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Does Hydrogen Have a Place in the Energy Transition?

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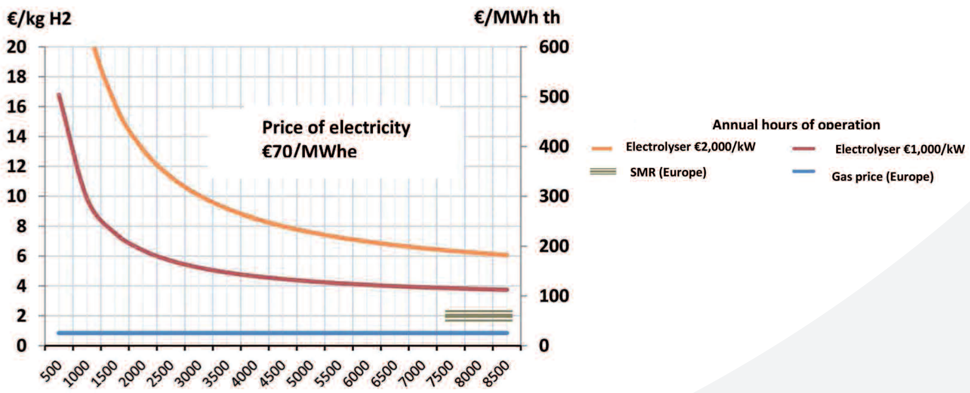
Despite the image of the burning Hindenburg zeppelin that has remained in our collective memory since 1937, hydrogen continues to be held in exceptional esteem. Since its combustion produces only pure water, it is perceived as “clean” and viewed as a possible future replacement for hydrocarbons. Germany, as part of its *Energiewende*, is counting on hydrogen to store massive quantities of intermittent energy from renewable sources (RES). The question has been raised whether this approach to energy transition is applicable in France.

This policy brief provides a particularly cautious response. Today, hydrogen is only produced for industrial purposes using a process that emits CO_2. Carbon-free generation of hydrogen is technically possible by electrolysing water, but the efficiency is poor and the costs are high. Using this approach to enhance the value of excess renewable energy risks increasing the price of electricity. There is ample enthusiasm in Germany for hydrogen powered vehicles, but it does not appear that they will be able to compete with combustion or electric powered vehicles for a long time because fuel cell technology is not yet mature. Additionally, the deployment of a distribution infrastructure would be quite costly.

We therefore recommend conducting further R&D work on electrolysers and fuel cells before considering their substantive or experimental deployment. An impact assessment of hydrogen solutions must take into account, among other things, the economic consequences on other energy sectors (gas, electricity, fuels) and the safety issues.

COSTS OF HYDROGEN PRODUCTION



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ISSUES

Projects using hydrogen surface regularly, usually triggered by oil crises. Hydrogen could indeed replace hydrocarbons for applications such as power generation, mobility and heating if resources become exhausted or if this becomes economically imperative in the fight against climate change.

In addition, hydrogen's ability to be produced and consumed locally by wind or solar farms has given rise to numerous experiments, particularly in Germany, both for energy storage and for "carbon-free" mobility. This is why its use in the framework of France's energy transition is sometimes defended, especially since it would promote a new territorial governance of energy[1]. Major players such as Air Liquide, GDF-Suez, the CEA (Commissariat à l'énergie atomique et aux énergies alternatives, French Alternative Energies and Atomic Energy Commission) and Areva, in quest of growth opportunities, or start-ups like McPhy, are already working to position themselves.

While the electricity market remains profitable in certain niche markets, its overall context – hopefully temporary – is one of profound dysfunction. If hydrogen solutions are developed, they will be in economic competition with gas, for which reserves have been multiplied by the discovery of unconventional resources[2], thus altering the economic calculation for alternative solutions.

INTRODUCTION

In the nineteenth century, the properties of electricity and hydrogen had already inspired the imagination of Jules Verne. Hydrogen gas has a high energy density by weight (2.5 times greater than methane), but carries the disadvantage that it is extremely explosive, making it more difficult to handle and more dangerous than natural gas, since a leak can have disastrous repercussions[3].

This policy brief discusses the techniques for producing hydrogen (H_2) and provides a prospective economic analysis of the processes. Its uses, existing or potential, are then reviewed (industrial, energy storage and mobility) and their likelihood for success is evaluated.

PRODUCTION COST REMAINS HIGH FOR CARBON-FREE HYDROGEN ENERGY

Very little elemental hydrogen exists in nature, so before putting it to use, we must first expend energy to produce it by decomposing molecules in which it is present.

Production by steam reforming

Steam reforming of methane (CH_4) is the most common technique for producing hydrogen, but it emits large quantities of CO_2. Known as SMR[4], this is the simplest technique for "breaking up" the methane molecule in the presence of water vapour. It is only useful to provide hydrogen for industrial use and holds no great interest in the energy domain because CH_4 is already a fuel. Its efficiency is good (70%), but the chemical reaction releases approximately 10 kg of CO_2 per kg of H_2 produced. R&D projects are attempting to produce carbon-free hydrogen by associating SMR with Carbon Capture and Storage (CCS) techniques[5].

The cost of hydrogen production using SMR is between €1.5 and €2.5/kg depending on the installation and the price of gas[6]. Measured in energy units, this cost is on average €50/thermal MWh or \$19/MBtu[7]. The latter figure must be compared to current gas prices of about \$10/MBtu[8] in European markets and \$4/MBtu in American markets. The "decarbonisation" of the process would increase the cost by between €0.5 and €1/kg.

1. See, for example: Kalinowski L. and Pastor J.-M. (2013), L'hydrogène : vecteur de la transition énergétique ? (Hydrogen: vector for energy transition?), OPECST report, 19 December.
2. Beeker E. (2011), "Les gaz non conventionnels : une révolution énergétique nord-américaine non sans conséquences pour l'Europe" (Unconventional gas: a North American energy revolution not without consequences for Europe), *La note d'analyse*, n° 215, Centre d'analyse stratégique, March.
3. See appendix for physicochemical properties.
4. Steam Methane Reforming.
5. Carbon Capture and Sequestration. This technique appeared promising a few years ago, but its implementation is now facing many challenges. The cost could be between €50 and €100/t CO_2.
6. Source: IFPEN, Air Liquide.
7. The Btu, or British thermal unit, is the standard unit of measure in the gas industry.
8. Average value representing the price of gas in Europe in early 2014, which has been declining since that time.

Alkaline electrolysis: proven, but quite expensive

Separating hydrogen from oxygen, the constituents of the water molecule, requires vastly more energy because the atomic bond between them is very strong[9]. Electrolysis has been carried out for more than two centuries by running an electric current between two electrodes immersed in an electrolyte. An advantage over SMR is that the hydrogen produced is very pure, with the possible exception of traces of oxygen, which are easily removed.

The electrodes do not use noble metals and the liquid electrolyte is cheap and replaceable. Currently, the cost of industrial electrolysers varies, depending on the source and size of the facilities, from €1,000/kWe[10] to €2,000/kWe[11]; the only hopes for a decrease in price would be large-scale mass production or economies of scale from the size of the facilities[12]. The efficiency is between 60% and 70%, but means to improve it are not clearly defined.

This type of device has a low current density, high inertia and cannot operate at high pressure: all characteristics that make it unsuitable for rapidly changing current. Electrochemical reactions (the potassium-based alkaline solution is caustic and leads, for example, to deterioration of joints) generate maintenance and monitoring requirements that account for a significant part of the cost.

PEM electrolysis: a promising but immature technology

Polymer Electrolyte Membrane (PEM) electrolysis[13] works quite differently. A membrane made of Nafion, a polymer component developed by Dupont de Nemours in the 1960s, is permeable only to protons. It is covered on both sides by conductive layers, forming electrodes on which are deposited traces of platinum, a noble metal that serves as a catalyst. Fed with water and placed under electrical current, the installation produces oxygen on one side and hydrogen on the other, the latter under pressure of up to 80 bar – a significant advantage over alkaline electrolysis, where compression costs are high. More compact, it is also more capable of handling rapid load variations and therefore better suited for intermittent energy storage. However, it has a much shorter lifespan (less than two or three years), as the composition of the catalyst degrades over time[14]. Its efficiency approaches 60%.

As noted by the French Academy of Sciences[15], given its rarity, the availability of platinum could be an obstacle to large-scale deployment. The cost of PEM electrolysers still exceeds €2,500/kWe[16] and lower costs are contingent on the unpredictable discovery of substitutes for the noble metals used and on economies of scale that are likely to remain limited.

Processes still in the R&D stage

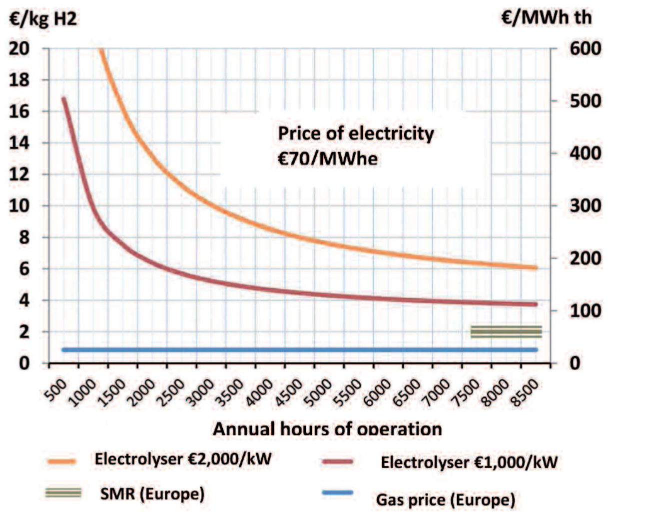
Some methods appear promising, such as those based on ceramic membrane (CERAPEM) or solid alkali electrolytes, notable for combining the advantages of both technologies described above. High-Temperature Electrolysis (HTE) of water vapour, tested by the CEA, is theoretically more efficient than electrolysis at room temperature because part of the energy required for the reaction is provided by the elevated temperature, which can be cogenerated. However, the requirement of a stable operating temperature is not compatible with variations in power, and the components currently have too short a lifetime.

Cost of production by electrolysis

The cost of hydrogen produced by electrolysis depends on the capital expenditure for electrolysers and the duration of use, but primarily on electricity prices (including network costs). The latter, divided by efficiency, represents the variable part of the cost of this production method. Longer lifetimes for electrolysers will increase profitability, since they are capital equipment.

9. This explains why water is a very stable molecule and, in a certain way, a historical waste product from hydrogen's association with oxygen, like CO_2 is for carbon.
10. Source: CEA, Air Liquide, McPhy; l'Étude sur le potentiel du stockage d'énergies (Study on the potential of energy storage) – ADEME-ATEE-DGCIS, October 2013 – recommends 1,400 €/kWe.
11. kWe: Kilowatt-electric, as opposed to Kilowatt-thermal, sometimes abbreviated kWth. Conversion of kWth to kWe implies Carnot efficiency losses, often exceeding 50%. This fact becomes important because hydrogen is a vector for thermal energy, rather than electrical energy.
12. As with many industrial facilities, the unit cost of production decreases with size.
13. Proton Exchange Membrane.
14. To use less material while increasing the active surface, the particles of platinum have a diameter of a few microns. However, over time, they aggregate due to coalescence, thus reducing the membrane's efficiency.
15. Comité de prospective en énergie (2012), La recherche scientifique face aux défis de l'énergie (Scientific research regarding energy challenges), Académie des sciences, report adopted in plenary session on 25 September 2012.
16. Source: Étude sur le potentiel du stockage d'énergies, op. cit.

COSTS OF HYDROGEN PRODUCTION



The graph above summarizes the results obtained with an average electricity price of €70/MWh. The production cost is given on the left vertical axis in €/kg (industrial hydrogen) for comparison with SMR, and on the right vertical axis in €/MWh for a comparison with other energy sources, particularly natural gas.

The appendix addresses several scenarios where the main parameters are altered: current and future investment costs, continuous or intermittent duty cycles. Even with continuous operation and the most optimistic assumptions – which will not be achieved for many years – the cost of producing hydrogen by electrolysis is still about twice as high as by SMR (€3.7/kg against €1.5 to €2.5/kg). With electricity from intermittent sources, it costs 3 to 8 times more (€6.1 to €12.2/kg). Currently, hydrogen produced by a wind turbine dedicated to electrolysis would cost more than €500/MWh, over twenty times the price of natural gas in Europe (fifty times the price in the United States).

It therefore appears that electrolysis can never become competitive with SMR, unless the price of natural gas in Europe increases by a factor of five (and even more in the United States), or even a factor of 10 if network costs are included. This also assumes a stable price for electricity, which seems unlikely because it has been demonstrated that the prices of various energies are linked (since electricity is a versatile energy vector, if the prices of other types of energy rise, its price would also increase as a result of increased demand due to transfer of other energy uses).

INDUSTRIAL USES OF HYDROGEN

Of the 600 billion m^3 of H_2 produced worldwide each year, almost 44% is consumed by petroleum refining (for the conversion of heavy crude and desulphurisation of gasoline and diesel fuel) and about 38% for production of ammonia. The remainder is used in the manufacture of chemicals such as methanol, amines and hydrogen peroxide. About 95% of hydrogen is produced by steam reforming of methane (CH_4). The remaining 5% is obtained by electrolysis of water, when hydrogen of high purity is required[17].

"Doping" biofuels with hydrogen is not discussed in this policy brief, but would likely be classified in this category because it can be likened to a refining process.

The value of industrial hydrogen is therefore much greater than that of hydrogen energy. Since the SMR process emits CO_2, it may appear useful to replace it with electrolysis, but the respective prices of gas, CO_2 and electricity clearly do not allow this. An industrial level changeover from SMR to electrolysis could be a harbinger of the beginnings of profitability for hydrogen energy.

HYDROGEN ENERGY: STORING ELECTRICITY

The substantial development of intermittent energy sources imposed by the European Directive of 2008 (known as "3 x 20%") recently revitalised research into new energy storage solutions. While Pumped-Storage Hydroelectricity (PSH) is the most interesting approach from an economic point of view, its development is constrained by the availability of sites. Electrochemical storage is still extremely expensive and limited to a few specific uses. Hydrogen is therefore sometimes proposed as the answer to this thorny question. Germany, in particular, faced with enormous technical challenges posed by its Energiewende[18], seeks to leverage its expertise in the chemical sector.

Power-to-gas

The simplest storage system, called "power-to-gas," consists of directly injecting the hydrogen that is produced into gas networks at a rate of a few percent. This is

17. Source: Air Liquide, IFPEN, OPECST report.
18. See Beeker E. (2012), "La transition énergétique allemande est-elle soutenable ?" (Is the German energy transition sustainable?), *La note d'analyse*, No. 281, Centre d'analyse stratégique, September.

technically possible, although the physicochemical and calorific properties of the natural gas are altered. GDF-Suez plans to inject 20 to 35 TWh of hydrogen each year into its networks by 2030-2050, amounting to 5% to 10% of French gas consumption. The electricity would come from RES, mainly wind, in the framework of highly proactive scenarios for development of these energy sources, resulting in excess production.

Because of its cost, energy storage via hydrogen in the gas network does not appear relevant in the foreseeable future. Indeed, the above graph shows that with optimistic assumptions, e.g. 1,000 hours of production per year (approximately 50% of the annual total for a wind turbine), the hydrogen produced is over ten times more expensive than gas in Europe (twenty-five times in the United States), and this cost will mushroom if the duration decreases. The notion of recovering traces of excess production is thus excluded. A study by Air Liquide[19] produced similar estimates and concluded that hydrogen can only be competitive with other storage solutions (e.g. batteries, compressed air) if the capital expenditure for electrolysers decreases drastically and, simutaneously, the power system's flexibility requirements increase significantly.

Some studies assign a zero cost to excess electricity on the grounds that it would otherwise be lost. This is a piecemeal viewpoint and it does not integrate all the costs of the system. Attributing zero, or even negative, prices, which are sometimes observed in the MWh market is relevant, but this implies that the return on investment for RES would occur over a shorter lifetime, burdening profitability. With RES remunerated at the purchase price, regardless of the market price, it is the electricity consumer who ultimately bears the cost of stored energy.

Electricity prices are low at present due to malfunctioning[20] of today's European market, in a context of economic crisis and poorly controlled development of RES. As in any industry, it is not clear whether excess production should be sold off at a discount, rather than investing in expensive equipment to store it. Moreover, this situation, which does not promote investment, is not sustainable in the long term.

Power-to-power

Since electricity generation is subject to losses (amounting to about 50%, according to of Carnot's theorem), a complete chain using hydrogen and dedicated to electricity storage is even less likely to be profitable. Techno-economic information available for the MYRTE solar generation project, which uses hydrogen storage (see appendix) reveals extraordinarily high production costs, even for an experiment. In summary, electricity storage via hydrogen currently appears to be quite far from profitability.

Methanation

To overcome difficulties with the physical limits of hydrogen injection in natural gas networks, methanation[21], which reduces CO_2 with H_2 to synthesize methane (Sabatier reaction), is attracting interest in Germany.

The complexity and yields of the successive operations (producing H_2, capturing CO_2[22], storage, compression of various gases, etc.) suggest a very low theoretical overall efficiency (at best 25%, but in reality probably much less). Economically, their already-high costs are cumulative , like those related to capturing CO_2[23] and the large and complex infrastructures required to transport all these fluxes (electricity; network and storage for CO_2, H_2, heat and CH_4). Additionally, managing and optimising the decentralisation of various production processes also appear delicate.

GERMANY IS CARRYING OUT NUMEROUS EXPERIMENTS ON VARIOUS SCALES

- *The energy park in **Mainz**, inaugurated 15 May 2014 by German Vice-Chancellor Sigmar Gabriel federates Siemens, the Linde Group and the Johannes Gutenberg University of Mainz to produce hydrogen from wind power. The project, with €17 million in funding, will have at its disposal the world's most powerful (6 MW) hydrogen electrolysis plant.*
- *An installation at the new **Berlin-Brandenburg** airport is under the direction of Enertrag in association with Total Deutschland and Vattenfall. It combines biogas and hydrogen produced by three wind turbines of 2.3 MW each, which also feed the network. Hydrogen (in a maximum proportion of 30%) and biogas can then be converted into electricity and*

19. Pierre Etienne Franc, Air Liquide, Sevilla, IPHE Conference, 16 November 2012.
20. See, in particular: CGSP (2014), La crise du système électrique européen. Diagnostic et solutions (The Crisis of the European Electricity System, Diagnosis and Possible Ways Forward), report, January.
21. Not to be confused with anaerobic digestion, which concerns the recovery of methane emitted during the fermentation of biomass or waste.
22. Capturing CO_2 in a thermal power plant consumes energy and therefore reduces the efficiency of the plant. The efficiency of the best CCGT (Combined Cycle Gas Turbines) will not be more than 60% or less than 50% (source: IEA).
23. If CO_2 is assigned zero cost, the power system will bear the extra production costs of thermal power plants.

heat to address peak consumption using two turbines of 366 kWe each. The H_2 also supplies service stations at a promotional price of €10/kg. The total investment, calculated to be €21 million, suggests extremely high costs for the MWh produced.

- ***Hamburg*** *("Wasserstofftankstelle HafenCity") has a hydrogen production capacity of 750 kg per day via electrolysis, fuelling the city's seven hydrogen buses.*
- ***Falkenhagen*** *(Brandenburg) has a pilot installation created by the energy company E.ON that targets the production of 30 kg/day of hydrogen from wind power, intended to be directly injected into the natural gas network.*
- *The "Audi e-gas Projekt" in* ***Lower Saxony****, produces methane fuel with hydrogen from RES and electrolysis (120 kg/day), combined with CO_2 from a biomass plant to generate biomethane, called "e-gas."*

However, these diverse projects remain on a small scale and their results have not yet been published to give an idea of their techno-economic performance.

HYDROGEN-BASED MOBILITY

Powering vehicles would be the other major prospect for hydrogen. Apart from its production, the two major challenges are the achievement of fuel-efficient vehicles and the development of a refuelling infrastructure. Hydrogen-based mobility only has a future if the cost of fuel cells decreases drastically and if the supply chain is secure.

H_2 mobility viewed as an answer to the scarcity of hydrocarbons

With the recurrent notion (as yet to be justified by facts) that the inexorable rise in oil prices will make this technology cost-effective in the not very distant future, vehicles running on hydrogen (HFCV, Hydrogen Fuel Cell Vehicles) appear regularly, the first dating from 1959. One notorious infatuation took place in 2004[24] in California[25] with the "Hydrogen Highways" initiative. Another was in Japan, where the International Energy Agency's annual report forecast 5 million HFCVs by 2020. Recently, firms including Toyota and BMW launched the sale of HFCVs, esteemed by the media despite their high price (about €50,000).

Hydrogen vehicles remain very expensive

In short, an HFCV is an electric vehicle that gets its energy from H_2 converted into electricity by a fuel cell[26]. Hybridisation of the two works well, with a hydrogen supply and a fuel cell serving to increase the range of electric vehicles.

Fuel cells are still cost prohibitive

The operation of a fuel cell is the opposite of an electrolyser, but both are based on classic principles[27]. Supplied with oxygen and hydrogen, it produces current between two electrodes separated by a (generally solid) electrolyte, emitting only pure water. There are many types of fuel cell, but for mobility, research currently focuses on PEM electrolysers. The hydrogen and oxygen they use must be very pure, which potentially prevents their use in heavily polluted urban centres, short of purifying the incoming air or providing an oxygen tank.

Sources indicate that the efficiency currently varies from 30% to 50%[28] and costs from €500/kWe[29] to $3,200/kWe[30]. An average electric vehicle engine has a power consumption of 60-70 kW, so the cost of the corresponding fuel cell is therefore €30,000 in the best case, which led Steven Chu, US Secretary of Energy (and Nobel physics prize winner in 1997), to state in 2009 that HFCVs would not see the light of day for another ten or twenty years, due to deficiencies in fuel cell technology. This cost must be divided by a factor of at least 10 before any significant development of this type of vehicle can take place, keeping in mind that supplies of noble metals constitute a constraint.

Hydrogen can only be stored on-board as a gas

Hydrogen is difficult to store due to its low density, its high volatility and its ability to escape through the tiniest cracks (it is the smallest molecule that exists in nature). Its liquefaction temperature is very low (-253°C) and this requires enormous amounts of energy (about 50% of

24. This was shortly after the publication of the popular book The Hydrogen Economy by American essayist Jeremy Rifkin, who in 2002 predicted the advent of a "third Industrial Revolution" based on hydrogen, not to mention the launch of a hydrogen initiative in 2003 by President Bush, with a budget of $1.2 billion, reduced considerably in 2009 by President Obama.
25. The project, launched in 2004 by Governor Arnold Schwarzenegger, involved the construction of 150 to 200 stations by 2010 at an estimated cost of $75 to 200 million. Note that the development of "natural gas highways" in the US helped to make this type of project obsolete.
26. The use of hydrogen for direct combustion is possible, but has many disadvantages.
27. Sir William Grove developed the first fuel cell in 1829.
28. Recovered heat is used to warm the passenger compartment.
29. Source: Daimler.
30. Source: Hydrogen-Based Energy Conversion, Schlumberger – SBC Energy Institute, December 2013.
31. Especially for space propulsion. We note that SpaceX recently revived a low cost kerosene-fuelled launcher that competes with hydrogen equivalents in a large segment of the market.

energy content). Liquid hydrogen is therefore limited to cryogenic uses[31].

Only storage as a gas[32] currently allows vehicle range comparable to that offered by petroleum-based fuels, and that with a 150 litre tank weighing 100 kg and pressurised to 700 bar[33]. Such a tank costs €2,000[34], of which about 40% is for the carbon fibre matrix composing its shell. Ultimately, progress on composite materials and polymers (for the tank's inner layer, intended to prevent leaks whose devastating effects were mentioned above) and, in the longer term, nanomaterials, could make tanks stronger and reduce their size and cost.

Hydrogen distribution

New solutions must be devised in order to transport hydrogen and distribute it to motorists. Pipelines are technically possible, but necessitate specific precautions. Road transport could be an alternative, but appears more difficult to implement.

The extremely high cost for development of a hydrogen infrastructure dictates distribution by truck

Hydrogen distribution is technically mastered, but while a network of about 1,000 km exists between France, Belgium and the Netherlands, it is reserved for industrial applications. A hydrogen pipeline requires twice the investment as for natural gas and it requires five times the energy to operate it. Distribution of liquid or compressed hydrogen is therefore obliged to be done with trucks, such as Air Liquide "tube trailers," which transport 400 kg of H_2 compressed to 200 bar (and soon to 500 bar). The compression process is very energy intensive; the cost is estimated at €2/kg H_2 transported.

Service stations for hydrogen remain very expensive

For an end-user, filling a tank with enough hydrogen to drive 500 km takes about five minutes, with a flow rate of about 1 kg H_2/min. A service station costs about €1.5 million. The compression required to fill a vehicle's tank to 700 bar expends the equivalent of 20% of the energy content of the H_2 distributed. The resulting cost of providing the hydrogen is €3 or €4/kg H_2[35].

The installation of an electrolyser in the service station would eliminate the transportation costs, but in this case, the full cost of a kWh should be taken into account. In Germany, where the price of electricity is very high (€0.30/kWh) while RES are being developed, the kWh portion alone of H_2 produced exceeds €15/kg, before adding all other costs.

The state of California, which, under the leadership of its governor A. Schwarzenegger, decided in 2004 to fund the development of 100 hydrogen service stations, suspended its support in 2008 because of the immaturity of fuel cells, leading to the closure of almost all stations already in place.

Now, Germany is targeting deployment of 400 stations by 2023, to supply 500,000 HFCVs, through the H_2 Mobility initiative. Its total budget is €350 million. This vast plan seems to indicate a strategic shift in Germany for carbon-free mobility and storage, because in 2010, the country had already adopted a similar plan envisioning one million electric vehicles for 2020, a goal confirmed by the German Chancellor in May 2013.

At the pump, the pre-tax price of H_2 is still double – or even triple – that of conventional fuels

If we add all these costs, the total cost of H_2 at the pump would be about €10/kg if produced by SMR, and (according to Air Liquide) €13/kg by electrolysis, but these costs are probably even higher, according to the calculations provided in the appendix. An average EV (and therefore an HFCV) corresponding to a combustion powered vehicle consuming 4.6 litres of diesel fuel per 100 km, needs an average of about 18 kWh/100 km for propulsion[36]. A fuel cell with an efficiency of 30% (as hypothesized in the Schlumberger study[37]) results in a consumption of 1.8 kg H_2/100 km. Daimler asserts that its vehicles have a consumption of 1 kg H_2/100 km, which corresponds to an overall efficiency of 50% or 60% for the fuel cell alone. Under this assumption – the most optimistic encountered in the multiple reports on this subject – the cost of H_2 per kilometre travelled would be €0.13 (according to Air Liquide; in reality probably much more) if it were produced by electrolysis. This should be compared to €0.035 for the

32. Hybrid storage, where hydrogen molecules are bonded to solid-state materials at low pressure (10 bar), e.g. as proposed by McPhy corporation, is an interesting alternative but remains confined to stationary applications because of its high mass density.
33. The ideal gas law PV=nRT=1.22*m (SI) defines the relationship between volume, pressure and on-board hydrogen mass.
34. Source: CEA.
35. Source: Air Liquide.
36. See, in this regard, Syrota J. (2011), La voiture de demain : carburants et électricité (The Car of Tomorrow: fuel and electricity), report, Centre d'analyse stratégique, March.
37. Hydrogen-Based Energy Conversion, op. cit.

diesel fuel (excluding taxes) required to cover the same distance.

This price differential is not justified by the reduction in CO_2 emissions

Use of H_2 produced with SMR is not economically or environmentally justified and, from the safety viewpoint, a simple calculation shows that it is more advantageous to use the gas directly in a combustion engine.

With H_2 produced and distributed in a completely carbon-free manner (which remains hypothetical), and under the most optimistic assumptions (€13/kg and 1 kg/100 km), the calculations in the appendix indicate that we must assign a price of approximately €1,000 per tonne of CO_2 emitted by a combustion powered vehicle of the same power to establish cost equivalence.

This price corresponds to ten times the shadow price of CO_2[38], indicating that many other methods of reducing greenhouse gas emissions are more efficient (e.g. insulating buildings, modal shifts). To completely transform the French domestic tax on petroleum products (TIPP) into a carbon tax, it would have to be approximately tripled, which would double fuel prices.

Moreover, as shown in the CAS report on the vehicle of the future (op. cit.), the potential to improve combustion powered vehicles has not been exhausted and research is underway within the framework of the "2l/100 km vehicle" programme initiated in September 2012 by the French government.

THE IEA'S "ENERGY TECHNOLOGY PERSPECTIVES 2014" ONLY SEES A MARGINAL ROLE FOR HYDROGEN IN ITS ENERGY SCENARIOS FOR 2050

The International Energy Agency (IEA) publishes a biannual report addressing technological prospects in the energy sector. The latest report, dated 12 May 2014, foresees massive development of RES before 2050 in order to decarbonise the power system, thus requiring substantial investment in intelligent transport networks, as well as gas plants, seen as "indispensable to integrate and balance RES production." The IEA prefers these means to hydrogen, while recognising that, over time, it could replace fossil fuels for road transport. In 2050, hydrogen is expected to account for less than 5% of final energy consumption, with fossil fuels remaining dominant in the transport sector. According to the IEA, hydrogen's use is limited by the difficulty of storing it with sufficient energy density and especially by the cost of carbon-free hydrogen production.

The obstacles to ensuring safety for the general public seem difficult to overcome

The public must be confident of hydrogen's safety in order to accept its use[39]. The associated dangers have been identified by INERIS[40]: more than any other fuel, it is a concentrated form of energy that presents risks of fire and explosion; it can escape through the smallest cracks[41] and, mixed with air, explodes very easily and with great violence.

In industry, only the refining and fertilizer sectors have experience handling hydrogen. Its specific safety measures – such as detecting any leaks that may occur and correcting them[42], monitoring the obsolescence of materials used for storage tanks, long-term degradation of joints (which must withstand 700 bar) and always following best practices – are difficult to apply to the general public. Even if hydrogen were to be widely distributed, a few accidents would delay or undermine its development.

At his hearing before the Parliamentary Office for Evaluation of Scientific and Technological Choices (OPECST, Office parlementaire d'évaluation des choix scientifiques), the General Director of Risk Prevention emphasised the amount of work needed to adapt existing regulations to projected applications of hydrogen.

NICHE APPLICATIONS FOR HYDROGEN

The use of hydrogen and fuel cells was originally demonstrated for niche applications (early markets), such as:

- materials-handling equipment that must function in a confined atmosphere; such equipment can be sold at higher prices (the combustion powered equivalents cannot be used and electric models are poorly adapted);
- supplying current for isolated sites, such as relay antennas and telecommunications bases;
- emergency electrical generators for critical and strategic applications (computer servers, hospitals, telecommunications relays);

38. See Centre d'analyse stratégique (2009), La valeur tutélaire du carbone (The shadow price of carbon), Paris, La Documentation française, March.
39. In Germany, consumer use of hydrogen does not seem to generate the same fears as in France.
40. INERIS (2008), Les techniques de production de l'hydrogène et les risques associés (Techniques for hydrogen production and associated risks), 10 June.
41. Note that, unlike other gases, the expansion of H_2 is exothermic – i.e., it is accompanied by a release of heat and therefore an increased risk of explosion – posing safety problems and requiring reinforced tanks.
42. French nuclear power plants are equipped with a hydrogen recombiner that prevents the formation of potentially explosive gas pockets in confined spaces. It is difficult to imagine equipping all road tunnels in this way.

- mobile applications: low power batteries can be used to supply mobile devices such as telephones, computers, MP3 players and portable lighting devices.

The amounts of hydrogen concerned are small in the perspective of energy transition, but these uses can gradually lead to greater technological expertise in its use.

MEDIUM AND LONG TERM PROSPECTS

Most experiments, whether in progress or planned, are often only integration projects, downstream of the hydrogen chain and posing no particular design problems: refining vehicles, installing service stations, integrating storage solutions with the electrical power network, etc. As long as the key components – electrolysers and fuel cells – have not reached economic maturity, they will still be supplied with hydrogen produced by SMR, with its associated CO_2 emissions, and, above all, for a duration that cannot be predicted.

This raises questions of the relevance of such experiments and whether it would not be better to focus public funds on R&D for electrolysers and fuel cells rather than subsidising prototypes without any real added value that are likely to be rapidly become obsolete. To provide a figure, as long as laboratory trials do not suggest that the costs necessary to ensure electrolysis' competitiveness with SMR can be reduced by at least a factor of 10, it should not leave the domain of quasi-fundamental research. Before testing an installation under actual operating conditions, each fundamental technological link (e.g. electrolysis, storage, fuel cells) should have already demonstrated profitability in the medium term on the basis of realistic learning curves.

Simultaneously, we must not lose sight of the overall picture, as the emergence of a new technology option in the energy landscape will certainly have repercussions on the others. Before plans are made to integrate hydrogen solutions with the gas and electrical networks, comprehensive studies must be conducted in order to assess requirements and capital expenditures in the various infrastructures needed for the multiple fluxes concerned (electricity, CO_2, methane, hydrogen, heat) and to study how they can be jointly managed. The establishment of a distribution infrastructure dedicated to hydrogen would require the extremely costly and technologically very risky development of a technology in competition with oil, electricity and, above all, gas.

Since petroleum products are subject to high excise duties, an economic study appears necessary if the hydrogen option is intended to replace a significant part of the hydrocarbon industry.

Finally, hydrogen, due to its physicochemical properties, is a gas whose use carries far greater risks than those for hydrocarbons (e.g. leaks, explosions, ignition). The safety and acceptability issues associated with its use should therefore be taken into account from the outset.

In the perspective of its use by the general public, their acceptance of hydrogen is predicated on the adoption of convincing rules for design and for technical, human and organisational safeguards. This regulation, which could be the key to the development of the hydrogen energy industry, must be addressed beginning with the R&D phase and throughout the development of these systems.

CONCLUSION

Industrial use of hydrogen, its principal potential market – and the only one currently operational (chemicals and advanced refining) – is not a focus of this policy brief. For these purposes, it is produced almost exclusively by steam methane reforming, with electrolysis reserved for the production of high-purity hydrogen. The beginning of a transition from SMR to electrolysis in order to produce industrial hydrogen, justified by economic criteria, would be a sign that the latter technology is sufficiently mature for the production of hydrogen energy.

The second market for hydrogen is electricity storage. Intellectually speaking, it represents an attractive solution, but various experiments conducted in recent years converge with the economic calculations for scenarios presented in this policy brief: while the processes are well understood technically, a successful business model remains to be seen. If, incidentally, applications like *power-to-gas* may appear profitable, it is under the assumption that hydrogen gets a "free ride" on other networks (gas or electricity), using their infrastructure without sharing the costs. Methanation (reduction of CO_2 with H_2), even more complex, will not be valuable in the foreseeable future. Moreover, the current revolution in the United States concerning unconventional gas is forcing competitors of gas to rethink their economic equation. As for *power-to-power* (converting stored H_2 back into electricity), its cost and low efficiency prevent it from competing, before the long-term, with hydraulic pumping stations and electrochemical batteries, which are better understood and more mature.

Mobility is the third potentially important market. Here, hydrogen is currently benefiting from a media frenzy completely out of line with realistic future prospects. While technical viability has been demonstrated for all the links in the hydrogen chain – production, storage, transport, distribution and reconversion into electricity – the hydrogen vehicle does not seem capable of competing with its combustion or electrical powered equivalent for years, or even decades. The use of scarce resources such as platinum also appears to be a stumbling block.

Finally, there is the key question of the general public's acceptance of this gas. Widespread use of hydrogen, under the tremendous pressure of 700 bars, gives rise to significant safety challenges; current industrial use is at much lower pressure[43].

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Keywords:
Hydrogen, electricity storage, renewable energy, energy transition, green growth, *Energiewende*, electrolysis, carbon-free vehicle, clean vehicle, methanation, *power-to-gas*, fuel cell.

43. The following have contributed to the preparation of this policy brief: Pascal Mauberger (McPhy and AFHYPAC); Philippe Boucly (GRT Gaz and AFHYPAC); Sylvain Hercberg (EDF); Lucie Tonnellier, Pierre-Etienne Franc, Louis Sentis, Aliette Quint and Pierre Gauthier (Air Liquide); Paul Lucchese, Jean Oriol and Pierre-André Jacques (CEA); Jean-Claude Perraudin and Hélène Benveniste (CEA and French Embassy in Berlin); Joerg Kleeman and Georg Frank (Daimler AG); Philippe Poggi (MYRTE, University of Corsica).
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APPENDIX

PHYSICOCHEMICAL PROPERTIES OF HYDROGEN: A HIGH-ENERGY BUT VERY EXPLOSIVE GAS

Hydrogen is the lightest element in the universe because its atomic nucleus consists of a single proton[1]. It was discovered in 1766, and separated for the first time in 1800[2]; it basically exists only in compounds (e.g. water, H_2O, C_nH_m hydrocarbons).

Very little hydrogen exists in a natural state, so energy must be expended in order to produce it by dissociating these molecules.

Hydrogen is therefore considered an energy vector, not an energy source, although IFPEN (IFP Énergies nouvelles, public-sector research and training centre in new energies) has indicated the existence of natural hydrogen reserves in certain geological formations[3].

It occupies a large volume (its mass density is almost 10 times lower than methane's). Its combustion is 2.5 times more exothermic than methane. Combustion of 1 kg of H_2 consumes 8 kg of oxygen (O_2), producing 9 litres of water. Conversely, to dissociate this water by electrolysis theoretically takes the same amount of energy. In practice, it takes much more, because of efficiency losses.

This high calorific power comes with certain disadvantages, such as its high explosivity per unit mass, large flammable range in air, very low ignition energy and is exothermic when it expands, all characteristics that make hydrogen more difficult to handle and more dangerous than natural gas, since a leak can turn into a disaster.

FIG. 1: PHYSICOCHEMICAL PROPERTIES COMPARED TO HYDROGEN AND METHANE

Physicochemical properties	*Hydrogen (H_2)*	*Methane (CH_4)*
Gross calorific value(GCV)	*39,4 kWh*	*15,4 kWh*
Net calorific value (NCV)[4]	*33,4 kWh*	*13,9 kWh*
Volume (Nm^3/kg)	*11,0*	*1,4*
Explosive energy per unit mass (g TNT/g)	*24*	*11*
Explosive energy per unit colume (g TNT/m^3)	*2,02*	*7,03*
Flammable range (% vol)	*13-65*	*6-14*
Minimum ignition energy (mJ)	*0,02*	*0,29*

Source: CEA, ISO TC 197

FACTORS AFFECTING THE ECONOMIC ASSESSMENT OF ELECTROLYSIS

Impact of the electrolyser's service life

Hydrogen production by electrolysis has the following cost parameters: the cost of electricity and of the electrolyser, the electrolyser's efficiency and service life. In order to determine the orders of magnitude, the graph of the cost of hydrogen production (page 4) shows a typical calculation of net present value (NPV) for two alternative assumptions of unit cost and electrolyser efficiency representative of current and future (2030) economic conditions, respectively (€2,000/kW, 60%) and (€1,000/kW, 80%).

The price used for electricity (€70/MWh) corresponds to its average production cost[5]. Except in the case of fully autonomous installations (power produced and consumed on site), infrastructure costs (networks in particular) should also be taken into account (which is not the case here, although they can be very significant).

1. In its most common isotope. The other two, deuterium (one proton, one neutron) and tritium (one proton, two neutrons), exist only in trace amounts.
2. Hydrogen and electricity have long been associated in science. The first water electrolysis was performed 2 May 1800 by Sir W. Nicholson and Sir A. Carlisle, just days after the invention of the first electric cell by A. Volta.
3. Source: IFPEN presentation at hearing before the OPECST in 2013.
4. The Gross calorific value (GCV) is the amount of energy released by the complete combustion of a unit of fuel, assuming condensation of the water vapour and recovery of the heat. This compares to the Net calorific value (NCV), which excludes vaporization energy (latent heat) for the water present at the end of the reaction. Since water is the sole product of hydrogen combustion, the GCV/NCV ratio is higher than for hydrocarbons, whose combustion also emits CO_2.
5. See Percebois J. and Mandil C. (2012), Énergies 2050 (Energies 2050), report, Centre d'analyse stratégique, February. This is also the average gross production cost of onshore wind (cf. report of the Commission de régulation de l'énergie - CRE, Commission for Energy Regulation), April 2014

Engineering costs (25% of capital expenditures) are assigned to the installation at a flat rate. The equipment lifetime is fifteen years, the discount rate is 8% and annual operating costs are 2% of the investment cost.

Note that, due to the capital intensive nature of electrolysers, they can only be profitable in the case of long operational lifetimes.

Sample scenarios

With the same overall hypotheses as in the preceding paragraph, we will calculate the NPV for six representative scenarios:

1. Alkaline electrolysis under current conditions for baseload use (7,000 hours/year), with an electricity price of €70/MWh and an electrolyser efficiency of 60%.
2. PEM electrolysis under current conditions to store wind energy (€70/MWh, 2,000 hours/year).
3. Same as scenario 2, but with an electrolyser cost of €800/kW and an efficiency of 80%, i.e. the conditions we can expect for the 2025-2030 horizon.
4. Same as scenario 3, but storing energy from solar photovoltaics (€140/MWh, 1,000 hours/year).
5. Same as scenario 3, but assigning a price of zero to stored electricity and with reduced periods of use (500 hours/year), corresponding to excess renewable energy. Some studies[6] assign a zero price to stored electrical kWh (usually produced by RES), reflecting the fact that this energy is otherwise lost when it cannot be consumed or carried on the network. Although this assumption is highly disputable[7], it has the advantage of highlighting the proportion of fixed costs for the installation.
6. A final scenario evaluates baseload hydrogen production under conditions one might hope for in the future.

Whether under current or future conditions, these costs appear very high as compared to those for steam reforming, i.e. about €2/kg. To be truly precise, the oxygen produced could have a market value, and its price should be included in the calculation, but it does not exceed a few euros per MWh[8].

FIG. 2: COST OF HYDROGEN PRODUCTION BY ELECTROLYSIS UNDER VARIOUS SCENARIOS

Scenario			*1*	*2*	*3*	*4*	*5*	*6*
Cost of the electrolyser		*€/kW*	*2 000*	*2 500*	*800*	*800*	*800*	*800*
Electrolysis efficiency			*60 %*	*50 %*	*80 %*	*80 %*	*80 %*	*80 %*
Annual production		*kWh*	*7 000*	*2 000*	*2 000*	*1 000*	*500*	*7 000*
Cost of stored electricity		*€/MWh*	*70*	*70*	*70*	*140*	*0*	*60*
Cost of H_2 produced		***€/kg***	***7,0***	***18,3***	***6,1***	***12,2***	***10,5***	***3,7***
	equivalent to	***$/MBtu***	***68***	***177***	***59***	***118***	***102***	***36***
	equivalent to	***€/MWh***	***178***	***463***	***154***	***309***	***267***	***94***

Source: CGSP

6. Such as the one carried out in February 2013 by the E-Cube consulting firm.
7. Since electricity from renewable sources is already paid for via its purchase price, this amounts to making electricity consumers bear this burden; they collectively pay the Contribution au service public de l'électricité (CSPE, renewable energy surcharge), which underwrites the extra cost of RES.
8. The production cost of industrial O^2 is about €0.03/kg O^2, equivalent to about €0.24/kg H_2 (for 1 kg of H_2 produced by electrolysis, 8 kg of O^2 are also produced) adding another €5/MWh. But France's current requirements for oxygen are rather low; in the case of massive production of H_2, new uses would need to be found in order to promote its value (source: E-Cube consulting firm, March 2013).

For energy applications, all scenarios show costs much higher than the price of gas (approximately $10/MBtu in Europe, $4/MBtu in the US), without considering numerous costs such as use of the electrical power network. This is not particularly surprising, because the cost of producing hydrogen by electrolysis is linked, above all, to the price of electricity. Divided by the efficiency, this accounts for the variable part of the price.

The result is that hydrogen production costs quickly become prohibitive as soon as we introduce assumptions that approximate realistic operating conditions. The price of natural gas would need to be multiplied by at least five (or even 10 if network costs are included) to make the production of hydrogen by electrolysis of water competitive with SMR. At the same time, this assumes a stable price for electricity, which seems unlikely because it has been demonstrated that the prices of various energies are linked (since electricity is a versatile energy vector, if the prices of other types of energy rise, its price would also increase as a result of increased demand due to transfer of other energy uses).

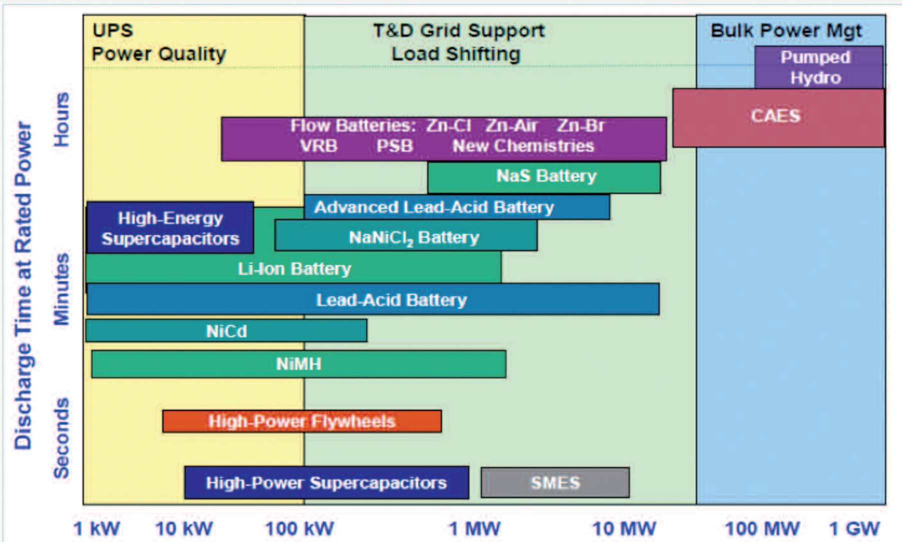
OVERALL PHYSICAL AND ECONOMIC CHARACTERISTICS OF STORAGE SYSTEMS

Storage systems are distinguished by their capacity (MWh) and power (MW) and, according to these characteristics, address different uses. While a hydroelectric reservoir represents several weeks of energy reserve, a flywheel or supercapacitor can only deliver high power for a limited time; this can be used to smooth voltage spikes.

The cost of an electrochemical battery is exactly proportional to its capacity, a function of the number of cells that are installed in parallel, making it poorly suited economically for mass storage. A hydrogen-based system may appear as a panacea, as its maximum power is a function of the size of the electrolyser and the cost of energy storage is of secondary importance.

The figure below, courtesy of the American research organisation EPRI, provides a classification of storage technologies. Hydrogen, clearly seen as immature by that organisation, does not appear, but could be placed at the top centre of the table, to the left of pumped hydro (STEP) and compressed air (CAES).

FIG. 3: COMPARATIVE CLASSIFICATION OF DIFFERENT ELECTRICAL STORAGE TECHNOLOGIES BY THEIR USEFULNESS FOR THE NETWORK (HYDROGEN WOULD APPEAR AT THE TOP CENTRE)



Source: extracted from EPRI's 2010 report "Electricity Energy Storage Technology Options"

Power-to-gas

This technology stores electricity by injecting hydrogen into the gas network. The calculations in the preceding paragraph show that parity with gas cannot be achieved, even under the most optimistic assumptions.

Moreover, assessments are often governed by local or piecemeal viewpoints. Several studies are based on scenarios where the electric or gas networks are underutilised at the moment when the electricity is stored, allowing them to justify assigning it zero cost. This cannot be justified, in any case, if development of storage facilities remains limited.

In the case of more significant development, we must map out an overall vision that, ideally, will allow planning the capacity of the infrastructures it requires. This task appears extremely complex in terms of the "simple" optimisation of an electrical power network, and will probably require new types of regulation that are difficult to envision in the context of this policy brief.

Reconversion into electricity

If the final product is electricity, profitability seems out of reach because of the limitations imposed by Carnot efficiency losses. The combined cycle for gas has a maximum efficiency of 60% (and somewhat less in reality), especially if the natural gas contains traces of hydrogen.

The cost per MWh output would be several hundred euros. While the market price of electricity sometimes reaches this level, it is always for a limited time, as a repercussion of a momentary load on the network. This is not sufficient to make the dedicated electrical storage or production equipment profitable.

In a system that is composed only of intermittent RES and storage facilities, the resulting cost per MWh depends on how the storage is managed and on the structure of the demand the system is addressing. The MYRTE experiment, a miniature-scale example of this system, is described in the following paragraph.

THE MYRTE PROJECT: AN UNCONVINCING EXPERIMENT IN HYDROGEN-BASED STORAGE

This demonstration unit, located in Ajaccio, federates the CEA, HELION and the University of Corsica. It uses photovoltaic solar production coupled with a hydrogen chain for storage. Electrical power is fed to the network from the photovoltaic array or from the fuel cell, the latter supplied from the stored hydrogen. Different operational strategies are implemented via specialised software, called ORIENTE, which simulates and optimizes the energy system by levelling peak consumption, mitigating production shortfalls (e.g. passing clouds) and limiting overvoltage when solar production is high and consumption is low.

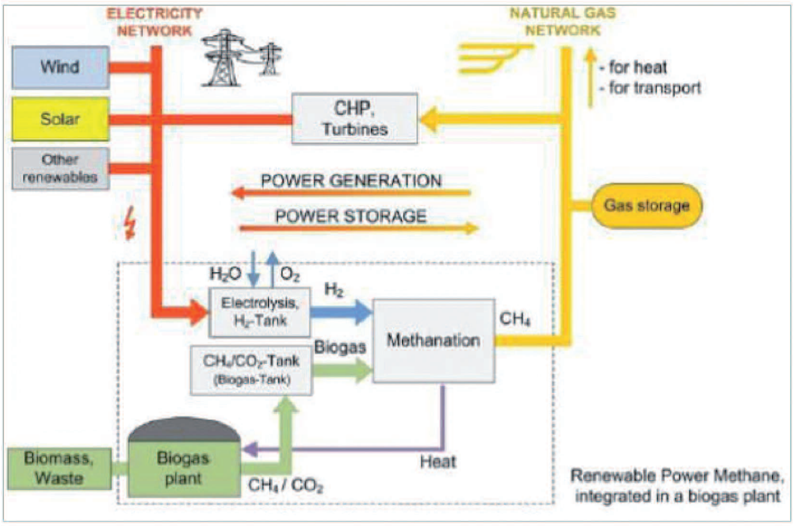
The peak power from the photovoltaic panels is 560 kW, and they produce 700 MWh/year (i.e. the equivalent of 1,250 hours/year at full power). The electrolyser and fuel cells each have an output of 200 kW. Given the facility's announced efficiency (35%), less than 250 MWh is finally delivered to the network. If we compare this production to the project's budget, €21 million, a quick calculation reveals an extremely high production cost of around €8,000/MWh (150 times the current wholesale market price).

It is therefore essential that lessons be learned from this experiment to help locate the potential areas for improvement: the electrolyser, the fuel cells and/or the hydrogen storage system.

Moreover, we might question the relevance of integrating these components in a single location, because MYRTE adds nothing to our knowledge of those links, and their integration is no particular challenge. Simulation of photovoltaic production allows analysis of the electrolyser and fuel cells in a laboratory setting, with easier and more refined conditions. This has been achieved at CEA-LITEN in Grenoble, France where the SENEPY experiment showed that certain links needed further experimental research in the laboratory before being tested in the field, in an unnecessarily costly manner.

METHANATION

FIG. 4: STORAGE BY METHANATION



Source: E-control

Methanation, which consists of reducing CO_2 with hydrogen to synthesize methane, only increases the already high cost of electrolysis, for the very debatable benefit of managing methane as a product instead of hydrogen.

Moreover, this operation simultaneously depends on multiple infrastructures:

- natural gas;
- electricity (low or medium voltage);
- hydrogen;
- CO_2 (which must first be captured);
- heat;
- others (e.g. biomass, biogas, oxygen).

These infrastructures are composed of networks and storage facilities that must be sized according to needs, the location of these needs, the sources of electrical power generation and CO_2. The apparent complexity of their integrated management makes these solutions unrealistic.

For all these reasons, it is difficult to imagine the utility of methanation in the foreseeable future, unless there is a major technological breakthrough in the direct catalytic conversion of CO_2. This condition, while necessary, is far from being sufficient for methane production to become competitive with natural gas in the near term, given the abundance of resources.

CALCULATION OF FUEL COSTS FOR HFCV AND COMBUSTION POWERED (DIESEL) VEHICLES AND THE COST OF CO_2 EMISSIONS AVOIDED

Assumptions about the hydrogen vehicle are taken from this policy brief and correspond to the most optimistic estimates provided by manufacturers. Those concerning the combustion powered (diesel) vehicle are taken from the March 2011 report of the CAS on the Car of Tomorrow.

Calculations exclude taxes and show that, with these assumptions, the fuel cost per kilometre for the HFCV is nearly four times that of the diesel vehicle.

	Vehicle Hydrogen	*Vehicle Combustion (diesel)*
Consumption	*1,00 kg H2/100 km*	*4,6 l/100 km*
Fuel price excl. tax	*13 €/kg H_2*	*0,75 €/l GO*
Fuel cost	*13,0 €/100 km*	*3,5 €/100 km*
Direct CO_2 emissions	*0,0 g/km*	*107,0 g/km*

Source: CGSP

Under these same assumptions, it would require a CO_2 price of €893/tonne to reconcile these two costs, meaning that numerous other actions to reduce emissions of greenhouse gases are more effective (e.g. insulating buildings, modal shifts). If the TIPP were to become a full-fledged carbon tax, it would need to be approximately tripled, thus doubling the price of fossil fuels at the pump.

This calculation does not take into account the costs associated with the purchase and maintenance of the vehicle itself, which would further increase the gap.

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