energy Transition, Springer, 2020

[2] Analysis of advanced H2 production & delivery pathways, Strategic Analysis, June 2018

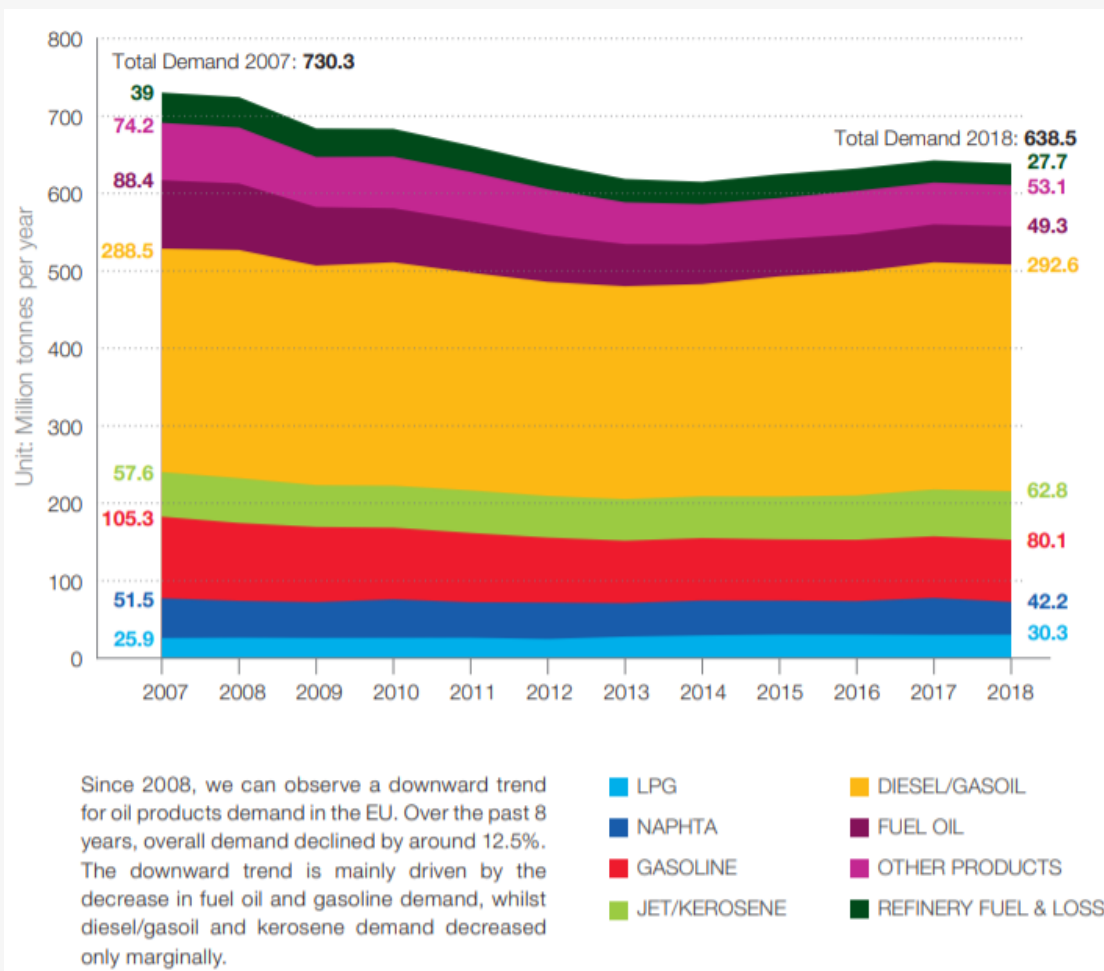


Figure 3. Historical demand for oil products in the EU 2018; source Wood McKenzie

Kerosene can also be produced by synthesis of hydrogen and carbon monoxide in a Fischer Tropsch (FT) process and is called synthetic kerosene. Theoretically, for the production of 1 tonne of kerosene about 0,3 tonnes of hydrogen is needed. However, the output of the Fischer Tropsch synthesis is not only kerosene. A Fischer Tropsch synthesis can deliver as output about 60% kerosene and 40% diesel. Therefore, 1,5 million tonnes hydrogen in a FT synthesis will deliver 3 million tonnes synthetic kerosene and 2 million tonnes synthetic diesel.

We assume that only the investment cost in a Fischer Tropsch installation is needed to produce synthetic kerosene and diesel. The CO will be supplied from other processes, from biomass gasification plants (green CO) or synthesis gasses from conventional steel plants or refineries where the CO is re-utilized (CCU carbon capture and utilization). Investment cost for Fischer Tropsch is estimated to be 650 Euro per tonne synthetic fuel output[1] (kerosene + diesel). The total investment is therefore 3,25 billion Euro. An investment grant of 25% could be considered.

[1] Carbon Neutral Aviation with current engine technology: the take-off of synthetic kerosene production in the Netherland, Quintel and Kalavasta, March 2018

2 MILLION TONNES HYDROGEN REPLACING OR BLENDED IN NATURAL GAS FOR HEATING

The final gas consumption in the EU28 in 2017 was 2.783 TWh. This was mainly for heating, both for space heating of houses and buildings, and for high and medium temperature heating in industry such as process heat in food and paper industry and high temperature heat in chemical, glass/ceramics industry. We assume that natural gas consumption in 2030 will be around 2.500 TWh. When 2 million tonnes hydrogen is used for low and high temperature heating, this will replace 3,33% (energy content) of the gas consumption (80 TWh) or will mean 10% (volume based) blending hydrogen into the gas system.

Scenario 1: 100% pure hydrogen for heating replacing 3,33% of natural gas demand

We assume in this scenario that 100% pure hydrogen is used to replace 3,33% of the gas demand in 2030. 75% of this hydrogen (1,5 million tonnes) is for heating houses and buildings and 25% for process/high temperature heat. This will imply the below numbers of hydrogen installations for heating in the EU in 2030.

Hydrogen for space (low temperature) heating in houses and buildings is an interesting option, especially for rural areas, small villages and old town/historical city centres. Other space heating options, such as all electric heat pump or district heating are in these areas not applicable and/or more expensive. We assume that 1,5 million tonnes of hydrogen in 2030 will be used in houses/buildings in these areas. After isolation, it is assumed that these houses consume on average about 250 kg of hydrogen (equivalent of 900 m³ natural gas) when heated by a hydrogen boiler. 125 kg of hydrogen is used to heat up a house with a hybrid heat pump hydrogen boiler system and 250 kilo hydrogen is used in a fuel cell heat pump system that produces both heat and electricity. Regions/areas/cities are fully converted from natural gas to hydrogen, which means that the natural gas distribution grid, including measurement equipment, in these areas is retrofitted to 100% hydrogen. Hydrogen boilers are already on the market and will not cost more than natural gas boilers when produced in large quantities. Also fuel cells, with a reformer to reform hydrogen from natural gas are already on the market in Japan, the so-called Ene-farm. In a 100% hydrogen supply, these reformers are not necessary, of course when 100% hydrogen is supplied, but on the other hand a small heat pump is required to produce enough heat.

A scenario in which 8 million houses/house equivalents are converted to 100% hydrogen, is given below which consumes 1,5 million tonnes hydrogen:

- 2 million houses/house equivalents with a hydrogen boiler. 1.500 Euro per boiler means total investments of 3 billion Euro.
- 4 million house/house equivalents with a hybrid system, heat pump plus a hydrogen boiler for peak heating and hot water. A 4.000 Euro investment per hybrid system means a total investment of 16 billion Euro.
- 2 million houses/houses equivalents with a 1-2 kWe fuel cell heat pump system for electricity and heat production. 7.500 Euro investment per system means a total investment of 15 billion Euro.
- 8 million houses/houses equivalents gas distribution grid infrastructure needs to be converted to hydrogen. Costs are about 200-300 Euro per house to convert natural gas distribution grid and measuring equipment into hydrogen. Total conversion cost are 2 Billion Euro[1].

Next to the hydrogen use for space heating, also 0,5 million tonnes of hydrogen for process heat and high temperature heat is estimated to be used in boilers, furnaces, gas-turbines, gas-engines, etc. If an average load factor of 5.000 hours is assumed, the total installed capacity that needs to be retrofitted to pure hydrogen is of about 4 GW. Retrofit cost for the installations plus gas infrastructure is about 250 Euro/kW. Total retrofit cost would be 1 billion Euro.

We can translate these numbers into a number of areas in Europe that will convert from natural gas to hydrogen. Each area is equivalent to 200.000 houses/house equivalents, plus industry. Which means 40 areas/hydrogen valleys in Europe converted from gas to hydrogen by 2030. The total investments in this scenario are estimated to be 37 billion Euro.

[1] Waterstof als optie voor een klimaatneutrale warmtevoorziening in de bestaande bouw, TNO Marcel Weeda, Robin Niessink, March 2020

Scenario 2: 10% volume hydrogen blending in natural gas system

We assume in this scenario that 10% volume hydrogen is blended in natural gas in 2030. Up to 20% volume can be blended in natural gas before gas appliances need to be retrofitted or replaced. Up to 20%, there is also no significant need to retrofit or adjust the natural gas infrastructure. However, due to the intermittency in hydrogen production by renewable hydrogen plants and especially the seasonal variations in gas demand for space heating, there will be fluctuations in the percentages of hydrogen blended in. Further research is needed, but rough estimates indicate that with an average of 10% hydrogen blending, actual blending percentages can vary between 0 and 40% when hydrogen is produced from solar and wind regionally. Keeping a constant blending percentage of hydrogen in natural gas needs therefore system re-design and adaptations.

The 10% blending of hydrogen in the natural gas system is equivalent to 2 million tonnes hydrogen.

In this blending scenario, there is, of course, no need to replace gas boilers and other heating equipment. However, anticipating full hydrogen conversion in areas that will convert to 100% hydrogen soon after 2030, could initiate the same numbers of heating appliances that are hydrogen ready. A hydrogen ready boiler is already on the market today and will not cost more than a new natural gas or hydrogen boiler. Also fuel cells, with on top a reformer to reform natural gas in hydrogen, are on the market in Japan, the so-called Ene-farm system, of which a couple of 100.000's systems are sold already in Japan.

- 2 million houses/house equivalents with a hydrogen ready boiler. 1.500 Euro per boiler means total investments of 3 billion Euro.
- 4 million house/house equivalents with a hybrid system, heat pump plus a hydrogen ready boiler for peak heating and hot water. 4.000 Euro investment per hybrid system means a total investment of 16 billion Euro.
- 2 million houses/houses equivalents with a 1-2 kWe natural gas reformer to hydrogen and fuel cell for electricity and heat production. 7.500 Euro investment per system means a total investment of 15 billion Euro.

The total investments in this scenario are about 34 billion Euro, but excludes the cost for blending hydrogen at a constant percentage into the natural gas system.

1,8 MILLION TONNES HYDROGEN FOR MOBILITY

In the Hydrogen Roadmap Europe, numbers for fuel cell electric vehicles are presented. Also, other hydrogen mobility applications will enter the market, such as fuel cell inland vessels, seagoing vessels that use ammonia as fuel in the diesel engine, tractors/heavy equipment that blend hydrogen in the air inlet in diesel engines, fuel cell drones, forklifts, etc. As investments we have taken the cost for the on-board fuel cell system or engine adaptation and the on-board hydrogen or ammonia storage tanks. Most of the fuel consumption and investment figures are from the FCH JU State of the Art and Future Targets KPI's 2024.[1]

The hydrogen needs to be transported to the hydrogen re-fuelling stations (HRS), which requires hydrogen tube trailers and liquid hydrogen trailers. 1 tube trailer can transport 350 kilo H₂ at 200 bar or 1.000 kilo on 500 bar. A liquid hydrogen trailer can transport 3.500 kilo H₂. We assume that 25% of the trailers is a liquid hydrogen trailer, 25% is a 500 bar tube trailer and 50% of the trailers is a 200 bar tube trailer. Each trailer supplies a re-fuelling station 1 time a day every day of the year. If 1 million tonne of hydrogen has to be supplied by tube trailers, there is a need of 2.400 tube and liquid hydrogen trailers. The liquid hydrogen trailers will transport about 750.000 tonnes hydrogen, while the tube trailers transport the other 250.000 tonnes hydrogen. However, to liquify the hydrogen, we need liquefaction plants. About 40 liquefaction plants that produce 50 tonnes liquid hydrogen per day are needed. Per kilo of liquid hydrogen 7 kWh of electricity is needed. The cost of a 50 tonnes per day liquefaction plant is about 40 million each.

Investments in transport/mobility hydrogen drive trains, mainly fuel cell systems and storage tanks plus the necessary liquefaction plants and trailers to transport hydrogen add up to about 40 billion Euro. We propose about half of this amount, 22 billion Euro as a subsidy to stimulate hydrogen mobility and especially fuel cell electric mobility.

[1] <https://www.fch.europa.eu/soa-and-targets>

	Number in 2030	H ₂ use per year per vehicle	Total H ₂ use per year	Investments in Euro • FC system • H ₂ tank	Total Investments Billion Euro	Subsidy Billion Euro
FC Passenger vehicles	3.700.000	25.000 km (lease cars, taxi's) 1 kg/100 km	0,93 Mt	• 5.000 • 2.500	27,8	4.000/car =14,8 billion
FC Light commercial vehicles	500.000	50.000 km 1,2 kg/100 km	0,30 Mt	• 5.000 • 3.000	4,0	6.000/car =3 billion
FC Trucks + busses	45.000	80.000 km 7,5 kg/100 km	0,27 Mt	• 75.000 • 12.000	3,4	50.000 per bus or truck =2billion
FC Trains	570	300.000 km 25 kg/100 km	0,05 Mt	1 million for FC system and hydrogen tanks	0,6	50% subsidy =0,3 billion
FC Inland Vessels Seagoing vessels Tractors/heavy equipment Drones, forklifts, etc.		Fuel Cell Ammonia in diesel engines Blending H ₂ in air inlet diesel Fuel cell	0,25 Mt		1,7	0,8 billion
Trailers for H ₂ transport to HRS	1.200 600 600	200 bar 500 bar liquid		250.000 Euro 500.000 Euro 500.000 Euro	0,9	50% subsidy =0,5 billion
Liquefaction plants	40	50 t per day		40 million	1,6	50% subsidy = 0,8 billion
TOTAL			1,8 Mt		40	22

Table 8: Numbers for hydrogen transport vehicles, ships, trailers, liquefaction plants with investments.

1,5 MILLION TONNES HYDROGEN FOR BALANCING ELECTRICITY PRODUCTION

The final electricity consumption in the EU28 in 2017 was 2.798 TWh. In 2030 it will grow to 3.000 TWh. With 1,5 million tonnes of hydrogen, efficiency of STAG (Steam and Gas turbine) powerplants at 50% and fuel cells at 60%, and half/half produced by STAG and fuel cells we can produce 32,5 TWh or about 1% of final electricity use. If we assume 3.250 h load factor for these power plants, total installed electricity production capacity with hydrogen would be 10 GW, 5 GW STAG power plants and 5 GW fuel cell power plants.

- 5 GW steam and gas turbine (STAG) hydrogen power plants. Capex of new STAG power plant between 1.000-1.500 Euro/kW. If we assume that this 5 GW will be retrofitting existing STAG power plants, with an investment cost of 250 Euro/kW, total investments are 1,25 billion Euro. A subordinated loan with low interest rate could help to do these investments.
- 5 GW fuel cell hydrogen power plants, new capacity. Capex of new fuel cell power plant between 500-1.000 Euro/kW. This is a total investment of 3,75 billion Euro. An investment grant of 1/3 of the investment could help to stimulate this, which would mean 1,25 billion Euro.

The total investments for retrofitting 5 GW STAG power plants and building 5 GW fuel cell hydrogen power plants is 5 billion Euro.

[1] <https://www.fch.europa.eu/soa-and-targets>

OVERVIEW HYDROGEN APPLICATION INVESTMENTS

Hydrogen Applications	Investments up to 2030 (Euro)	Support up to 2030 (Euro)
20 Mt steel production (10% of total) using 1 Mt hydrogen	8 billion	25% grants plus subordinated loans
3 Mt synthetic kerosene (5% of total) and 2 Mt synthetic diesel production using 1,5 Mt hydrogen	3 billion	25% grants plus subordinated loans
1,8 Mt hydrogen for mobility applications	40 billion	22 billion Euro subsidies.
2 Mt hydrogen replacing or blended in natural gas consumption for low and high temperature heating <ul style="list-style-type: none"> • Scenario; 100% pure hydrogen for heating replacing 3,33% of natural gas demand <ul style="list-style-type: none"> ○ 8 million houses, hydrogen appliances ○ Natural gas grid to hydrogen ○ High temp Hydrogen appliances • Scenario 10 volume% hydrogen blending in natural gas system <ul style="list-style-type: none"> ○ 8 million houses, hydrogen ready appliances ○ Blending cost to keep constant % H₂ ○ High temp Hydrogen appliances 	34 Billion Euro (2 Billion Euro) 1 Billion Euro 34 Billion Euro not known	20% grant, 6,8 billion Euro Fully covered by DSO/TSO 20% grant, 0,2 billion Euro 20% grant, 6,8 billion Euro Fully covered by TSO/DSO -
32,5 TWh (1%) electricity production for balancing, using 1,5 Mt hydrogen	5 billion Euro	1,25 billion grants Plus subordinated loans
TOTAL	90 billion Euro	Subsidies 35 billion Euro

Table 9: Investments in new hydrogen applications

06 SCALE UP HYDROGEN MANUFACTURING CAPACITY

Investing in renewable energy and hydrogen production, hydrogen infrastructure and storage and in hydrogen applications up to 2030 an amount of 430 billion Euro, creates an interesting market for the European manufacturing industry. The manufacturing industry can scale up manufacturing production capacity and will be able to produce at competitive prices if this hydrogen markets will become reality. There is a variety of hydrogen manufacturing industry, but especially electrolyser and fuel cell manufacturing together with a large variety of hydrogen application manufacturing needs to scale up their production capacity.

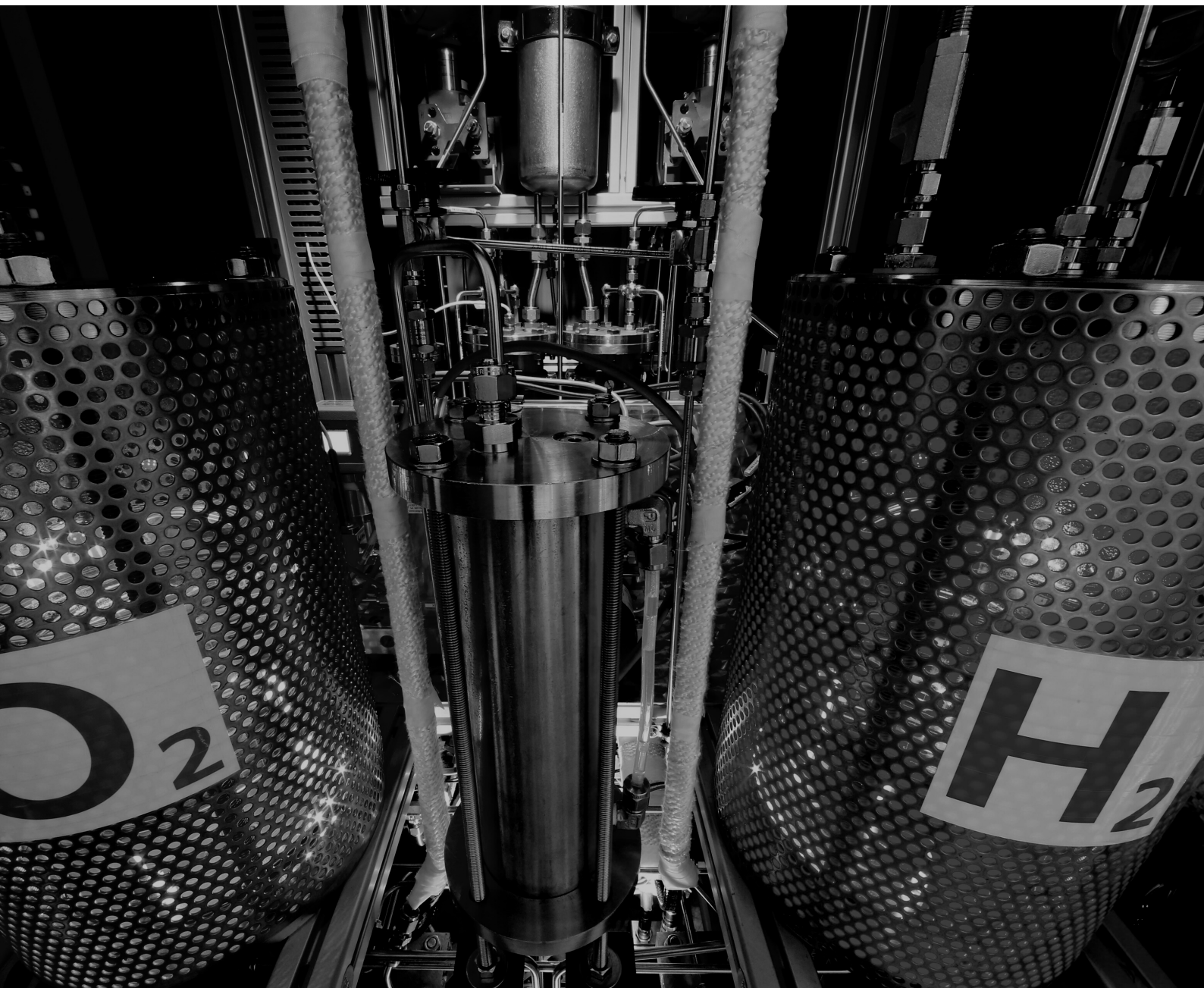
Scaling up electrolyser with supply chain manufacturing capacity: Currently, the European manufacturing capacity is about 1 GW per year, it needs to be scaled up to 25 GW/year in 2030 to fulfil the 2x40 GW Green Hydrogen Initiative.

Scaling up fuel cell with supply chain manufacturing capacity: Currently, the fuel cell manufacturing capacity is very limited. This fuel cell capacity needs to be scaled up to a 10-100 GW/year range. Fuel cells are needed for a variety of applications for automotive, maritime, drones, planes, for power plants and for micro CHP (Combined Heat and Power) home fuel cells.

Scaling up hydrogen application manufacturing capacity: The manufacturing capacity for hydrogen compressors, boilers, hydrogen drive trains and storage tanks for cars, trucks, busses, vans, ships, trains, drones, planes, hydrogen refuelling stations, bunkering facilities, pipelines, sensors, measuring equipment, liquefaction plants, ammonia cracking, etc., etc. needs to be build up. Existing manufacturing industry for natural gas, automotive, chemistry and others could adapt or change their activities to these new hydrogen applications and markets.

In order to support a European hydrogen manufacturing industry, the following steps and actions are required:

- The EU and Member States could provide loans, mezzanine financing and equity. They should try to build world champions (like Airbus) and pay for education cost, part of salary for a couple of years, land cost, tax exemptions, etc.
- The EU needs also policies to prevent take overs by companies outside the EU.
- The EU needs to formulate and implement criteria that in tender procedures, subsidy programmes and procurement will allow European companies to get a preferential treatment. For example, by formulating number of jobs created in the EU, innovation and research budget spending in the EU, tax payment in EU, etc.
- Above all, many companies mention that the most important factor to decide to expand manufacturing capacity is that they can be sure that targets for the market, such as the 2x40 GW electrolyser capacity in 2030 and hydrogen demand increase are secured and guaranteed by governments and European Union



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