Study on Hydrogen and methanation as means to give value to electricity surpluses

Executive summary

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1. Scope and content of the study

This specific study takes place in the framework of the efforts currently made with a view to implement an energy transition that achieves a drastic reduction (by a factor 4) of greenhouse gases emissions, based on energy savings and a strong development of renewable energy sources, without tapping new fossil resources.

ADEME, GRT-Gaz and GRdF, the three sponsors of the study, consider that gas and electricity must take a role as complementary energy carriers in the process of this transition. The conversion of renewable electricity surpluses into hydrogen or methane to be injected into the gas network, that has recently become an issue in France especially in the energy scenarios such as « Vision 2030-2050 » (ADEME), « négaWatt 2011 » or « GrDF 2050 », seems to be a new example of this vision: this study contributes by building a shared knowledge of this new concept. It also aims at completing and feeding other more comprehensive or cross-disciplinary studies about the energy system, amongst which:

- « Study on energy storage potential », published and financed by ADEME in 2013, DGIS (Industry an Services Department of the French Ministry of Economics) and ATEE (Energy and Environment Technical Association), that evaluated the needs of France for power and heat storage in 2030, and is currently being complemented by a further projection up to 2050 and a better consideration of the energy system integration at a European level.
- « Towards 100% electrical RES in 2050 » ordered in 2013 by ADEME and still in progress, that aims at proposing different scenarios for the French power system being 100% renewable in 2050.

2. What is “Power-to-Gas” ?

2.1. Concept

The purpose of this study is to examine the use of technologies that allow converting power into gas as ways of providing added value to power surpluses. In the anglo-saxon world, and in numerous other countries, this concept is known as Power-to-Gas (PtG or P2G): for convenience, we will use this denomination.

The massive integration of fluctuating renewable energy sources ((wind and photovoltaics principally) into electricity systems implies more and more time periods during which production will exceed consumption. The volumes at stake could surpass the conventional capacities of flexibility and storage of the electricity system: the conversion into another energy carrier therefore appears as a solution for giving value to these surpluses.

As the basic technology of Power-to-Gas, electrolysis converts electrical energy into chemical energy in the form of hydrogen gas (H_2), by separating molecules of water (H_2O). The gas produced can be used on-site in different manners, for example by a manufacturer for it’s own process needs or by a filling station for hydrogen-fuelled vehicles (fuel-cell motorisation), or it can be stored locally for being later converted back into power through a fuel-cell.

However it can also be directly injected into the gas distribution or transmission networks, thus creating a coupling of various energy networks and carriers : in this way the possibilities to create added-value from power surpluses are significantly increased and diversified both in terms of final use as well as across a scope of time and space.

The possibility to inject hydrogen into gas networks provides access to huge storage and transmission capacities - in France alone, the gas storage capacities are 300 times bigger than those of electricity (137 TWh vs 0.4). However the quantity of hydrogen that can actually be injected is limited today to a few percents (around 2% in energy content) for several reasons (safety, leakage, suitability with final use or with pipe configuration,…) Even if the proportion considered as acceptable by networks operators is likely to increase in the coming years, it seems hardly possible that it could exceed 20 to 30% in volume (i.e. 15 to 20% in energy content) – and that is indeed a limiting factor in the medium- to long-term.

With this in mind, the so-called « methanation reaction » offers an additional possible step through which hydrogen atoms are combined with some carbon atoms extracted from carbon dioxide (CO_2) to produce synthetic methane (CH_4), which is 100% mixable with natural gas. There are many available sources of carbon dioxide: recovery of CO_2 from the purification process of biogas (from biomass methanisation) or syngas (from biomass gasification), CO_2 capture on industrial emission sources (cement or oil- based chemical processes, but also any kind of combustion facility), or even emission coming from power production.

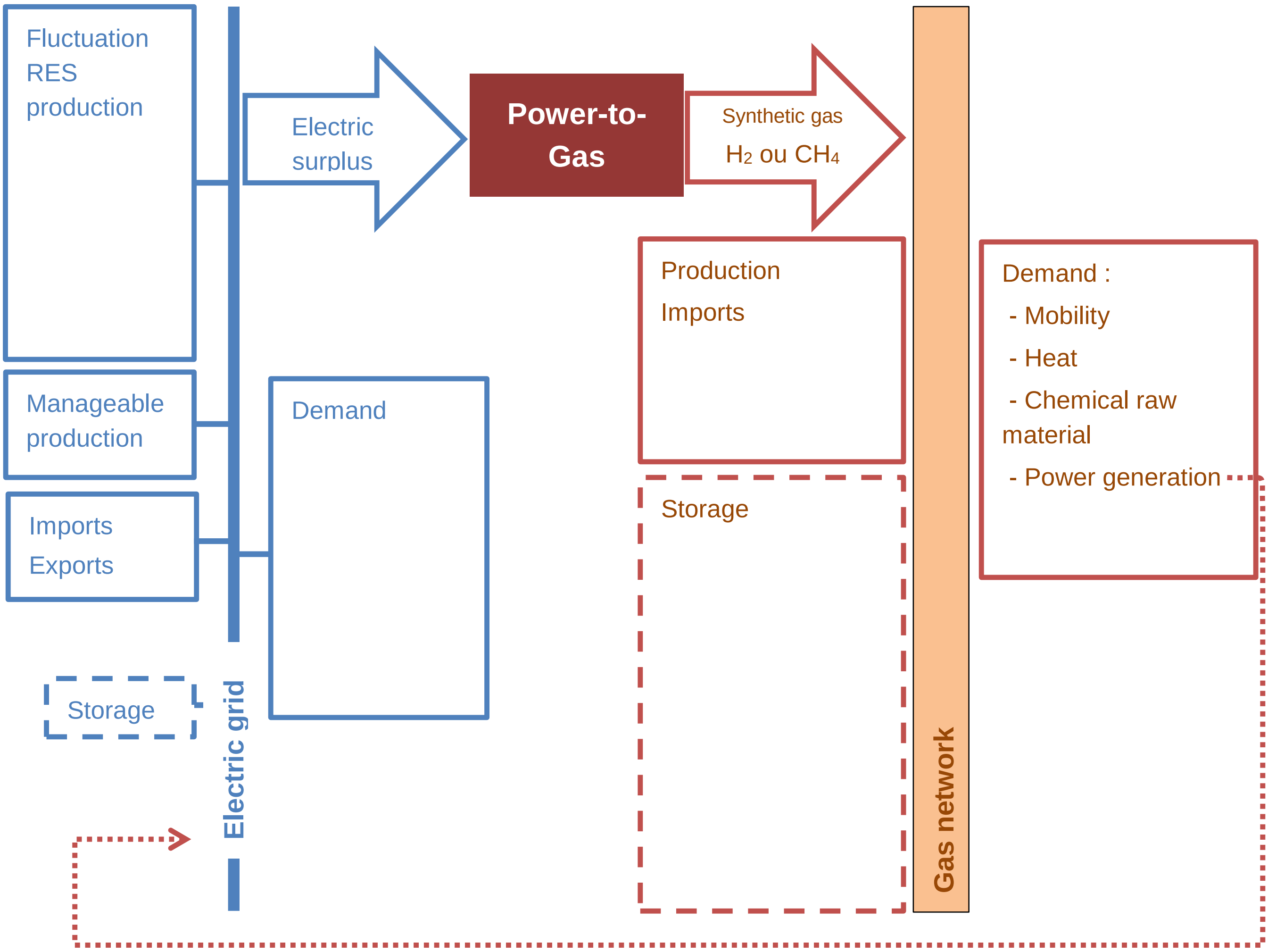
While not totally ignoring the possibility of on-site direct exploitation of hydrogen or methane that is already subject of numerous studies and recommendations, the present study focuses on the « network-tied » version that offers a real synergy with existing infrastructures and a large panel of uses for the gas produced:

- heat (for residential and offices space heating, industry, processes, domestic hot water, cooking,…)
- raw material for chemical industry
- mobility via conventional combustion engine vehicles (gasoline or Diesel) adapted for running with methane (Natural Gas Vehicles, NGV), as around 15 millions are doing today worldwide [1] ;
- power production

[1] Unlike electrical or hydrogen vehicles, it does not require a deep reconversion of both automobile manufacturing and fuel distribution.

Figure 1 summarizes the concept of Power-to-Gas as defined in this study.

Figure 1 – Schematic layout of Power-to-Gas



3. What role for Power-to-Gas in European scenarios?

An in depth analysis of 24 recent European energy scenarios as undertaken in the framework of this study identified the main lessons to be learnt concerning Power-to-Gas:

1. **A strong link to the massive penetration of fluctuating renewable sources is important.** A high share of fluctuating renewable electricity actually triggers a need for the switch to conversion technologies for absorbing the surpluses, using them directly or eventually storing them from one season to another. Power-to-Gas therefore appears essentially in scenarios with an ambitious share of renewables, and only from 2030 onwards, when they become significant or even dominant, or at least strongly influential to the electricity system's operation.
2. **The need for conversion between energy carriers depends on the scope of the scenario**. Those scenarios that address only the electricity system do not identify many benefits from Power-to-Gas. Since the issue in that case is only to achieve short-term conversions from production to consumption, synthetic methane or even hydrogen on it's own needs high investments and engenders high yield losses. Taking into account the needs of industry and, even more, of the transport sector, where gas is a highly valuable substitute to oil products profoundly changes the landscape and considerably increases the interest of energy carriers conversions

3. **Only Hydrogen and / or synthetic methane?** Some scenarios only investigate one of these options but imagine a possible evolution, depending on future observed technological progress. Others exploit both options simultaneously, but within a different time frame, CH_4 being generally used for higher shares of renewables in the energy mix. Some scenarios exclusively exploit synthetic methane so as to minimize the need for technology leaps for end uses and reap the highest benefits from existing infrastructures (network and storage facilities), and from those technologies proven within industry (gas motors).
4. The **energy mix of different renewable sources affects the attractiveness of Power-to-Gas**. Several scenarios make reference to Power-to-Gas (especially hydrogen) without integrating it: these cases are always for countries equipped with, or neighbouring a large hydropower portfolio feeding their own electricity mix. Other scenarios rely on a significant share of biomass in transport, eventually for balancing the electricity system, thus reducing the need for Power-to-Gas.

4. Efficiency, environment and economic balance

A preliminary assessment of energy, environment and economic performance has been achieved, based on today's current technological level but also on expected future improvements.

4.1. Technology

The electrolyser is the central component of Power-o-Gas, as it enables the conversion of electrical energy into chemical energy contained in hydrogen from water separation. Nowadays, there are three main electrolysers technologies: alkaline, PEM (Proton Exchange Membrane) and SOEC (Solid Oxyde Electrolyser Cell).

The first one is mature technology that is well known and used in industry. The second one, more recent and derived from fuel cells is used in small facilities. The last one (SOEC), operating at high temperature, is still at the laboratory stage; it differs mainly by the substitution of a part of the electricity needed for water dissociation by heat, thus improving the conversion of electricity to chemical energy efficiency..

In the case of synthetic methane production, a methanation reactor is used in series for converting hydrogen into methane through a reaction with CO2. Two technologies exist for this:

- the catalytic path using catalyser bed reactors (i.e. : nickel), quite similar to the monoxide carbon (CO) *methanation* process that has been used on an industrial scale for half a century at least.
- the biological path that uses microorganisms to achieve this conversion, in a manner quite close to *methanisation* that produces biogas through anaerobic fermentation, even if the microorganisms used and the reaction conditions are different.

Either way, there is no need for a technological leap: all the basic components of the technology are already available, even if each of these "bricks" is improvable or even replaceable by some future promising variant. Assembling and using these "bricks" for balancing the electricity grid represent *per se* a novelty that calls for adaptation and optimisation, especially considering intermittent operation.

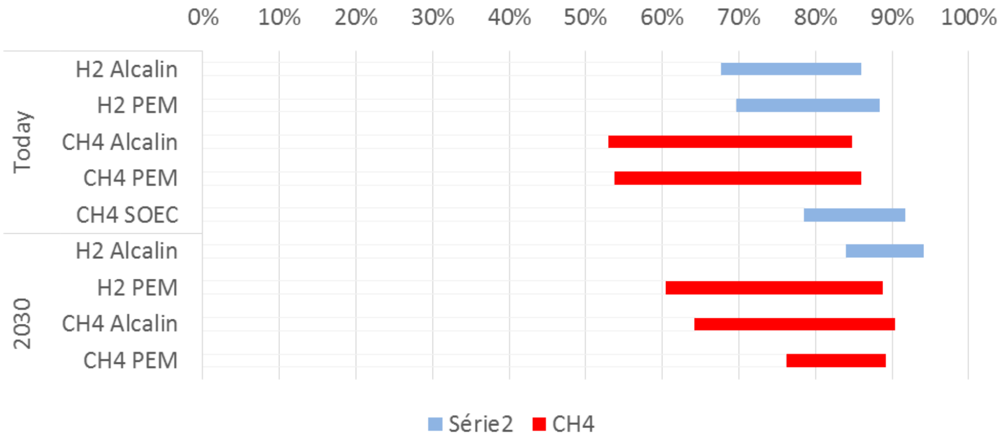
Significant improvements in the technical, economical and environmental performances are expected from the numerous developments that are presently on-track. The reduction in production costs will largely depend on the increasing facilities and equipment size, but above all on their manufacturing in larger series.

4.2. Performances

4.2.1. Energy performances

The Figure 2 below shows the energy performance currently expected in 2030. Today, the conversion yields from electricity to synthetic gas are around 70% $_{HHV}$ for hydrogen and 55% $_{HHV}$ for methane, but if the high and low temperature heat released by each of these processes is recovered and used, these yields can increase to over 85%. In the mid to long term, these performances without heat recovery could be significantly increased with a yield of 80-85%$_{HHV}$ for electrolysis and between 65 and 70% for methane, the highest yield being reached with the synergy of the SOEC electrolysis coupled with a catalytic methanation reactor whose high temperature heat (at 350 °C) can feed the electrolyser.

Figure 2 – Conversion efficiency according to technologies (based on HHV)



NB: The lower end of the spread refers only to synthetic gas-related value creation (H_2 or CH_4), the higher one also takes into account heat recovery.

Source: E&E Consultant[2]

4.2.1. Environmental performances

There is a lack of life-cycle assessment studies on this topic.

Concerning greenhouse gases (GHG), there are no direct emissions, and one study concludes to a life-cycle emission of 25 g_{eqCO2}/kWh$_{HHV}$ for hydrogen and another one at 37 g_{eqCO2}/kWh$_{HHV}$ for synthetic methane.

Concerning water, the gross consumption can be evaluated at around 0,45 m^3/MWh$_{HHV}$ for hydrogen and 0.6 to 1.1 m^3/MWh$_{GVC}$ for methane depending where the CO_2 is obtained. It is important to understand that in both cases, and particularly for methane, a significant proportion of the water used in the process can be returned to it's source or recycled after treatment[3]..

4.2.2. Economical performances

Currently, the production cost of hydrogen of around 100 €/MWh[4] is consistent with the levels of French feed-in-tariffs for biogas (between 45 and 125 €/MWh depending on facility capacity and the type of raw materials used). Its cost is however almost 3 times higher than natural gas wholesale prices.

The cost of methanation is today clearly far above levels that would allow for a competitive entry to the energy market, but it could approach the higher end of biogas feed-in-tariffs (i.e. 125 €/MWh) as of 2020 if co-products such as O_2 and heat are recovered and valued or, in the case of biological methanation, if the technology confirms its relatively low cost.

In 2030, the cost of hydrogen could remain around twice that of natural gas wholesale prices according to the price evolution expected by the IEA ((34 €/MWh$_{HHV}$), and the cost of methane between 2.8 and 4 time higher, depending on the technology used and on the rate of by-products value recovery.

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[2] From a technical sourced review of the different components, see full report, parts 2 & 3

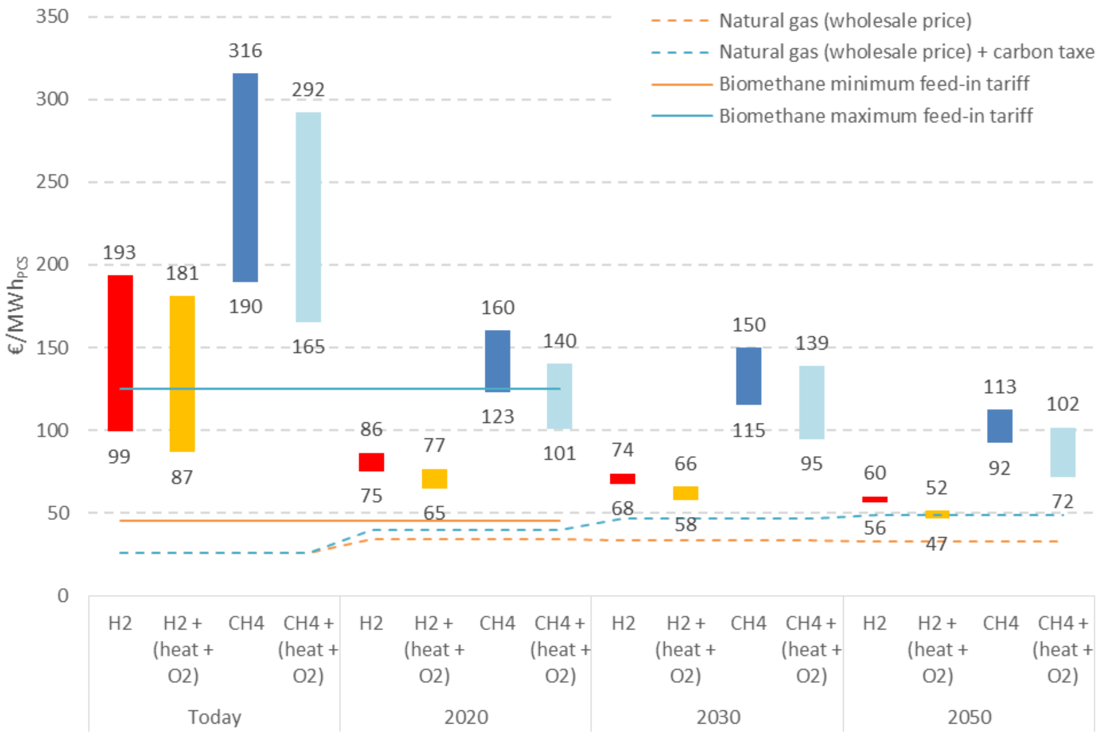
[3] by reference to two different studies whose hypothesis are not all published : the comparison must therefore be taken with reservations. See details in the full report.

[4] The higher end of the spread shown in *Figure 3* relates to a PEM électrolyser, today much more expensive than an alkaline one.

In 2050, production costs of hydrogen could fall to be around 1.7 higher than fossil natural gas wholesale prices, (taking into account all uncertainties at such a distant date), but could be competitive assuming a carbon tax at 90 €/t_{CO2}, as the IEA actually does in its « 450 ppm scenario »

The cost of synthetic methane could be in the range between 2 and 3.5 times higher than fossil natural gas wholesale prices at this date. In these conditions, a carbon tax at 220 €/t_{CO2} would be necessary to compensate with the higher production costs including co-products value recovery, and 330 €/t_{CO2} without.

Figure 3 – Summary of production costs of H_2 & CH_4 paths and sales prices according to uses



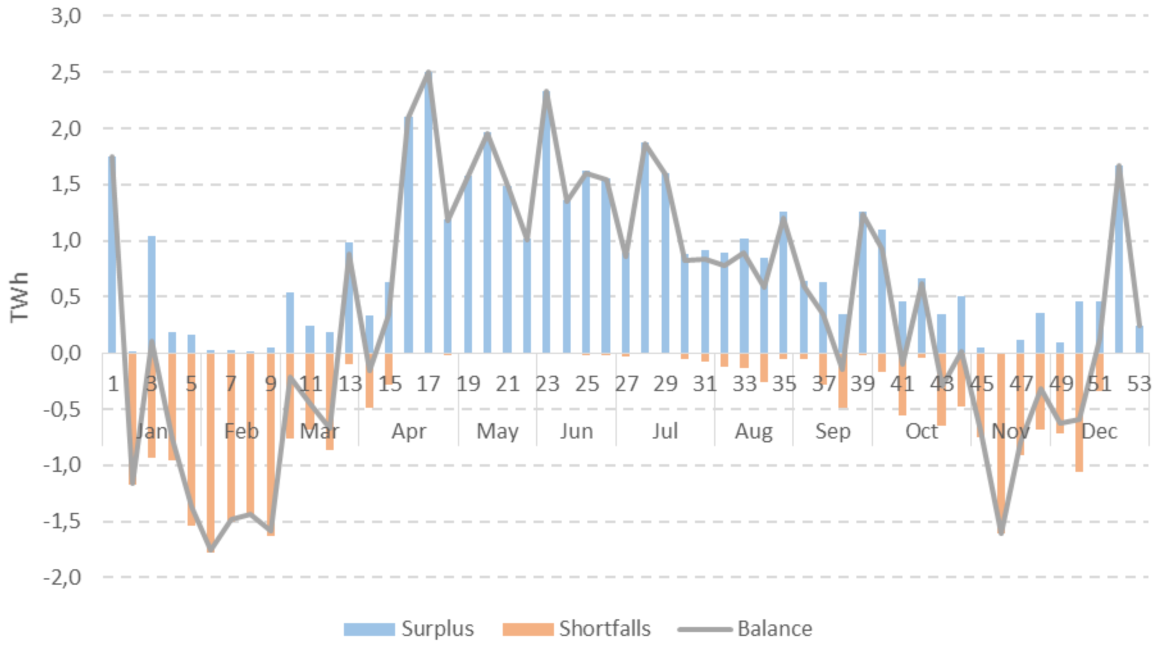
NB : production costs of each technology path are differentiated according to the estimated value of by-products.

Source: E&E Consultant

5. A possible development scenario

To assess the need for Power-to-Gas, a simplified model of surpluses and shortfalls between electricity demand and offer has been achieved, based on hypothesis from the ADEME « Vision 2030-2050 » study for the reference scenario and from the négaWatt 2011 study for the higher scenario.

Figure 4 – Weekly production surpluses and shortfalls for 2050 in the reference scenario



Main hypothesis:

- *Hourly demand*
- *Fluctuating RES profiles based on 2012 weather records*
- *Nuclear power : technical minimum / seasonal availability / +/-5%/h load variation constraint*
- *Technical minimum share for other RES*
- *No power exchange at interconnections*
- *PPSP included (5.4 GWe of pumping – lower tank 100 GWh)*
- *Local grid constraints not considered*

Source: E&E Consultant

Building on these scenarios, residual surpluses account for 15 TWh in 2030 and between 44 and 91 TWh in 2050 depending on the scenario variants. If the surpluses that can be balanced on a weekly basis are deducted, then the figures are 13 TWh and between 34 and 67 TWh, respectively. Such large surpluses cannot be absorbed by any specific power storage system and must therefore be converted otherwise they would be lost.

A recovery of value as heat (Power-to-Heat or PtH) is possible but limited: most high surpluses peaks take place in summer when the need for heat is low and seasonal storage capacity is expected to remain limited in capacity. The recovery of value as synthetic gas provides the highest potential, specifically with regards to its advantages in terms of flexibility resulting from the very large storage capacity and its ability to replace oil products in the transport sector which is hard to decarbonise.

Considering this range of surpluses and taking into account technical and economical constraints, a credible development scenario for 2030 appears to be in the range from 1 200 to 1 400 MWe of installed Power-to-Gas capacity, able to convert between 2.5 and 3 TWh of electricity (and produce between 1.8 and 2 TWh of synthetic gas.

In 2050, the installed capacity could reach between 7 700 and 24 000 MWe, converting between 21 and 72 TWh of electricity i.e. between 6 and 24 % of the national power consumption) and producing between 14 and 46 TWh_{HHV} of synthetic gas, t hydrogen processes accounting for 5 to 10% and methanation processes for the rest. The study shows that the CO2 needed for producing methane could be entirely covered by renewable sources through methanisation and gasification of biomass as developed in the corresponding scenarios.

Finally, these Power-to-Gas facilities would also be able to produce altogether between 5 and 18 TWh of valuable heat, and between 3 400 and 11 700 kt of oxygen usable by the industry or health sectors[5].

6. A legal and economic framework to be built

6.1. What shares for market and regulated sectors?

Without being an absolute pre-requisite for its development, the issue of the place of Power-to-Gas in the energy system as a whole will undoubtedly be a decisive element for the actual contribution it will be able to bring to the energy transition.

Two contrasting visions induce specific technical solutions and economical models that will depend on the approach chosen:

- the first one considers that Power-to-Gas is just a new way of producing hydrogen or methane and must therefore be integrated in the corresponding markets as they currently operate and follow the usual market rules ;
- the second one takes into consideration the systemic character of Power-to-Gas regarding the energy system as a whole, and its capacity to provide a balancing solution that designates it as an intrinsic part of the regulated sector, in the same way as the transport or distribution grid, for instance.

Even if a hybrid vision is possible, a legal, regulatory and fiscal framework must be established, based on well informed choices, especially considering economical efficiency criteria but also considering the technologies capability to ensure, over the long term, a consistent answer both to the technical constraints of electric grid balancing and of the renewable energy sources development goals.

6.2. A need to define a stable economical model

The need for visibility, and a certain stability of the economic model within which operators will have to integrate their future activity is a prerequisite for industry if it is to invest in the necessary R&D programmes required to bring the technologies through R&D to Demonstration and thence industrial deployment phases ready for a massive roll-out on time.

It will be particularly important to determine how and to what extent the electricity markets' design and functioning can be modified, specifically in light of the markets inability to keep the most modern and least polluting fossil fuel power stations on line.

It will also be necessary to evaluate the impact of changes to renewable electricity support mechanisms, as well as those to CO_2 and greenhouse gas emission regulatory instruments such as the ETS market and the carbon tax.

6.3. Adapt the current regulatory framework in the short term

Although a widespread deployment of Power-to-Gas will not take place by any measure before 10 (for hydrogen) to 15 years (for methane), some aspects of the present regulatory framework seriously curtail the development of demonstration projects[6], even though they are clearly necessary so that industry can acquire the experience necessary to correctly orientate their R&D activities. In light of this it would be pertinent to initiate and/or accelerate discussions and works involving the possible adaptation and evolution of the legal framework in several areas keys to Power-to-Gas – for example the strict regulatory framework of hydrogen production and storage that was specifically designed for industrial uses of the gas, but that is not really relevant for PtG production and uses.

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[5] In 2011 the production of oxygen was estimated at 4 700 kt by EUROSTAT

[6] Such projects are currently emerging in Denmark or Germany

6.4. A need for collaboration between gas and power industries.

Power-to-Gas necessarily interacts horizontally with electricity and gas infrastructure and markets. It does not adapt itself well to the present structure of the French energy sector that has a long history and still bears the marks of its inherited strict legal separation between gas and electricity, for example in the way actors are organised, or in the perception by the political body and ordinary citizens that electricity and gas are rival energy sources; these structural factors and misconceptions may be as many barriers to the development of PtG..

In contrast, the example of Denmark, where the electricity and gas transmission networks are operated by a single company (Energinet.dk), is striking. The generally sterile competition between these two energy vectors is not a subject in this country, where their complementarity characteristics are taken for granted – as is the complementary carrier of distributed heat from the district heat networks that supplies more than half of all buildings. Whilst electricians and gas operators do not have an entirely common culture, they nonetheless have a common practice of informed dialogue and open cooperation that are an indispensable base from which to reach any technically and economically optimised solution.

The issue of gas and electricity transmission networks operators coming closer together is not the topic of this study, but the collaboration between them, as well as between distribution network operators at relevant scales that could be in the range of the current Regions' areas, should be reinforced and put on the agenda of present and future discussions and working groups around energy transition.

7. Recommendations

The development of Power-to-Gas can be summarized in three key steps.

In the short to mid-term, hydrogen represents, when incorporated into the gas network in limited proportions (a few %) and/or used directly in some niche markets (particularly via fuel cells) a way to provide added value to substantial renewable electricity surpluses. .

In the longer term, a transition toward synthetic methane production would allow to overcome all technical barriers linked with gas injection and would open access to the huge storage capacity provided by underground reservoirs. In addition, by adding value to CO_2 coming from the purification of biogas produced through methanisation process, methanation can also significantly contribute to the massive development of renewable gas for major uses such as mobility or heat that prove to be hard to decarbonise.

In parallel with these developments in the energy sector, and from now, possible substitutions can be identified for industrial uses of hydrogen, whose consumption accounts for around 1 million tons per year. In particular, diffuse low quantity uses (food-processing or electronic industries, …) could already be supplied by hydrogen produced through electrolysis. These substitution potentials represent an opportunity for Power-to-Gas through the technical and economical development of several elements, but also in terms of GHG emissions reduction since the production of hydrogen, essentially based on natural gas steam-reforming (cracking), causes emissions of around 10 $MtCO_2$ per year

These steps are not so much technical milestones, with each one needing the previous one to be fully completed before being implemented, but a way to plan a more deeply integrated and systemic development of Power-to-Gas technologies. In practice, the uses described above will to some extent develop simultaneously anyway.

Encompassing this vision, the recommendations below are directed to public authorities and to industrial and economical stakeholders and take into account the lessons learnt previously mentioned and clearly intend to create a dynamic movement towards at least full scale testing and technical and economical characterization of Power-to-Gas technologies in the French energy system.

- **R&D (short term – 5 years)**
  - To undertake a complete life-cycle assessment (resources, GHG balance, infrastructures, land uses, …) of available alternatives to oil products in road transports : 2nd an 3rd generation biofuels, bio-methane, H2, NGV, electric and/or hybrid vehicles, Power-to-Liquid,[7],
  - To develop large scale demonstrators that include services provided to the electric system in coordination with transmission and distribution power and gas networks operators
  - To launch a mid to long term R&D program (in coordination with Germany and other countries more advanced on the topic) including technical but also economical and financial aspects at a detailed micro-economic scale (business plans)

- **Coordination of stakeholders – participative working groups (medium term 5 to 10 years)**
  - To establish a multi-stakeholder working group to elaborating a regulatory, technical and economical framework, similar to the workgroups on bio-methane injection created by the State Administration in 2008 and successfully managed by ADEME and GrDF since 2009.
  - To define development goals (Roadmap)

- **Information and awareness-raising (mid-term – 5-10 years)**
  - To inform economic decision-makers and the general public through neutral and independent media (i.e. not only the industry)
  - To develop a professional training program

- **Regulatory framework (mid-term – 10 years)**
  - To define in which conditions the renewable and decarbonised character of Power-to-Gas (H_2 and CH_4) could be recognized in legal, regulatory and fiscal texts in France and in the European Union.
  - To update the regulatory framework, firstly on H_2 production, storage and uses and on CH_4 injection, in accordance with the results of the actual risk evaluation studies taking into account the environment (industrial uses vs general public)
  - To adapt and standardise across Europe regulations, codes and standards

- **Examples of support mechanisms (mid term - 10-15 years)**
  - To implement an environmental and carbon taxation system (immediately)
  - To exempt Power-to-Gas (H_2 and CH_4) from any taxation (as heat or transport fuel) while taking into account the origin of CO_2 depending on the GHG emissions
  - To enforce a « super-ecological-Bonus » for the purchase of a vehicle fuelled by Power-to-Gas (H_2 and NGV)
  - To give priority to the injection in gas networks without forgetting the possibilities of (off grid) niche markets in industry such as refineries, ammonia production and in the transport sector (H_2 filling stations, Power-to-Liquid, …,)

[7] Production of liquid synthetic fuel for cars from electricity, for example methanol