



SEVENTH FRAMEWORK PROGRAMME

Joint Technology Initiatives - Collaborative Project (FCH)

Water decomposition with solar heat sources

Deliverables D 6.3 & 6.4

Analysis of market introduction scenarios

&

Potential synergies with other technologies

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Table of Contents

1.	Introduction	1
2.	Overview of the current hydrogen Market	1
2.1	General	1
2.2	Consumption	1
2.3	Production	2
2.3.1	General	2
	<i>Production from hydrocarbon feedstock</i>	3
	<i>Production by electrolysis of water</i>	3
2.4	Transportation and its impact on market structure	4
3.	The hydrogen Market – Perspectives	5
3.1	General	5
3.2	Short to mid-Term perspectives (2020)	5
a)	<i>Crude oil refining</i>	5
b)	<i>Non-ethanol Bio-fuel upgrading</i>	7
c)	<i>Production of synthetic fuels from coal</i>	7
d)	<i>Hydrogen make-up in gaseous fuel</i>	8
e)	<i>Fuel cell vehicles supply</i>	8
f)	<i>Stationary hydrogen Fuel Cells</i>	11
g)	<i>Chemical usages of hydrogen</i>	11
h)	<i>Conclusion / Global hydrogen market</i>	11
3.3	Long-Term perspectives (2050)	12
a)	<i>Fuel Cell Vehicles adoption</i>	12
b)	<i>Stationary Fuel Cells for buildings</i>	13
c)	<i>Stationary Fuel Cells for renewable power storage</i>	14
d)	<i>Bio-fuel upgrading</i>	14
e)	<i>Refining and hydrocarbon conversion</i>	14
f)	<i>Chemical usages of hydrogen</i>	14
g)	<i>Conclusion / Global hydrogen market</i>	14
4.	Criteria for defining market introduction scenarios	14
4.1	Definition of criteria	14
4.2	Economical benchmarking for the production of hydrogen	15
4.3	Solar resource	18
4.4	Water availability	19
4.5	Sensitivity to discontinuous production	19

4.6	Hydrogen quality requirement	20
4.7	Consumer unit size	20
4.8	Downstream hydrogen delivery chain	20
4.9	Review of possible synergies with other technologies	20
a)	<i>Opportunities for horizontal integration</i>	20
b)	<i>Opportunities for vertical integration</i>	21
4.10	Market Introduction & Deployment scenarios - Assessment matrix	21
5.	Introduction scenarios (mid-term)	23
5.1	Foreword – First plant preceding market introduction	23
a)	<i>General philosophy of market introduction</i>	23
	<i>Introduction scenarios proposed</i>	23
6.	Deployment scenarios (long-term)	24
7.	Conclusion	25
8.	References	25

List of abbreviations

CSP	Concentrated Solar Processes or Concentrated Solar Power
CTL	Coal To Liquid processes
DNI	Direct Normal Irradiance
FC	Fuel Cell
GHI	Global Horizontal Irradiation
HC	Hydrocarbons
LCA	Life Cycle Analysis
PSA	Pressure Swing Absorption
PV	Photovoltaic
RE	Renewable Energy or Renewable Electricity
SMR	Steam Methane Reforming

1. Introduction

This single document reports on the work performed under the tasks 6.3 and 6.4 of the Hydrosol 3D program.

Within the Work Package 6 dedicated to the technical-economic studies and market analysis, the tasks 6.3 and 6.4 together cover the 2nd theme (market analysis). The analysis performed identifies and quantifies the markets that can be addressed by the Hydrosol 3D process in the mid to long term. Realistic scenarios are built for the initial market introduction, followed by a real market deployment. For so, the Hydrosol 3D process is considered either stand-alone or in synergy with another process when this brings a technical and/or economical advantage.

The report first presents the current state of the hydrogen market, then its mid and long term perspectives. Criteria for selecting the best market strategy – including synergy opportunities - are then reviewed. On the basis of the information gathered, introduction and deployment scenarios are proposed.

2. Overview of the current hydrogen Market

2.1 General

Still today, hydrogen is predominantly produced and consumed either in one single plant or in nearby plants connected physically by short hydrogen pipelines and commercially by long term contracts (“captive producers” & “captive users”). Therefore, it’s not a product widely traded on marketplaces and the worldwide hydrogen production data are not precisely monitored but only estimated.

This chapter presents the main available facts about the current status of hydrogen consumption, production and transportation.

2.2 Consumption

The hydrogen market is currently dominated by the oil refining and fertilizer production.

In 2006, the worldwide hydrogen production was estimated to 56,7 Mt with the following allocation by market segments [1-3].

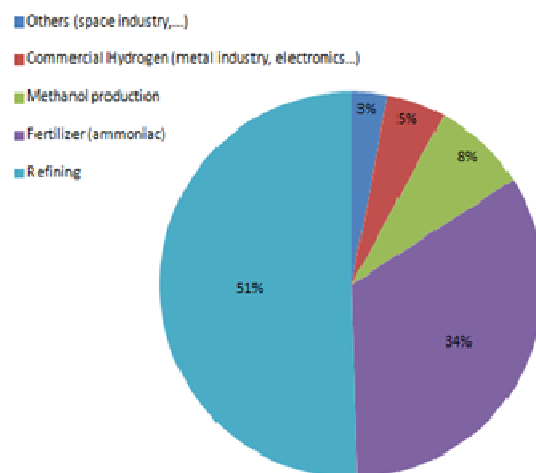


Figure 1 - Hydrogen market repartition [1-3]

The chemical usages of hydrogen (oil refining, methanol and ammoniac production) cover 92% of the total market.

Oil refiners, ammoniac and - to a certain extent - methanol producers are generally “captive users” [2]. In 2003, hydrogen “bought on the market” in Western Europe was estimated to only 9% of the total consumption [4].

Even if widely discussed in the scientific and economic literature, the direct usage of hydrogen for transport is still below the statistics detection lines.

Figure 2 below summarizes the current hydrogen markets and the typical consumption per client on each market segment.

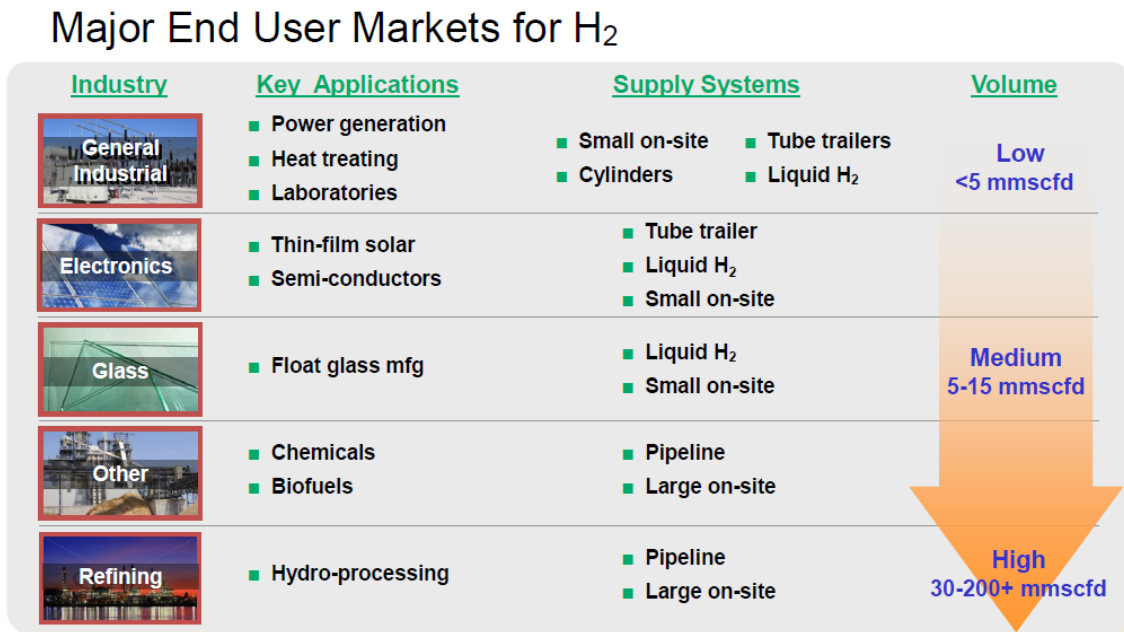


Figure 2 - Major end-users of hydrogen [6]

2.3 Production

2.3.1 General

Hydrogen producers can be classified in 3 categories:

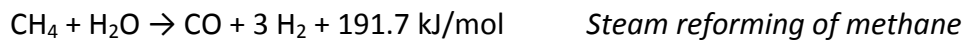
- the captive producers (producing hydrogen for their own use or for the one of their “stranded” customers),
- the by-product hydrogen producers (producing hydrogen as a secondary product of their main business – e.g. chloro-alkali process industries)
- the merchant producers (producing hydrogen for trading purposes) [2, 6].

The captive producers represent by far the largest share of the market.

Only 4% of the hydrogen produced worldwide is produced by electrolysis of water (year 2006 estimates). 96% is derived from hydrocarbons (HC) feedstock (49 % from Natural Gas, 29 % from liquid hydrocarbons and 18 % from coal) [2].

Production from hydrocarbon feedstock

- H₂ from natural gas and part of the one from liquid hydrocarbons is produced through steam reforming of the HC feedstock, followed by a water gas shift reaction to increase hydrogen production. The chemistry of this 2 step process is described below for a methane feedstock:



- Hydrogen is also generated from liquid hydrocarbon feedstock as a by-product of catalytic reforming units. Catalytic reforming is a refining operation conducted to increase the octane rating of gasoline. It involves a number of chemical reactions, among which the dehydrogenation of naphthenes into aromatics and the aromatization of paraffins which both produce hydrogen.
- H₂ from coal is produced by gasification of the feedstock followed by water gas shift.

Production by electrolysis of water

1) Dedicated production process

Electrolysis of water corresponds to the decomposition of the H₂O molecule into oxygen (O₂) and hydrogen (H₂) driven by an electric power (see principle below).

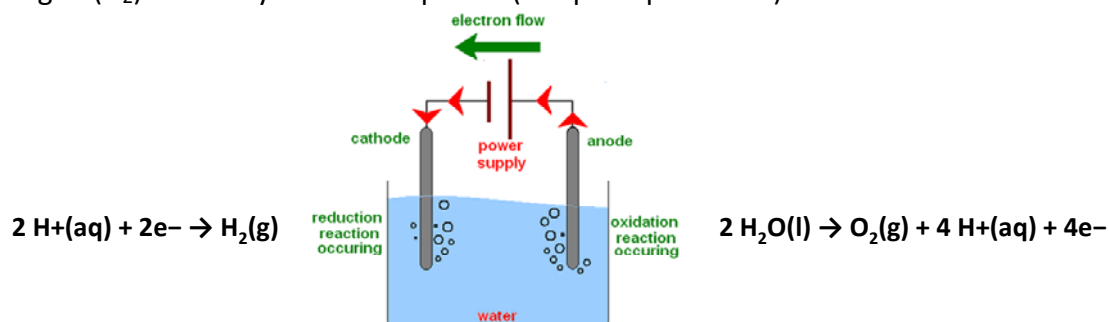


Figure 3 - Principle of electrolysis

Most industrial electrolysis cells use complex platinum plates or honeycombs as electrodes. Their use is currently limited to niche applications where production and consumption are closely connected or when extremely high hydrogen purity is required.

2) Generation as by-product of chlor-alkali processes

Chlor-alkali processes correspond to the electrolysis of brine for the production of chlorine, caustic soda and their derivatives (see principle below). The electrochemical reactions involved generate hydrogen at the cathode.

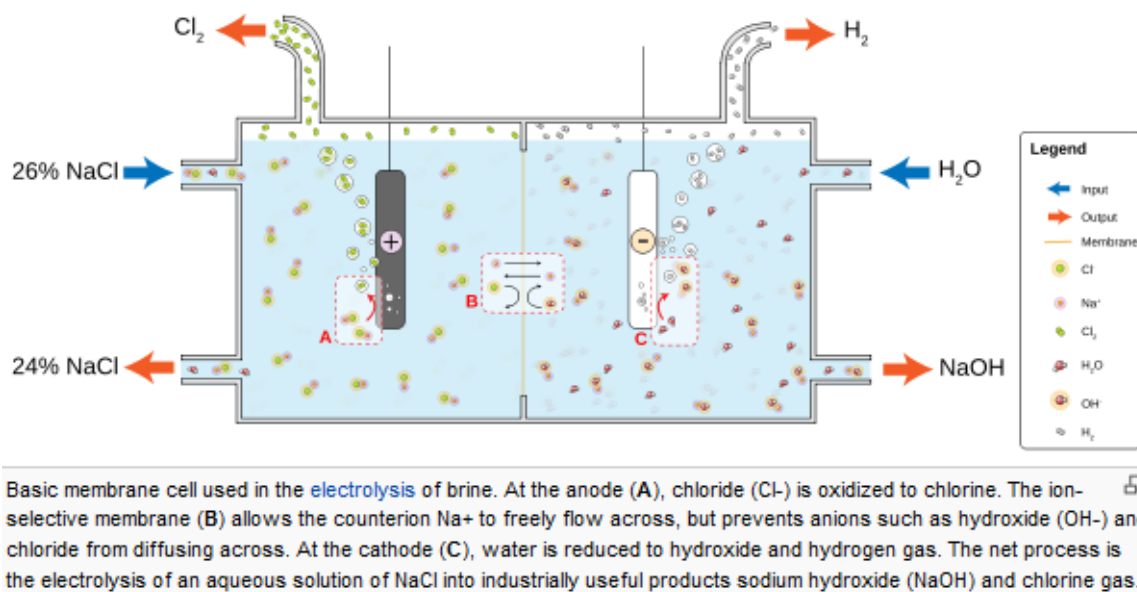


Figure 4 - Principle of the chlor-alkali process [7]

The world production of chlor-alkali hydrogen is estimated to about 1.4 million tons/year [8]. Chlor-alkali product producers usually recover and market this valuable by-product (but about 15% of this hydrogen remain vented).

2.4 Transportation and its impact on market structure

With current technologies, hydrogen storage and transportation are costly, which is a clear obstacle to the development of merchant producers and limits hydrogen valorisation when it comes as a by-product of a chemical process. For hydrogen as for natural gas, product transportation issues model the market.

Hydrogen is produced in vapour phase and is generally used locally. Only a very limited share of it is transported over more than a few hundred meters.

- Transport by pipeline covers 95% of the transport of “merchant hydrogen”. Nevertheless, this mode of transport is limited to areas where demand from oil refining and chemical industries is dense (the cumulated length of hydrogen grids is estimated to about 3000 km in total, mostly located in Europe and the US. As a comparison natural gas transport grid is over 2 million km) [9].
- Hydrogen can alternatively be transported under gaseous form by trailers loaded with special high pressure containers (200 or 300 bar). In such trailers, the weight of hydrogen transported is less than 2% of the total weight of the truck and the containers [9]. This limits this type of transport to medium capacity consumers located at distances from the production facility short enough to allow frequent and regular deliveries (200 to 300 km maximum).

Road transportation is easier for liquid hydrogen. A lorry carrying cryogenic hydrogen can load 10 times as much hydrogen as a trailer carrying gas containers, thus allowing higher capacity deliveries over longer distances. On the other hand, hydrogen liquefaction is costly, both in

investment and in energy (liquefaction consumes about 3 times more power than compression for transport) and liquefaction units aren't widely available [9].

3. The hydrogen Market – Perspectives

3.1 General

Short term markets perspectives (< year 2020) are modelled by the expected evolutions of mature and already emerging markets. If growth rate figures may vary between estimation sources, tendency and orders of magnitude are quite consensual.

Long terms perspectives, on the other hands, are closely dependent on scenarios describing the possible evolution of the worldwide energy mix in the next decades. Possible scenarios are numerous, creating a wide span of possible market sizes for hydrogen in 2050.

This chapter first presents the expected market evolution until 2020 and then introduces its long-term perspectives.

3.2 Short to mid-Term perspectives (2020)

Worldwide hydrogen consumption is growing and will continue to grow under the combined influence of evolving mature market and emerging applications. This paragraph details expected short term market evolution for each major segment.

The main identified growth driver corresponds to the increasing role of hydrogen in the fuel sector, but more for hydrocarbon or biomass upgrading than for direct use as combustible. Other hydrogen applications are not expected to undergo major changes by 2020.

a) Crude oil refining

The oil refining industry uses hydrogen for two mains “fuel upgrading” applications:

- The hydrotreatment of fuels for sulfur removal (Hydrodesulfurization)

Example of the hydrodesulfurization reaction for ethanethiol: $C_2H_5SH + H_2 \rightarrow C_2H_6 + H_2S$

- The hydrocracking of heavy distillate cuts for their conversion into lighter saturated hydrocarbons

The proportion of heavy crudes in the world oil production is constantly increasing and, simultaneously, the regulation on sulfur content in fuels is becoming more and more stringent. The consumption of hydrogen per barrel of oil refined will consequently increase very significantly in the near future, as illustrated on the figures below [5].

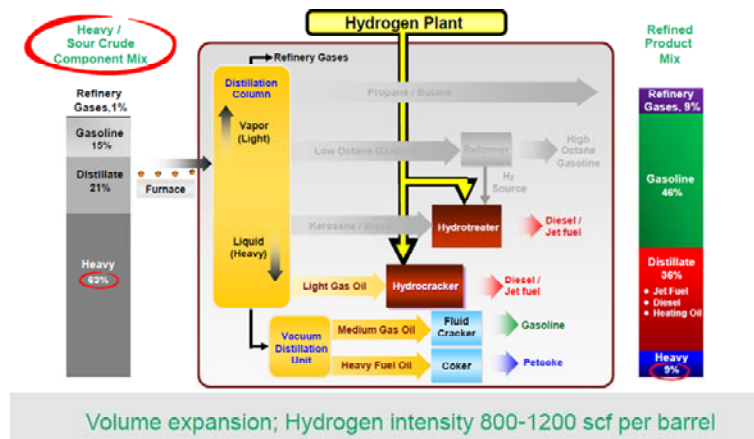
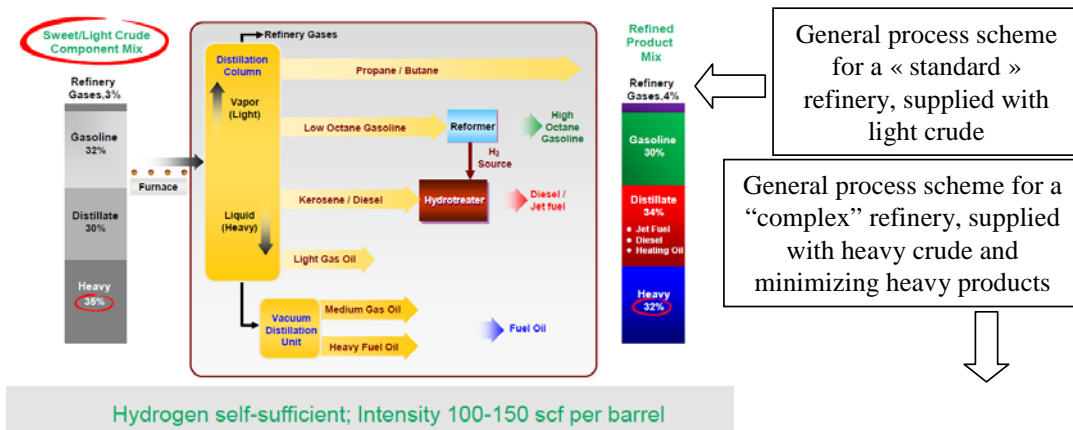


Figure 5 - Hydrogen for oil refining [5]

Figure 6 shows the estimated growth of hydrogen demand for the refining industry under the combined effect of the growth of the worldwide refining capacity and the increase of the average hydrogen consumption per barrel of oil refined (estimates from the hydrogen producer Praxair – [5]).

Between 2012 and 2020, the increase of hydrogen demand for refining can be estimated to about 10.5 Mt/year (corresponding to 12Bscfd). This represents more than 15% of the estimated year 2012 global market size.

Hydrogen Demand Growth

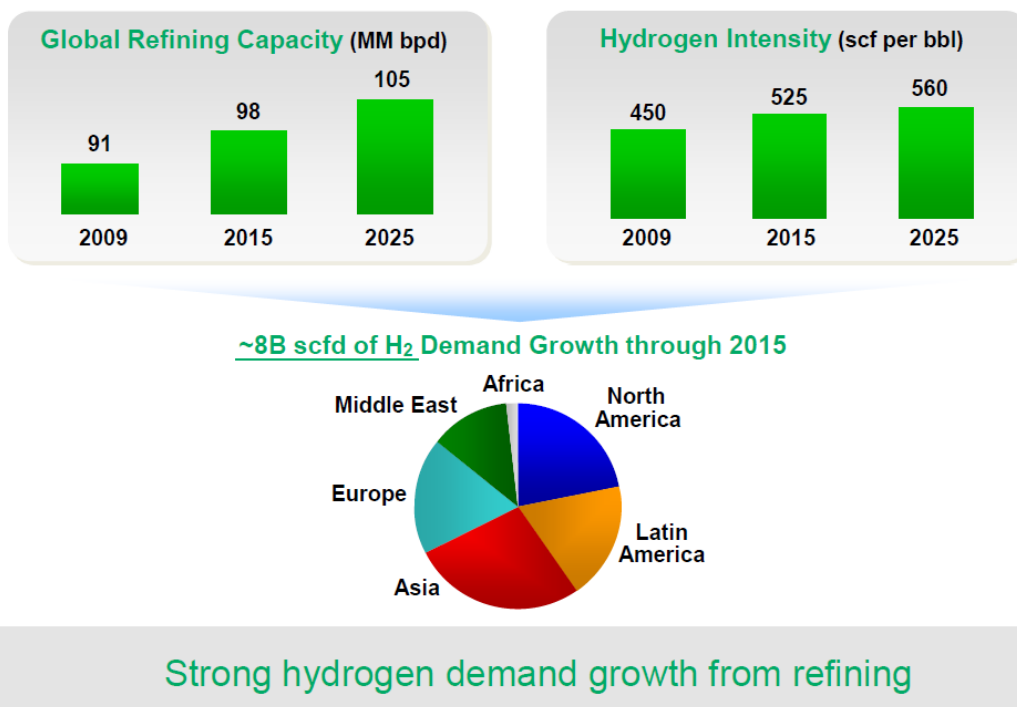


Figure 6 - Growth of hydrogen demand for refining

b) Non-ethanol Bio-fuel upgrading

Ligno-cellulosic biomass feedstocks can generally be represented by the average formula $C_6H_9O_4$ while fuel oil composition is close to CH_n with n close to 2 [10]. So hydrogen plays an important role in the conversion of biomass into non-ethanol liquid fuels. It is used both to

- remove the oxygen under the form of H_2O (alternate to the O removal under the form of CO_2 , which lead to a loss of carbon and to direct greenhouse gas emission)
- increase hydrogen concentration in the molecules

Biomass transformation processes are numerous and won't be detailed in this document. But it can be outlined that hydrogen supply to these processes can be either direct (e.g. hydrogenation of vegetal oils) or hidden (when hydrogen is brought through methanol).

The bio-fuel market is increasing worldwide, driven by the increased cost of oil and political incentives in specific countries. This consequently creates an increasing demand of hydrogen for that sector, with a clear premium given to green hydrogen as it increases the "green rating" of biofuels and helps them meeting legal requirements.

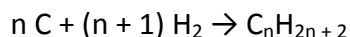
c) Production of synthetic fuels from coal

Coal can be used as raw material for synthetic fuel production. As the ratio H/C of coal is much lower than that of liquid hydrocarbons, transformation processes either eliminate carbon or incorporate hydrogen to the feedstock (H/C ratios range between 0.4 & 0.85 for coals versus 1.5 to 2 for standard oil and benzine).

Pyrolysis processes convert part of the carbon of coal into coke and produce a limited amount of liquid hydrocarbons. These processes, still at industrial demo stage, are not detailed here.

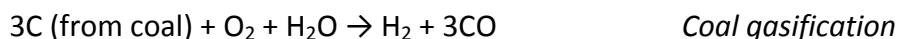
Liquefaction processes (“Coal To Liquid” or CTL) add hydrogen to coal to favour liquid HC production. Liquefaction can be “direct” or “indirect”.

- *Direct coal liquefaction processes* consist in specific types of hydrogenation processes. Their global aim is to enrich coal with hydrogen. They can globally be summarized by the following reaction:



Liquefaction is performed under hydrogen pressure within a slurry of coal dissolved into an “hydrogen donor solvent”.

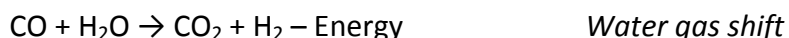
- The *indirect coal liquefaction* involves two reaction steps. Coal first reacts with oxygen and steam in a gasifier to produce a syngas (CO & H₂ mixture) with low hydrogen content.



The syngas has then to be transformed into synthetic fuel in a Fischer Tropsch process. The major Fischer Tropsch reaction corresponds to the production of alkanes as indicated below:



Hydrogen content of the syngas from the coal gasifier is significantly lower than the stoichiometric requirements of the alkane synthesis. Syngas composition can be adjusted through water-gas shift reaction where part of the CO is used with water to generate CO₂ and H₂, but this creates high carbon dioxide emissions.



Alternatively, hydrogen could be injected in the syngas upstream of the Fischer Tropsch. This would imply large volume of H₂.

Conclusion - Hydrogen for synthetic fuel production from coal

The paragraphs above clearly show that the deployment of coal liquefaction processes will create a significant demand for hydrogen.

These processes have already been applied at large scales in some industrial sectors. But they have high capital costs as well as high operation and maintenance costs, which make them profitable only in a context of high price of crude oil. The simultaneous stability of oil prices at high level and the increasing concerns on greenhouse gas emission may lead to a visible increase of Coal To Liquid projects based on hydrogen make-up rather than water-gas shift adjustment. Nevertheless, considering the time required to develop such projects, this increase is not considered significant by 2020.

d) Hydrogen make-up in gaseous fuel

Upgrading of NGV (Natural Gas for Vehicles) with hydrogen is possible and marketable products are already proposed under the names HCNG and Hythane®. Despite the interest of these products for the control of pollutant emissions, their use has been limited to demonstration operations. This market is not expected to contribute significantly to hydrogen demand by 2020.

e) Fuel cell vehicles supply

Use of hydrogen in fuel cells for vehicles is probably the opportunity for hydrogen market growth most discussed in literature.

Fuel cells convert the chemical energy of a fuel into electricity through a chemical reaction with an oxidizing agent. Hydrogen is the fuel most commonly used, especially for mobile applications.

All fuel cells assemble an anode, a cathode and an electrolyte that allows charges to move between the two sides of the fuel cell [11]. Electrons flow from the anode to the cathode through an external electrical circuit, thus producing electricity (see figure hereafter). The fuel cells differ from batteries in that they need a continuous supply of fuel to generate electricity.

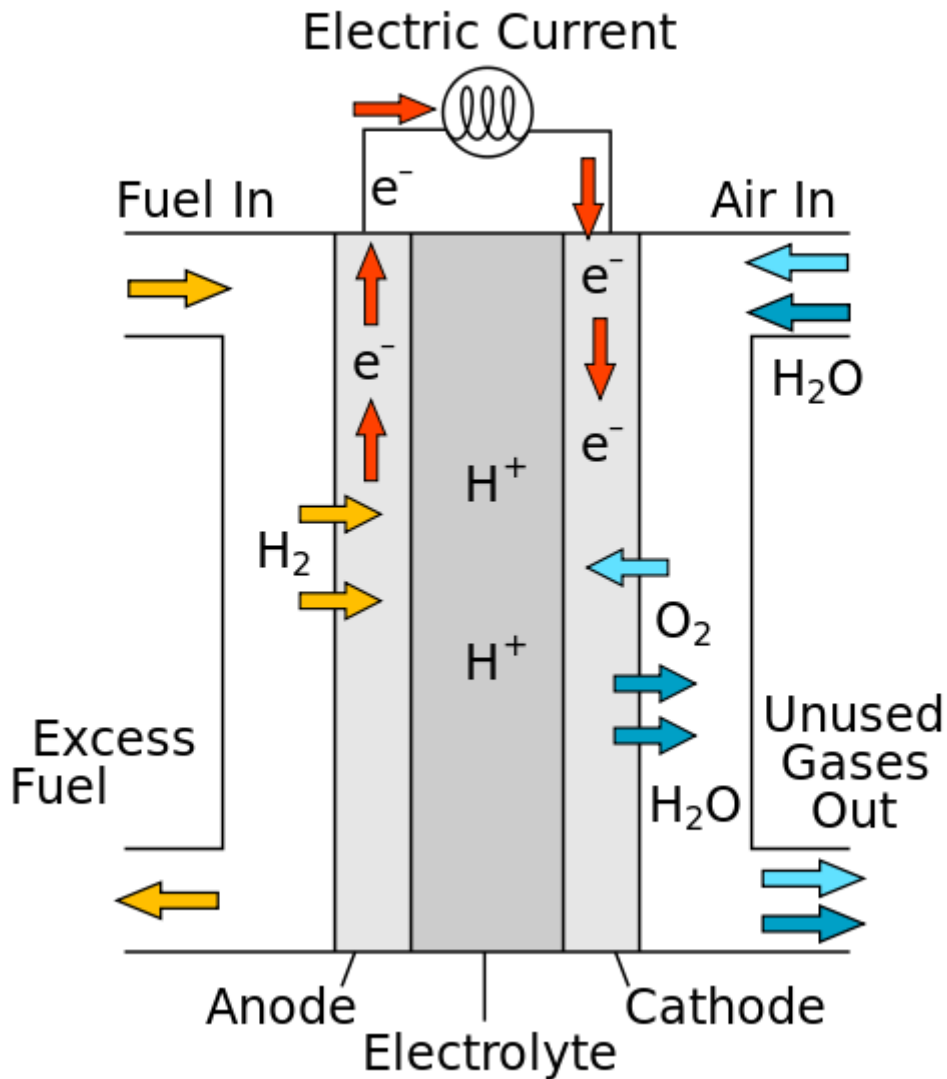


Figure 7 - Principle of a proton fuel cell [11]

There are many types of fuel cells involving different electrolytes. The main ones are the followings:

- Proton exchange membrane fuel cells (PEMFC)
- Solid oxide fuel cells (SOFC)
- Molten carbonate fuel cells (MCFC)

These fuel cells are generally developed to run with hydrogen rather than hydrocarbons, so that the only waste they produce is water.

Great expectations about Fuel Cells market growth have been on for years and R&D effort has been significant to make this growth happen. Nevertheless, Fuel Cells technologies are still struggling to find a real market. The table below shows the estimated numbers of Fuel Cell units shipped in 2012.

Table 1 – Estimated FC technology deployment as of 2012 [12]

Technology	Transportation	Stationary	Portable
PEM fuel cells	3,100	17,800	50,000
SOFCs	0	2,600	0
MCFCs	0	0	0
Alkaline fuel cells	0	0	0

Up to now, Fuel Cells have found cost-effective applications only for niche markets (i.e. power supply to remote telecom systems and material handling vehicles) [12]. Their large scale market (passenger vehicles) is only emerging and its development will depend on a number of economical parameters, hydrogen and oil prices being among the major ones.

Lux Research performed a critical analysis of the Hydrogen Fuel Cells market perspectives and ended-out with the following view of the market expected growth according to the evolution of the global economical frame (i.e. evolution of crude oil and hydrogen prices).

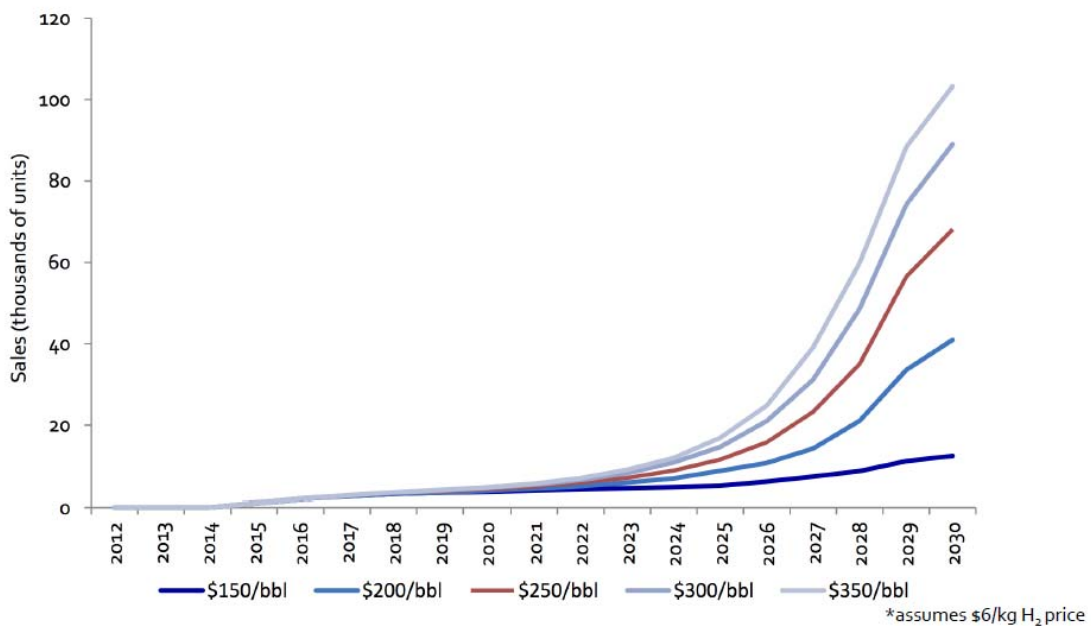


Figure 8 - FC vehicles market as a function of 2030 oil price [12]

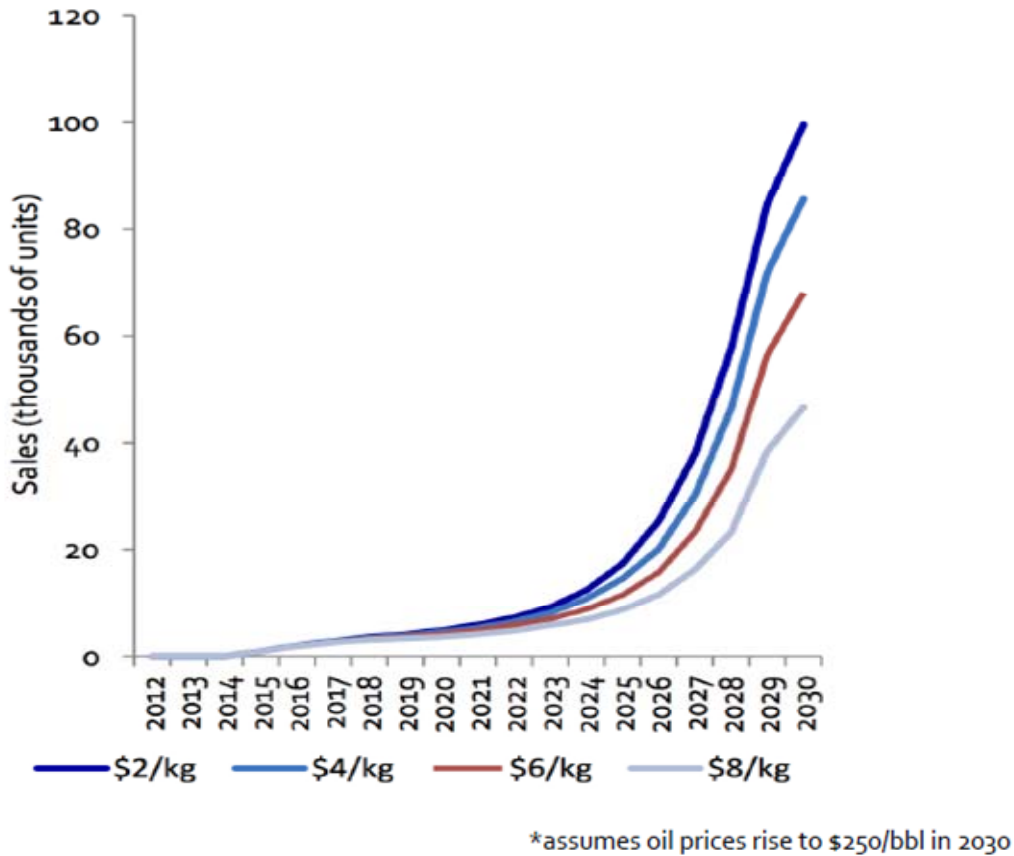


Figure 9 - Expected Vehicle FC market growth according to H₂ price [12]

If global economical frame impacts significantly 2030 perspectives, no significant take-off of the FC market is expected by 2020, whatever the price of oil and hydrogen supplies. Nevertheless, it is expected that efforts made to initiate a “green infrastructure and supply chain” for fuel cell vehicles will offer niche market opportunities for green hydrogen before 2020.

f) Stationary hydrogen Fuel Cells

As shown in Table 1, stationary application of Fuel Cells are currently very limited and, according to the International Energy Agency, prospect remains very limited until 2030 [13]. Therefore, no significant contribution of stationary fuel cells to H₂ market is expected by 2020.

g) Chemical usages of hydrogen

No paradigm change is expected on other usages of hydrogen (ammonia/fertilizers, methanol, float glass industry, food industry....). The growth of hydrogen market for these sectors is assumed to follow the growth of each sector, i.e.

- +7%/year for methanol (assessment from data from [14])
- +5%/year for ammonia (assessment from data from [15])
- +3%/year for other market (based on expected world economic growth – low estimate)

h) Conclusion / Global hydrogen market

From the data presented above for each market segment, the global hydrogen market is expected to grow by about 5,5% per year by 2020 and reach a global volume exceeding 100 Mt/year.

93% of this market correspond to applications using very large volumes of hydrogen (refining, ammonia, methanol) where hydrogen producers and consumers will generally remains stranded. The remaining 7% (i.e. about 7MT/y) could – at least partly - be supplied with merchant hydrogen.

3.3 Long-Term perspectives (2050)

As mentioned in §3.1, long terms hydrogen market perspectives are closely dependent on scenarios describing the possible evolution of the worldwide energy mix in the next decades. Global growth will be a combination of the contribution of new market drivers and mature market evolutions.

a) Fuel Cell Vehicles adoption

The main new driver identified is the expected adoption of Fuel Cell passenger vehicles.

The graph below illustrates the 2050 perspectives for vehicle fuel mix according to the MAP scenario¹ and Base scenario¹ of the International Energy Agency [13].

Capacities are expressed in “equivalent hydrogen energy” per year (1EJ/y corresponds to 8.4Mt H₂/y on H₂ LHV basis).

Perspectives for fuel hydrogen (bright blue part) vary from about 10MT/y in the base scenario to about 110MT/y in the MAP scenario.

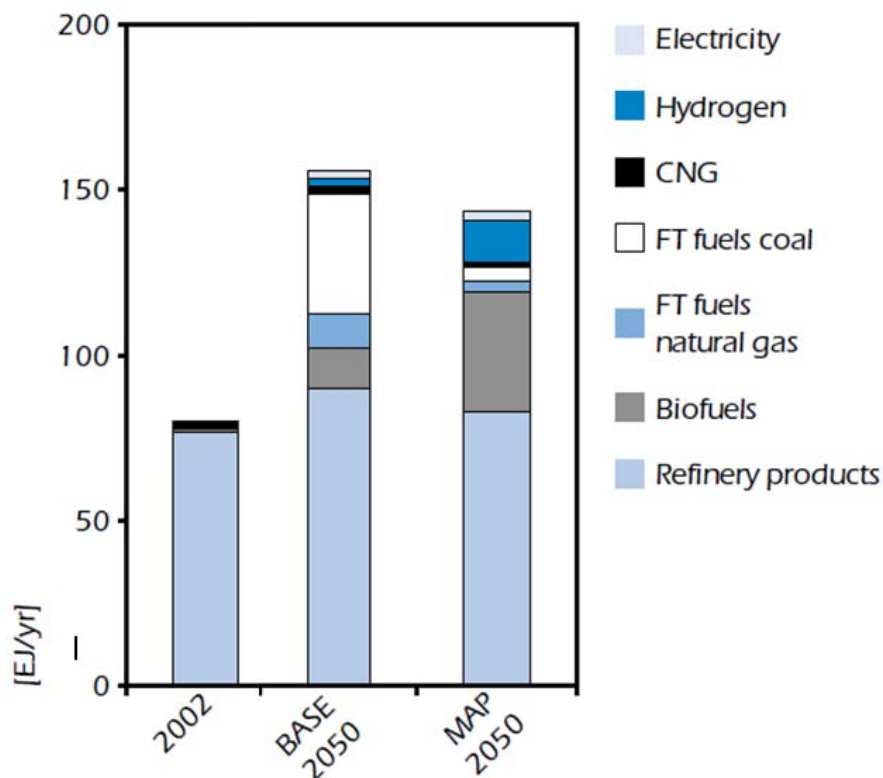


Figure 10 - Transport sector fuel demand by scenario [13]

¹ In the BASE scenario, the prices of energies increase moderately and the only climate and energy security policies are those enacted before mid-2004. In the MAP scenario, an incentive to reduce CO₂ is applied to all emitters. This incentive increases gradually to eventually reach 50US\$/t of CO₂ [15].

As illustrated on Figure 11, changes on the level of incentives for CO₂ emission reduction will directly impact the hydrogen fuel market size. MAP100 and MAP25 scenarios are similar to the MAP one but with incentives for limiting greenhouse gas emissions set respectively to 100US\$/t and 25US\$/t.

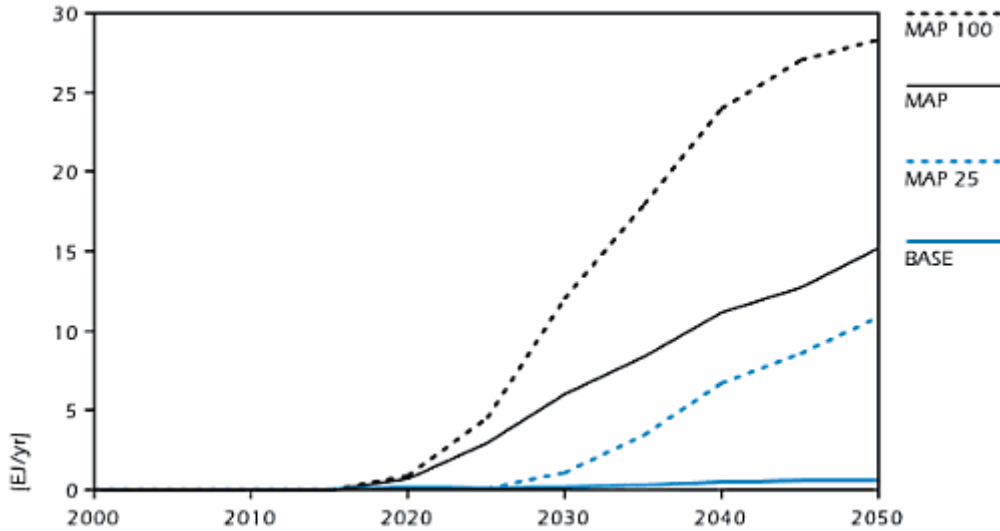


Figure 11 - Hydrogen for FC according to incentive policies [13]

b) Stationary Fuel Cells for buildings

Stationary FC market is expected to take-off only after 2030 and to remain dominated by natural gas fuel cells. Even in the MAP scenario, the H₂ stationary FC capacity reaches only about 40 GW by 2050 (implying an hydrogen consumption of about 10Mt/y²).

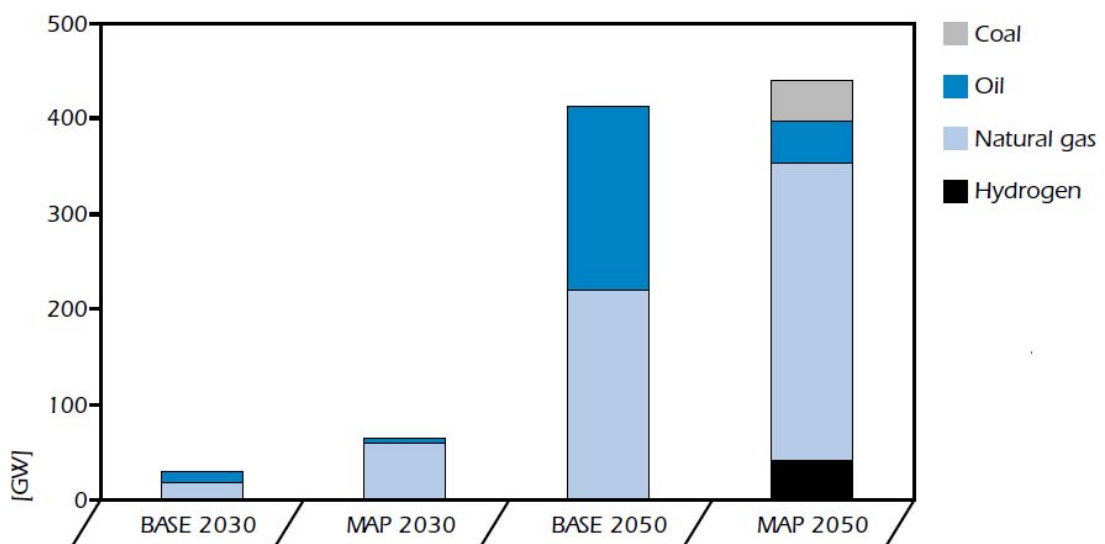


Figure 12- Stationary Fuel Cell by Fuel Type [13]

² Estimate based on a FC efficiency of 60% and an average load factor of 60%.

c) Stationary Fuel Cells for renewable power storage

Hydrogen is identified as a possible storage media for intermittent Renewable Electricity (Wind and PV power). Hydrogen would be produced by electrolysis of water when power production is in excess and electricity restituted to the grid during high demand / low production periods, thanks to fuel cells. This application will create a market for hydrogen equipment but not for hydrogen, as production and consumption are intimately linked in such application. Therefore, the development of these RE storage technologies is not considered in this market analysis.

d) Bio-fuel upgrading

Figure 10 shows a dramatic increase of bio-fuel market by 2050, even in the BASE scenario. Bio-fuel market is supposed to range between 10 and 50EJ/y. Most of this market will probably remain dedicated to ethanol but part of it will be biodiesel, needing hydrogen upgrading. As explained in § 3.2, this implies an increase of the hydrogen consumption on this market sector. Combining Base scenario with a high ethanol share hypothesis and MAP scenario with a low ethanol share hypothesis, the estimated span of 2050 market perspectives for hydrogen for bio-fuel ranges from 2Mt/y to 25Mt/y.

e) Refining and hydrocarbon conversion

The volume of refined crude may have passed its peak by 2050 and be declining. Nevertheless, as shown on Figure 10, the HC fuel market will remain high and will come from heavy crudes needing deep refining. In addition, synthetic fuel production from coal will take a visible share of the fuel market, especially in the base scenario. So hydrogen needs for hydrocarbon refining and conversion will continue to grow. A low and a high growth hypothesis can be considered for this market (respectively +1%/y and +3%/y).

f) Chemical usages of hydrogen

This domain encompasses various applications and it's difficult to build one single hydrogen demand scenario. One low and one high hypothesis can be made to assess the hydrogen market evolution for this sector. The low and high growth hypothesis considered are respectively +1%/y and +4%/y.

g) Conclusion / Global hydrogen market

From the data presented above for each market segment, the global hydrogen market is expected to reach a global volume between 150 Mt/year and 450Mt/y by 2050.

Within this global market, between 20 and 170Mt/y could correspond to non-stranded consumers. The main uncertainty on this estimate, explaining the wide span of possibilities, corresponds to the penetration of Fuel Cell Vehicles.

4. Criteria for defining market introduction scenarios

4.1 Definition of criteria

An effective market introduction of the technology will be based on the assessment of the strengths and weaknesses of the Hydrosol technology with regards to the characteristics of each market segment and market location.

The first criterion that has to be assessed is the economical competitiveness of the Hydrosol H₂ production with regards to others hydrogen production passes.

Then, for markets where competitiveness can be achieved, the following set of criteria has to be evaluated:

- Availability of solar resource
- Water availability
- Sensitivity of users to discontinuous production
- Hydrogen quality requirement
- Consumer unit size
- Downstream hydrogen delivery chain
- Review of possible synergies with other technologies
- General economic criteria

Note: market introduction of the technology is considered to start after the first industrial plant has demonstrated the full viability of the technology. The location of this first industrial plant may depend more on political support to green technologies than on an objective assessment of competitive market criteria. Therefore, the listed criteria may not apply for the first industrial plant.

4.2 Economical benchmarking for the production of hydrogen

As presented in paragraph 2.3, there are various ways to produce hydrogen. The most developed ones extract it from fossil hydrocarbon feedstocks and/or use conventional power to produce it. They so emit carbon dioxide either directly or indirectly. New production paths, based on renewable energies and/or feedstocks, produce H₂ with no - or low - greenhouse gases emission.

Cost of hydrogen from fossil HC feedstocks

Current costs

Table 2 - Non renewable hydrogen generation costs [12]

	Feedstock	Cost of Feedstock	Capital Costs, per Kilogram of Daily Hydrogen Output	Annual Availability	Efficiency of Conversion (Energy of Feedstock into Energy in Hydrogen Output)	Byproducts	Cost of Production (\$/kg of Hydrogen)
Steam reforming (centralized)	Natural gas	\$4/MMBTU	\$1,000	90%	77%	Heat, carbon dioxide	\$0.99
Steam reforming (distributed)	Natural gas	\$4/MMBTU	\$1,650	75%	47%	Heat, carbon dioxide	\$1.74
Electrolysis (centralized)	Electricity	\$0.10/kWh	\$1,500	90%	65%	Oxygen	\$6.81
Electrolysis (distributed)	Electricity	\$0.10/kWh	\$4,000	75%	65%	Oxygen	\$8.70
Coal gasification (centralized)	Coal	\$1.10/MMBTU	\$1,720	90%	64%	Heat, carbon dioxide, ash, other emissions	\$2.60

Hydrogen production from Stream Methane Reforming (SMR) is currently by far the cheapest technology, with a production cost estimated to about 1\$/kg for centralized units on the basis of US gas cost (4\$/MMBTU – cost observed in US were shale gas production has recently led to a dramatic decrease of gas price). Considering that 50% of this production cost corresponds to the methane feedstock [12] and that gas prices in Europe and Asia are between twice and three times the US price [16], the current range of SMR hydrogen cost is estimated to 1 to 2 \$/kg (about

0.8 €/kg to 1.6 €/kg) when centralized units are considered. For small distributed units, costs can be twice these values.

Mid to long term perspectives

Price of various fossil hydrocarbons are closely related to each other because of pricing formulas applied in long-term contracts but also because of their interchangeability for main applications (power generation mostly). Perspectives for oil price increase by 2030 usually range from +150% to %300%, which would lead to SMR hydrogen cost comprised between 1.5 \$/kg to 6 \$/kg (1.15 to 4.6 €/kg) for centralized units without considering any carbon taxation.

Reference cost of green hydrogen

In addition to solar thermochemical processes, there are several ways to produce H₂ without emitting greenhouse gases: water electrolysis, biomass gasification or biological metabolism. All these technological paths are not at the same stage of development and industrial maturity.

Technology	Maturity	Efficiency	Greenhouse gases emission
Fossil fuel / Steam Reforming	++	+	-
Electrolysis	+	~	<i>Depends upon the electricity used</i>
Biomass Gasification and Water Gas Shift	~	-	+
Photocatalysis / Solar ThermoChemical water splitting	-	+	+
Fossil fuel / Steam Reforming with Capture of CO ₂	-	+	+

Figure 13 - Green H₂ production ways alternate to Hydrosol

Today, the only mature way to produce green hydrogen is the water electrolysis using carbon free electricity from solar, wind or biomass power generators. Alkaline electrolyzers are the most mature equipments available at large scale and are currently being operated in multiple industrial sites for electronics, metallurgy or fine chemicals. Thus, in order to set-up an economical reference point for Solar Thermo-Chemical water Splitting technologies, it makes sense to use the combination of photovoltaic solar panels (PV) with an electrolyser (see Figure 14) .

Note: the optimal location for solar thermo-chemical water splitting and PV/electrolysis may differ. Solar Thermo-chemical water splitting is targeting high DNI areas for concentration. Photovoltaic devices are mainly sensitive to global irradiance. Therefore, cost comparison between the two technologies may vary from one sunny site to another.

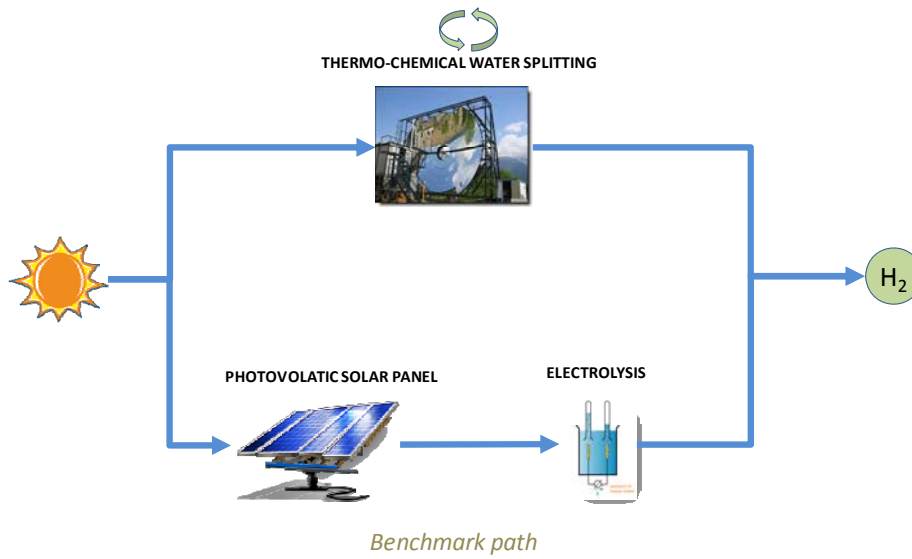


Figure 14 : Benchmark scenario for thermo-chemical water splitting using PV and water electrolysis.

Both PV and electrolysis are technologies which have still significant room for improvement in the coming years. A scenario is built using both actual and prospective data for performance and cost of equipments.

The reference scenario is considering an average irradiance allowing a load factor for the PV plant of 20% (4.8 hours equivalent a day). The electrolyser is sized at the peak power of the PV plant and run with a flexible operating capacity from 0 to 100 without changing its efficiency.

Table 3 - Operating parameters for the benchmark scenario

	unit	value (actual)	value (prospective)
PV capacity	MW	1	1
Average load factor	%	20%	20%
Electrolyser efficiency	kWh _e /kg H ₂ produced	66	47
electrolyser capex	€/kW	1500	750
electrolyser opex	% capex	4%	4%

As shown in Figure 15, the cost of production of hydrogen depends mainly upon the cost of production of electricity fed into the electrolyser and the efficiency of the same. The cost of production of electricity with PV is varying with irradiance and technology improvement.

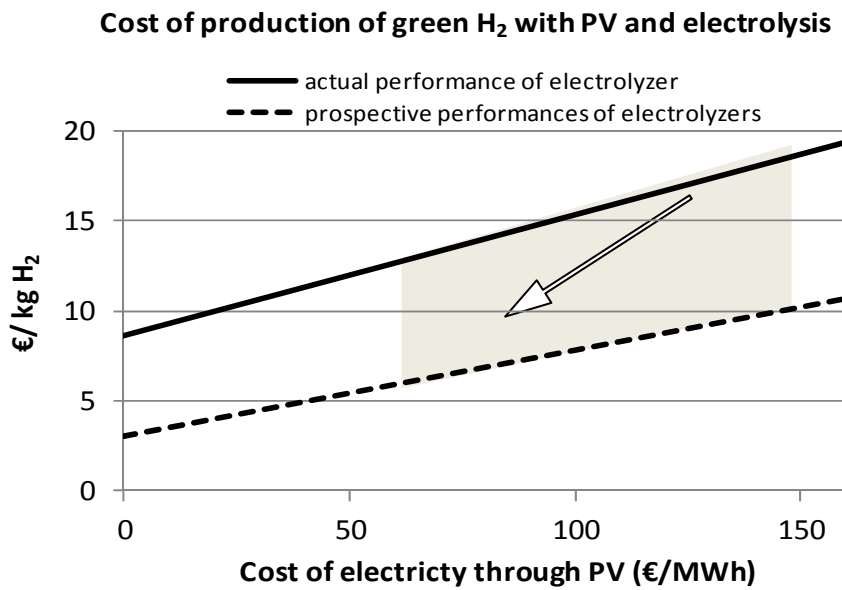


Figure 15 : Cost of production of hydrogen with benchmark scenario

Current costs

As of today, new PV farms can produce electricity with a cost roughly ranging from 100 €/MWh and 200 €/MWh depending on location.

As a consequence, the lowest cost of production of green hydrogen through electrolysis using electricity produced through PV plant is close to 15 €/kg today.

Perspectives

Analysts consider that PV generation costs may continue to drop quickly in the next decade and be cut by half by 2020 [17]. Under the combined influence of the PV power cost drop and of the improvement of electrolyser efficiency, the reference price of green hydrogen could decrease down to 6-7 €/kg in the future.

Competitiveness of Hydrosol hydrogen

As evaluated in [18], the cost of hydrogen produced from the first Hydrosol industrial plants should range between 5.4€/kg and 20.3€/kg with an medium estimated price of 14€/kg.

In the short-term, the Hydrosol hydrogen can't compete with SMR hydrogen but is well placed with regards to alternate green hydrogen technologies. Therefore, market introduction scenarios will have to focus on applications where a premium is given to green products.

In the mid to long-term, cost of hydrogen SMR is expected to rise with the cost of fossil hydrocarbons and possibly with the introduction of stringent environmental taxes. In parallel, the cost of solar thermo-cycles should decrease thanks to the technology learning curve. Therefore, in the long-term (>year 2030), thermocycles could reach competitiveness with regards to SMR while remaining competitive with regards to PV supplied electrolysis. So, from the cost point of view, the market deployment scenarios could target any hydrogen market.

4.3 Solar resource

Solar resource directly impacts the productivity and cost competitiveness of solar technologies.

As all solar concentration technologies, the solar towers value only the direct irradiation (i.e. the incident radiation coming directly from the solar disk, without being diffused by atmospheric components). Zones with a high Direct Normal Irradiation (DNI) are generally desertic areas located between 10° and 40° of latitudes (see map below).

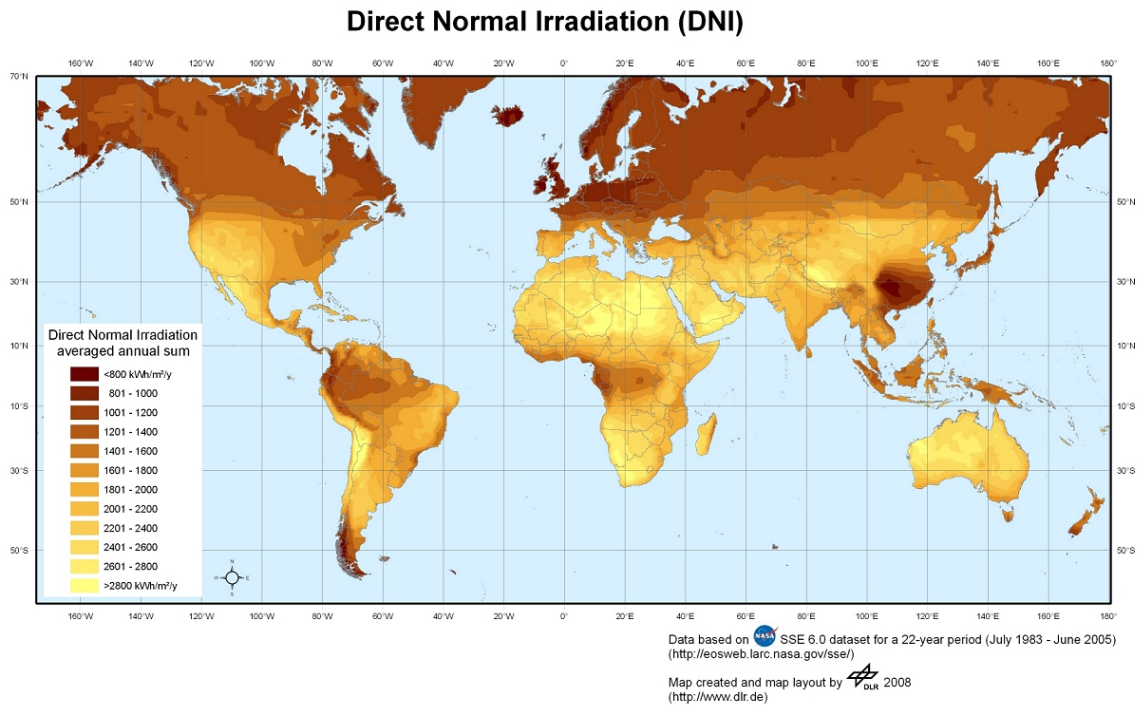


Figure 16- DNI Map

For introduction scenarios, the highest DNI locations will be targeted ($DNI > 2500 \text{ kWh/m}^2/\text{y}$) to limit as far as possible the green premium that the hydrogen consumers will have to pay over the hydrogen market price. Nevertheless, this criterion may be lower if subsidies are given under a green technology support program.

Progressively, as Hydrosol production costs decrease and SMR cost increases, other locations will be considered for market deployment (locations with DNI down to $2000 \text{ kWh/m}^2/\text{year}$).

4.4 Water availability

The Hydrosol process uses water as feedstock but may also use it as a utility for cooling.

The first usage is, of course, unavoidable but is also quite limited. Considering that non-split steam is recycled to the process, consumption of water as feedstock is limited to 9 m^3 of water per ton of H_2 produced (i.e. about 0.8 liter of water per Nm^3 of hydrogen).

Utility water consumption for cooling purposes (compressor interstage, steam condenser...) is much higher but – with a limited increase of plant cost - it can be substituted with dry or hybrid cooling in areas where water scarcity is a concern.

Therefore, non-constrained access to water is a plus for Hydrosol process location but it is not considered one of the major parameters to orientate plant location.

4.5 Sensitivity to discontinuous production

Production of hydrogen with a solar process is discontinuous. This may be a concern for the downstream hydrogen supply chain but can be overcome through storage or by clubbing Hydrosol

production with a large scale hydrogen producer operating on continuous mode. This point is further developed in § 4.9.

4.6 Hydrogen quality requirement

To the contrary of Steam Reformers, Hydrosol thermochemical cycle generates hydrogen free of usual H₂ impurities which may cause issues at consumer level, especially catalyst poisoning in fuel cells (these impurities include sulfur dioxide, carbon monoxide, hydrocarbons..). The process is consequently well adapted to supply any industry consuming H₂.

Nevertheless, specifications regarding nitrogen content impact the Hydrosol process as very low specification values increase design constraint on the pressure swing absorption unit.

Therefore, markets where nitrogen content isn't a constraint will be more favourable than others, especially for market introduction. But nitrogen specification is not considered one of the major parameters for the selection of target markets.

4.7 Consumer unit size

Solar energy reaching Earth is not dense and wide collection areas are required to feed industrial processes. The widest solar towers under construction in the world are designed to collect about 500 MWth at solar receiver level. Extrapolating similar solar fields for an Hydrosol tower collecting heat at higher temperature, one can estimate that the maximum production from a single Hydrosol tower is about 13 000 t/y (about 150 M.Nm³/y or 400 000Nm³/d).

Hydrosol technology is so better fitted to supply small to medium scale consumers, unless it is clubbed with another hydrogen generation system.

4.8 Downstream hydrogen delivery chain

As presented in §2.4, with the current state of technologies, hydrogen is difficult and costly to store and transport. Location of production plants with regards to consumers is consequently critical. Research on storage and transport issues is active but no change of paradigm is expected in the coming years.

Unless it can be connected to an existing hydrogen transport pipeline, each Hydrosol unit will have to be located less than 200 or 300 km maximum from the hydrogen end-user that it supplies.

4.9 Review of possible synergies with other technologies

Several types of synergies can be developed between Hydrosol and other technologies:

- 1) Synergies based on "horizontal integration": the two technologies can be heat-integrated and/or share manpower, utilities systems and/or buildings,...
- 2) Synergies based on "vertical integration": the Hydrosol unit supplies hydrogen or by-product to a "stranded" downstream transformation process

a) Opportunities for horizontal integration

a) Utilities, manpower and building sharing is possible with any process industry.

The implementation of such synergies would reduce the CAPEX and OPEX of the system and could improve its availability as it may allow for redundant supply of utilities (when such redundancy would be too costly for a single intermittent plant).

b) Heat integration could value heat lost on the Hydrosol process.

As high grade heat is already valued within the process itself, waste heat is available only at rather low temperature. The recoverable heat flows are the followings:

- low grade heat recovered at the steam condenser. The flow temperature is close to 75°C if full cooling heat is recovered in one stage but most of the heat can be valued at 95°C with a slightly more complex cooling system.
- low grade heat recovered at the interstage cooling of PSA and final compression (roughly same temperature levels as above).

These levels of heat available are quite common and easy to achieve, therefore they are worth valuing only when the heat integration is simple and inexpensive. Application cases could be

- the supply of domestic heat to a community nearby the plant
- the supply of air cooling to a community nearby the plant (cold generated from waste heat through absorption coolers)
- heat supply to food industry applications
- make-up heat to a desalination plant...

b) Opportunities for vertical integration

As shown in § 2, vertical integration of hydrogen producers and consumers is already very common.

Providing that a buffer storage or an alternate supply insures continuous availability of hydrogen supply to the consumer, Hydrosol technology can efficiently be clubbed with any H₂ consuming process.

- Industries that could be connected to Hydrosol units and fully supplied by them include float glass factories, thin film PV manufactures, heat treatment plants, semi-conductor facilities, food oil hydrogenation plants, biofuel hydrotreatment units...
- Hydrosol units could also partly supply large-scale consumers mainly fed from steam reformers. During the day, when Hydrosol units would be producing, the load of the steam reformer could be decreased thanks to the “green H₂” make-up. In that case, Hydrosol H₂ would be an “hydrocarbon saver” (similarly to the “fuel saver” role of CSP steam on Integrated Solar Combined Cycles). Those large scale consumers could be refineries, ammonia plants or methanol plants. This scheme has the supplementary advantage of suppressing the need for a storage unit dedicated to the Hydrosol production.

Another very promising possibility is to combine Hydrosol units with similar solar thermochemical CO₂ reduction units to produce syngas. It has already been proven that the two-step water splitting process can be modified to enable the split of carbon dioxide (CO₂) into carbon monoxide (CO). The syngas can then be used as a building block to synthesize fully renewable methanol, gasoline, diesel, jet fuel or other chemical products.

The combined construction of Hydrosol units and their stranded customer plants would be opportunities for green economical growth in high irradiations regions.

4.10 Market Introduction & Deployment scenarios - Assessment matrix

From the considerations presented above, a matrix can be built for the assessment of the possible market introduction and market deployment scenarios (see next page).

Table 4 - Scenario assessment matrix

	Criteria for Market Introduction	Criteria for Market Deployment 1st stage (<2030)	Criteria for Market Deployment 2nd stage (>2030)
Benchmark hydrogen on the target market	Green Hydrogen	Green Hydrogen	Any Hydrogen
Solar resource at location	DNI > 2500kWh/m ² /y ³	DNI > 2000kWh/m ² /y	DNI > 2000kWh/m ² /y
Water Availability	Non-constrained access to water is a plus	Non-constrained access to water is a plus	Non-constrained access to water is a plus
Sensitivity of target consumer to discontinuous production	Integration with target consumer should not required large scale storage	Integration with target consumer should preferably not required large scale storage	n.a.
Hydrogen quality requirement	Absence of stringent specification on nitrogen content is a plus	n.a.	n.a.
Consumer unit size	Small scale consumers or large consumers with alternate supply	Small to medium scale consumers or large consumers with alternate supply	Small to medium scale consumers or large consumers with alternate supply
Downstream Hydrogen delivery chain	Connection to an hydrogen pipeline or consumer located less than 200 km from Hydrosol plant	Connection to an hydrogen pipeline or consumer located less than 300 km from Hydrosol plant	n.a.
Favourable factors for horizontal synergies with other technologies	Horizontal integration with a nearby site Vicinity of a low grade heat consumer	Same as for market introduction	Same as for market introduction
Favourable vertical integration	Vicinity of a heat treatment plant, a thin-film solar or semi-conductor plant... Connection to a refinery, a methanol plant or an ammonia plant	Vicinity of float glass factories, thin film PV manufactures, heat treatment plants, semi-conductor facilities, food oil hydrogenation plants, biofuel hydrotreatment units Connection to a refinery, a methanol plant or an ammonia plant	Same as for year<2030 plus Connection to a solar CO ₂ reduction plant

³ If « green subsidies » are given to plants, then this criteria can be reduced down to 2000 kWh/m²/y

5. Introduction scenarios (mid-term)

5.1 Foreword – First plant preceding market introduction

As stated in § 4.1, market introduction of the technology will be preceded by the construction, start-up and one-year operation of the first industrial plant. This stage is meant to fully demonstrate the technology and, as far as possible, to ease its “bankability” (i.e. ability to get financing from bank loans). Neither the location nor the market of the first industrial plant will be selected only on the basis defined in §4. The main selection driver will probably be the public support that this technology demonstration project will get. Therefore, it is expected that the first plant will be built in a sunny European area (e.g. South of Spain or Greece) to benefit from the strong EU political support to the development of RE and green technologies.

The market introduction scenarios deal with the step which will follow the start-up of this first industrial plant.

a) General philosophy of market introduction

The Market Introduction stage pursues several aims. It has to

- test the commercial implementation of the technology at small to medium scale before further scale-up
- position the technology as “proven technology”
- increase its visibility
- give opportunity for operational return of experience, leading to improvement of process operation
- initiate a process of industrialisation / standardisation of the technology components which, in turn, leads to cost decrease

Introduction scenarios proposed

Considering the elements summarized in Table 3 and the general objectives set above, the following introduction scenarios are proposed.

1) Scenario 1

Scenario 1 considers the supply of green hydrogen to an industry where the use of H₂ from hydrocarbons is a issue. This industry could be the bio-diesel industry, where life-cycle analysis (LCA) of the products have to show that they meet a certain level of greenhouse gas reduction compared to HC fuels. Hydrogenation with hydrogen from HC reforming can jeopardize the results of the LCA, so green hydrogen is favoured.

Locations where biomass is abundant are generally not the ones where DNI exceeds 2500 kWh/m²/y but the hydrogenation of already liquid components (e.g. vegetal oils) can be done close to the end-users or at an intermediate location on the supply chain, where existing hydrogenation facilities are already connected to a conventional source of hydrogen (e.g. In California, or in Morocco for biofuels from Brazil shipped to Europe). In such schemes, the Hydrosol plants could develop both vertical and horizontal synergies with these hydrogenation facilities.

2) Scenario 2

Scenario 2 considers the supply of hydrogen to an industry where the use of renewable H₂ gives a “marketable green premium” to the product, or a soft competitive advantage, or brings a public image benefit to the company. This industry could be the solar cell thin film industry or the semi-conductor industry in areas where the public image of brands is important (e.g. cell phone industry, for plants located in California, in some part of China...).

3) Scenario 3

Scenario 3 considers the construction of a set of demonstration cases of green hydrogen supply chains for Fuel Cell Vehicles. As stated in § 3.2, this will remain a niche market until 2020 but a strong attention should be put on the implementation of this scenario as a preparation of the expected later large deployment of Hydrosol technology for this application (see § 6).

4) Scenario 4

Scenario 4 considers the supply of hydrogen as make-up to a large H₂ consumer (e.g. a methanol plant). Even before the technology reaches economic competitiveness outside “green markets”, large H₂ consumers may be willing to early invest in an integrated small-scale unit to get to know the technology with the idea to prepare a later large-scale deployment, when economically worthwhile. This scenario could take place in any high irradiation countries where refining, petrochemistry or fertilizers facilities exist (e.g. US, Egypt, KSA, Australia...)

The general descriptions of scenarios given above have to be complemented with the set of “softer” criteria from table 3 to select a detailed application case when relevant.

6. Deployment scenarios (long-term)

Deployment scenarios can be numerous as they depend both on the success of the market introduction of the technology and of the general development of new hydrogen markets. The overall scenario will be a combination of the following sub-scenarios:

1) Deployment on Fuel Cell Vehicle supply market

Considering the adaptation of Hydrosol technology to medium-scale production, it is well suited to support the development of Fuel Cell Vehicles in sunny locations, especially where no hydrogen pipeline network is available. Hydrosol plants could be dispatched across high irradiance territories and used to supply a network of vehicle retail stations (supply by truck trailers).

This market could become the first market for the technology.

Moreover, the deployment of this network of production facilities could also support the market acceptance of stationary fuel cells based on hydrogen.

2) Deployment on bio-fuels upgrading market

As shown on Figure 10, bio-fuels will become a large market and Hydrosol technology could take a visible share of the production of green hydrogen for bio-diesel upgrading.

3) Deployment on “conventional” hydrogen markets

When economical competitiveness with hydrogen from HC steam reforming is achieved, the Hydrosol technology will be able to take a share on any “conventional” H₂ market (refining, methanol, fertilizer, glass industries...) where solar irradiation and land availability nearby plants are favourable.

7. Conclusion

This report has shown that the hydrogen market is a very dynamic one, with strong growth expectations in the coming years and decades both for stranded and merchant hydrogen productions. The Hydrosol technology could take a visible share of this market in the long-term – especially alongside the deployment of Fuel Cell Vehicles -, provided that a pro-active, but yet careful, staged market introduction and deployment process is followed (first a full industrial demonstration, followed by a set of well chosen market introduction cases, paving the way for a later large scale deployment on a wide range of sub-markets).

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