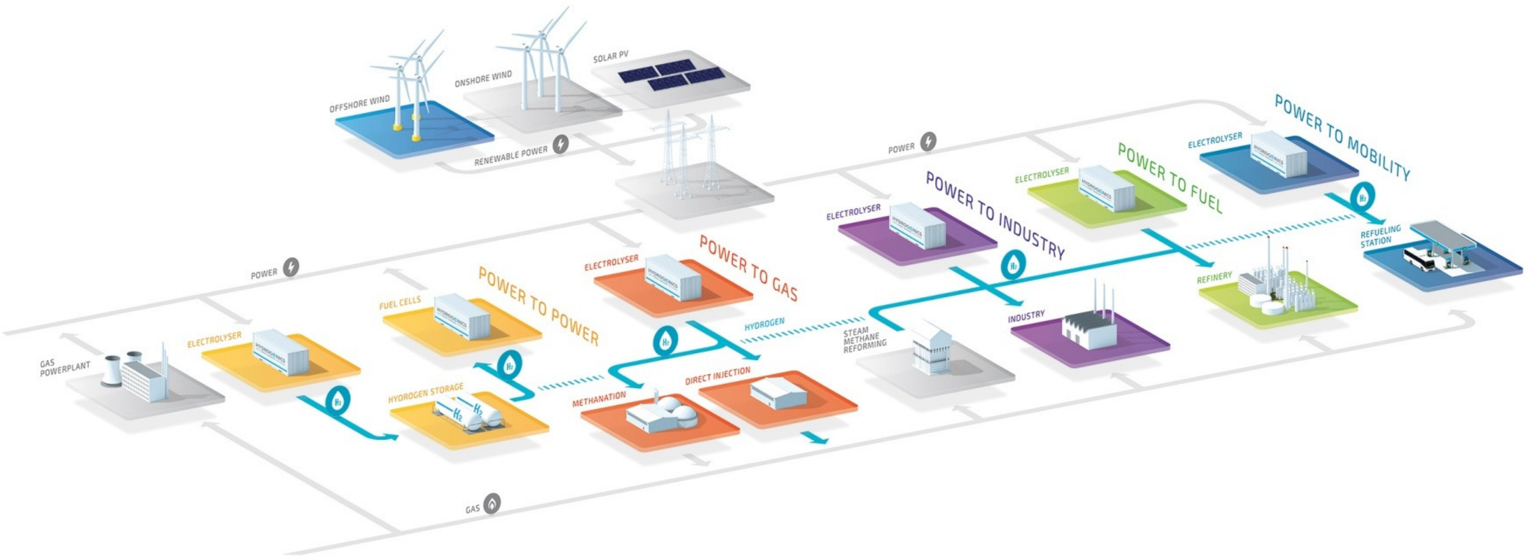
POWERTOGAS
Roadmap for Flanders



EXECUTIVE SUMMARY

October 2016

www.power-to-gas.be

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KEY METRICS FOR HYDROGEN PRODUCTION AND MOBILITY APPLICATIONS

Cars and buses

FCEV	H_2 tank	H_2 consumption	Driving range	Annual driving distance	Annual H_2 consumption
Car (passenger)	5 kg	1 kg/100 km	500 km	15.000 km	150 kg
Bus (12 m)	35 kg	10 kg/100 km	350 km	60.000 km	9 tons

Hydrogen production from electrolysis

- **Power:** 1 MW electrolyser > 200 Nm^3/h H_2 > ± 18 kg/h H_2
- **Energy:** 1 kg H_2 > 11.1 Nm^3 > ± 10 liters demineralized water > +/- 55 kWh of electricity

Renewable hydrogen for transport applications

	Solar PV	On shore wind	Off shore wind
Project size (MW)	1	5	325
Annual energy yield (GWh/MW)	1	2,2	3,3
Annual energy production (GWh)	1	11	1.073
Annual hydrogen production (tons)	18	200	19.500
# Buses (12 m)	3	33	3.250
# Car (passenger)	121	1.333	130.000

NB: These are indicative figures only, provided for back of the envelope calculations. They might slightly differ from the values used in the current study.

1. CONTEXT

Environmental and energy policies in Europe are based mainly on three main pillars: fight climate change (through CO_2 reduction measures in the power, gas and transport sectors), improve energy security of supply (reduce dependency from countries outside de EU) and improve air quality (especially in urban areas). Thanks to these policies, the production of renewable electricity from wind and solar energy is increasing in Flanders, Belgium and all across Europe. The ultimate goal is to have an energy system based upon 100% renewable energy, so milestones to reach this final target are developed and a huge increase in the share of renewable electricity in the overall electricity system is expected in the near future.

Increasing use of renewable and especially fluctuating electricity sources will become an increasing challenge for the existing electricity grid and requires additional investments in distribution and transmission networks, additional need for grid flexibility, demand side management and energy storage.

Massive deployment of renewable electricity however is not possible without energy storage and especially large amounts of electricity to be stored will ask for new approaches.
Power-to-Gas (the conversion from renewable electricity to hydrogen) as conceptual idea has a large potential to become a “bridge” between electricity, fuel, gas and industrial sectors, thus providing flexibility and enabling the conversion of renewable electricity into sustainable fuels, gases and products.

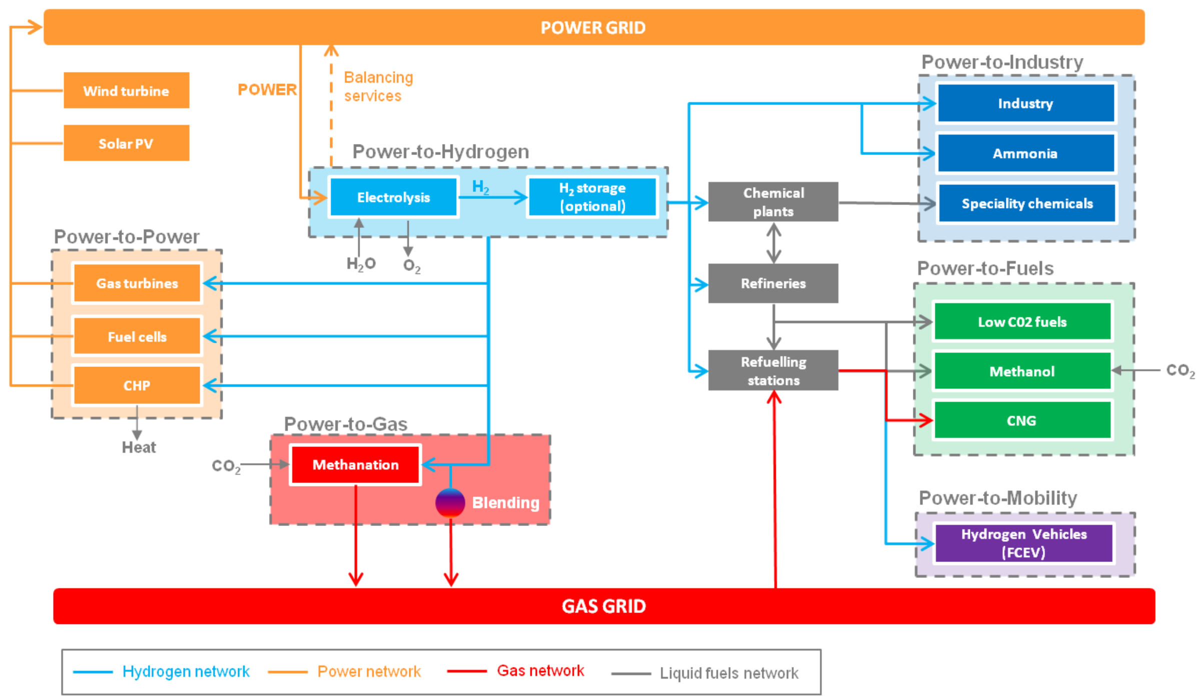
In Flanders different companies are active in this field and have the potential to play an important role in the Power-to Gas development.
The objectives of this Power-to-Gas roadmap for Flanders were the following:

- Describing what Power-to-Gas is, the state of the technology in presence and the application fields
- Defining business models for various valorisation routes
- Studying the actual and future outlook of these business models (technological and economical) with a medium (2030) and long term (2050) perspective;
- Developing and prioritizing a set of recommendations for a successful implementation of the Power-to-Gas concept in Flanders and abroad (appropriate regulatory framework);
- Defining a Flemish value chain and create an industrial cluster concerning Power-to-Gas.

2. ECONOMIC FEASIBILITY OF POWER-TO-GAS CONCEPTS

The key-element of the different Power-to-Gas concepts is the valorisation strategy of renewable hydrogen, produced out of renewable power.

Figure 1: Different Power-to-Gas concepts analysed in the roadmap study



In Figure 1, the five different Power-to-Gas concepts analysed in this roadmap are presented in different colours:

- **Power-to-Power:** renewable hydrogen as a medium for electrical energy storage (conversion of renewable power into hydrogen, hydrogen storage and repowering).
- **Power-to-Gas:** renewable hydrogen directly injected in the natural gas grid or used as a feedstock for the production of synthetic methane.
- **Power-to-Mobility:** renewable hydrogen as a fuel for mobility for fuel-cell electrical vehicles (FCEV).
- **Power-to-Fuels:** renewable hydrogen as a source for the production of sustainable fuels like biomethanol, biomethane or the use of renewable hydrogen in refineries (mainly for desulphurization) to lower the CO_2 footprint of conventional fuels.
- **Power-to-Industry:** renewable hydrogen as a source for sustainable production of chemical products (e.g. Ammonia or methanol).

The Power-to-Gas concept addresses various challenges of the transition towards a decarbonised energy system.

The conversion of excess of renewable power to hydrogen allows storing the energy into a chemical form for a long period of time without losses and the stored hydrogen can then be used in various forms or for many different applications.

The common step for all Power-to-Gas processes is the conversion of renewable power to hydrogen via an electrolysis process which splits water (H_2O) into hydrogen (H_2) and oxygen (O_2). The electrolysis process can be operated very dynamically to help balancing the increased amount of fluctuating renewable energy sources.

Alkaline electrolysers exist for many decades in the industry (float glass, steel, power plants and semiconductors) and the technology itself is very mature. PEM electrolysers are more recent and are in the performance validation phase. For both technologies, the cost reduction potential with large production volume is significant (Bertuccioli, et al., February 2014).

Based upon assumptions/definitions (e.g. costs hydrogen equipment, electricity prices, grid fees, CO_2 prices, ancillary services and other commodities) for the different valorisation pathways, the economic feasibility has been calculated for a wide variety of configurations for actual (2015) and future (2030 and 2050) configurations. General information about the main cases is presented in the following table.

Table 1: Overview of the calculated business cases

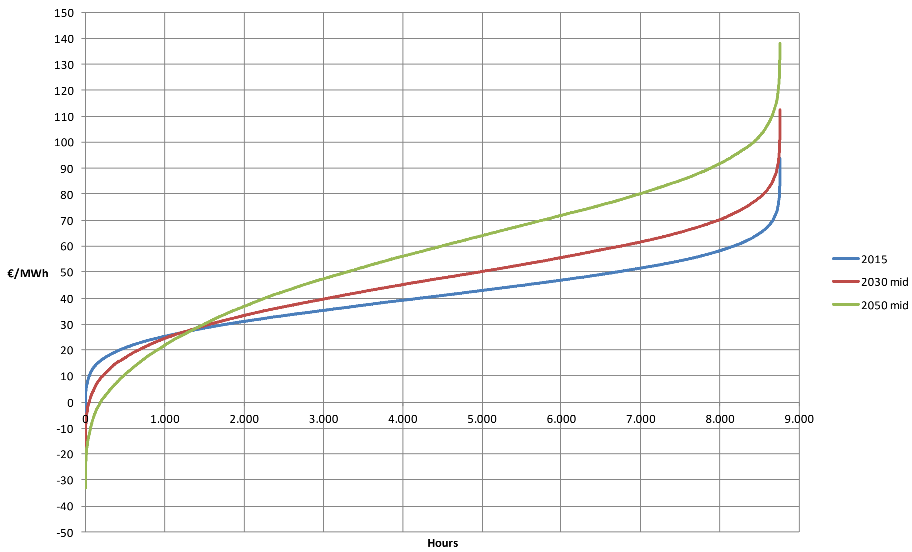
Case	Size electrolyser	Typical application	Reference product
POWER-TO-INDUSTRY			
PtH_2 (large): Power-to-Hydrogen (large scale)	100 MW	H_2 as feedstock in large industry (Ammonia production or refinery)	H_2 produced with onsite SMR from CH_4 or H_2 delivered by pipeline
PtH_2 (small): Power-to-Hydrogen (small scale)	1.2MW	H_2 as feedstock in small to medium size industry	H_2 delivered by tube trailers trucks
POWER-TO-GAS			
PtH_2 (blend) : Power-to-Gas (direct injection)	15 MW	Direct injection of hydrogen in gas grid	Natural gas from gas grid
$PtCH_4$: Power-to-Gas (methanation)	15 MW	Transformation H_2 into SNG and injection in gas grid	Natural gas from gas grid
POWER-TO-MOBILITY			
PtFCEV(cars): Hydrogen Refuelling Station for cars	500 kW	Hydrogen as a fuel for FCEV (cars)	Diesel
PtFCEV(buses): Hydrogen Refuelling Station for buses	2.2 MW	Hydrogen as a fuel for FCEV (buses)	Diesel
POWER-TO-FUELS			
$PtCH_3OH$ (fuel): Power-to-Methanol (as a fuel)	50 MW	Partial substitution of diesel with bio-methanol produced from H_2 and CO_2 in a methanolisation process.	Diesel
POWER-TO-POWER			
PtP (small): Power-to-Power (small scale)	500 kW	Hydrogen-based electrical energy storage in medium-sized industry with own renewable energy production (*prosumer*)	Power from the grid
PtP (large): Power-to-Power (large scale)	400 MW	Hydrogen-based electrical energy storage (at utility scale)	Power from the grid

The detailed assumptions used for the calculation of these business cases are presented in the full report.

3. POWER PRICE ASSUMPTION

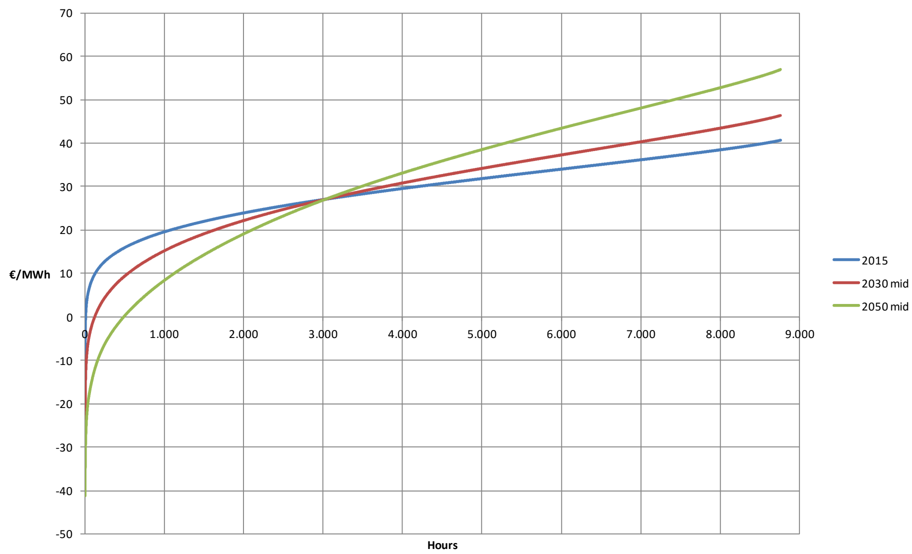
Among these assumptions, we need to underline the power price duration curve expected for 2030 and 2050 in the model (see full report) which has a strong influence on the results. Under these conservative assumptions, we expect more hours with cheap (even negative) power prices but limited in the number of hours, but also more hours with more expensive power prices due to the need to produce more expensive power when there is a low renewable production in the energy system.

Figure 2: Expected power price duration curve for Belgium in 2030 and 2050 compared to 2015 [1]



All in all, these assumptions lead to a general higher average electricity price in 2030 and 2050 when electricity is needed more than during the cheapest first 3000 hours of the year.

Figure 3: Expected average power price duration curve for Belgium in 2030 and 2050 compared to 2015 [2]



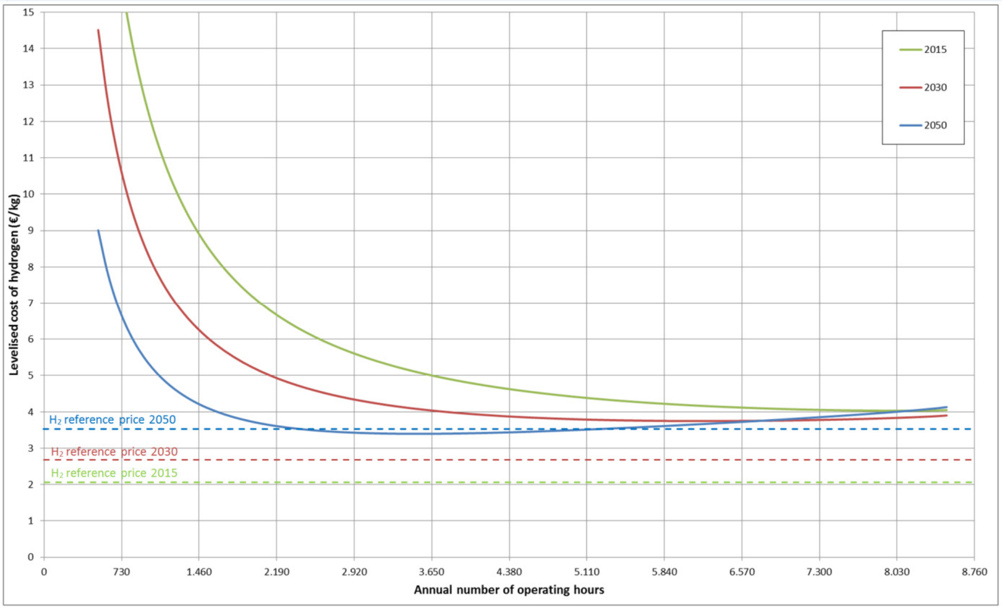
[1] Source: own calculation
[2] Source: own calculation

4. MAIN ANALYTICAL RESULTS

4.1. Power-to-Industry

The economics of a very large scale electrolyser (100 MW, ~43 tpd) system have been analysed and the levelized cost (LCmax) of hydrogen has been calculated according to the amount of operating hours per year (see Figure 4), assuming the electrolyser would operate firstly during the cheapest hours.

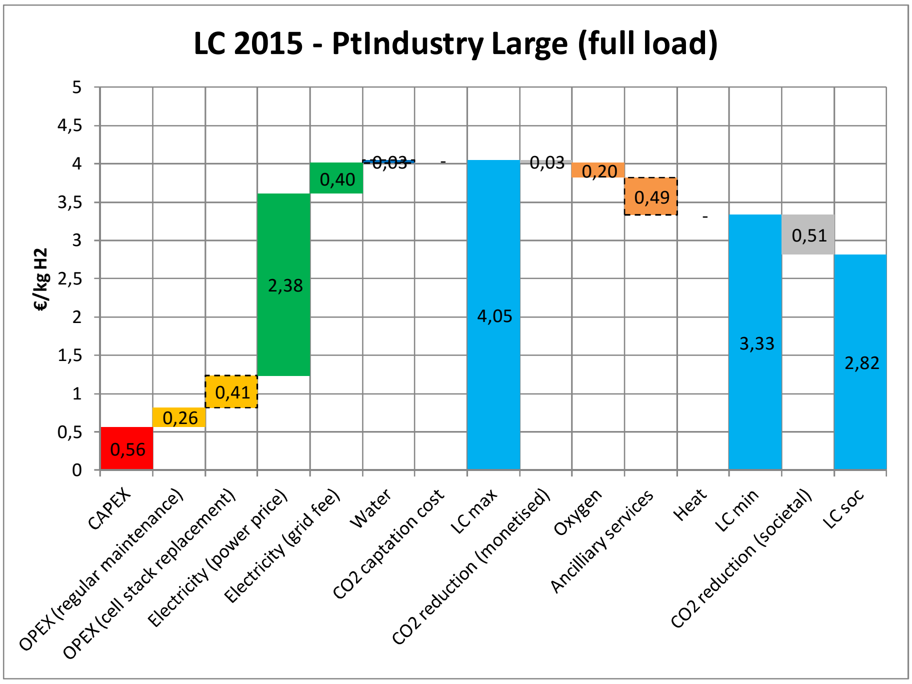
Figure 4: Levelized cost of hydrogen (LCmax) vs. operating time (Power-to-Industry - large scale)



For such a large system, production costs of electrolytic hydrogen are expected today in the range of 4 to 5 €/kg with an operating time above 3500h. On the long term, hydrogen production costs are expected in the range of 3 to 4 €/kg, with the underlying future power price assumption explained previously.

Looking at the cost structure of 1 kg of hydrogen (see Figure 5), we can notice the power price (including transport/distribution costs and grid fees) represents more than 68% of the LCmax.

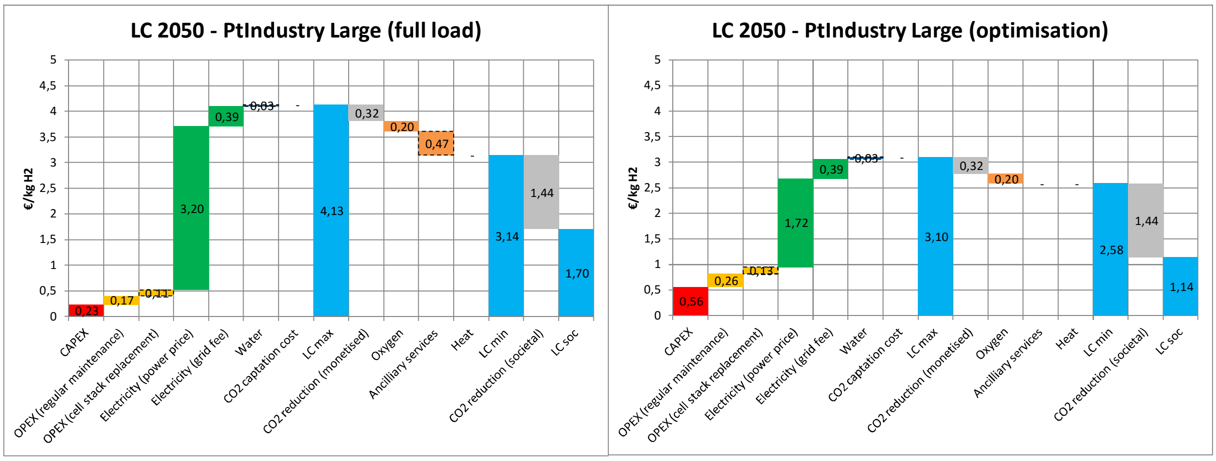
Figure 5: Waterfall graph 2015 (Power-to-Industry - large scale - at full load operation)



***Waterfall graphs** represent the decomposition of the Levelized Cost (LC) of the end product (hydrogen, methane ...) among the various cost drivers. Next to the base case LCmax valid for all situations and including the capital cost, a LC including the additional revenues (monetized CO_2 revenues from EU ETS scheme, oxygen and heat valorisation) is calculated ('LCmin'). Finally, also the avoided societal cost of CO_2 -emissions (non monetized part) is taken into account, leading to a LCsoc including additional benefits. These graphs show to which extent costs and revenues contribute to the LC, and can therefore also give an indication of the sensitivity.*

The hydrogen generation cost breakdown for the Power-to-Industry case is expected to be slightly different for the medium and long term, with the emergence of an optimum point between the power price and distribution of fixed costs over the number of operating hours (see Figure 4). This is also illustrated in Figure 6 where we notice the importance of power prices when operating at full load (representing 77% of the LCmax) and the limited power price impact at the optimum point (representing 68% of the LCmax). When operating a lower amount of operating hours, fixed costs (CAPEX/OPEX) are obviously gaining importance on the LCmax.

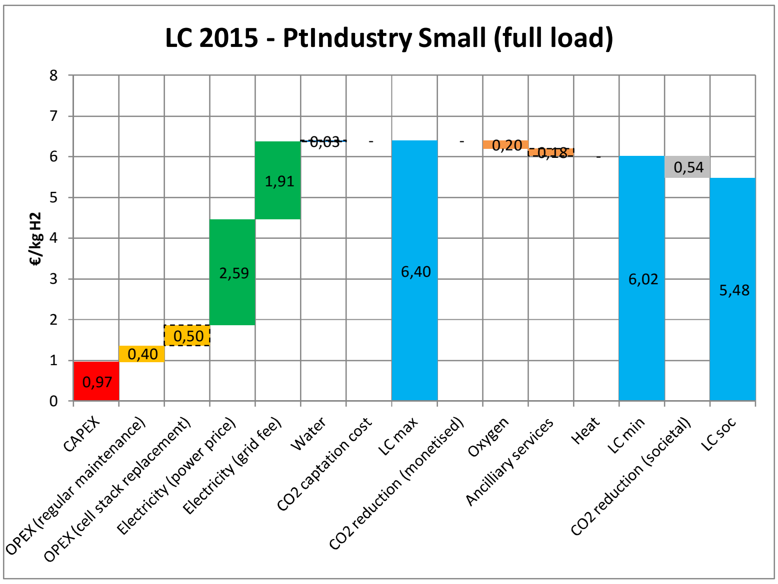
Figure 6: Power-to-Industry (large scale) - Waterfall graph 2050 at full load operation and optimum point



To assess the competitiveness of the hydrogen produced from electrolysis, it should be compared with the price for hydrogen generated from large scale Steam Methane Reforming and its expected development. These are typically in the range of 2-3 €/kg today. Future projections (cf. full report, including increasing CO_2 emissions allowance costs and gas price increase) show it could reach 3-4 €/kg in 2030-2050, meaning that **large scale electrolysers could generate in the future cheaper hydrogen than onsite SMR units (or hydrogen delivered via pipeline) if they can operate during the cheapest power price hours.**

Applying the same methodology, we have analysed the competitive situation of small scale onsite hydrogen production from electrolysers (1,2 MW, ~0,5 tpd) which give an LCmax in the range of 6 €/kg which is in the same price range as hydrogen delivered by tube trailers trucks from a central SMR unit (Esprit Associates, August 2014).

Figure 7: Waterfall graph 2015 (Power-to-Industry - small scale - at full load operation)

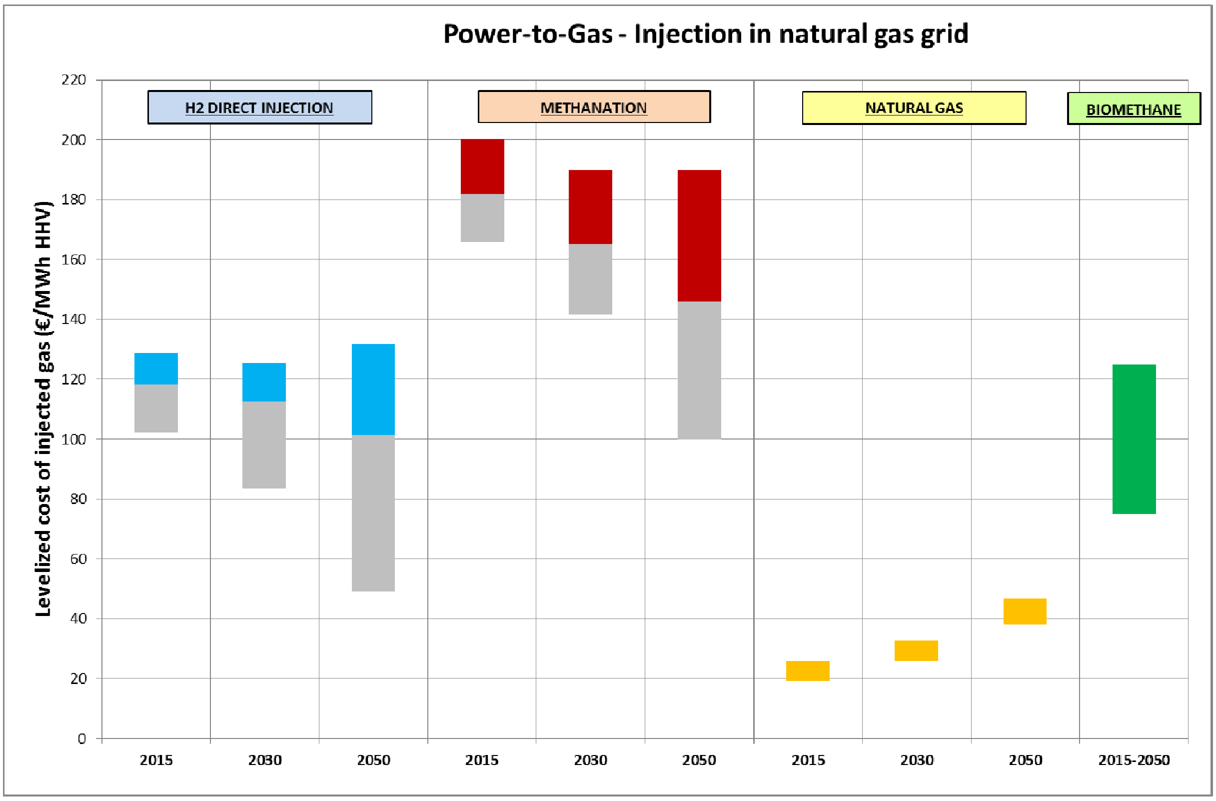


Depending on the actual price of hydrogen for small industrial hydrogen consumer (function of the delivery distance and the hydrogen demand volume), onsite hydrogen production from electrolysis can already be competitive with hydrogen delivered by tube trailers trucks from a central SMR unit.

4.2. Power-to-Gas

For the Power-to-Gas applications, we have considered a 15 MW electrolyser system injecting either pure hydrogen or synthetic methane (after a methanation step) into natural gas grids.

Figure 8: Levelized cost of Power-to-Gas: direct injection and methanation in 2015, 2030 and 2050 [3]



For such systems, we expect Power-to-Gas options to remain more expensive than natural gas. If we consider the available options to transport/distribute green gases in the future, there is only biomethane injection which has a potential contribute to it, even if limited due to the availability of biomass.

Direct injection of hydrogen in gas grids (~125 €/MWh) seems already competitive today with some biomethane feed-in tariffs existing in France or Germany (75-125 €/MWh)[4]. If such Power-to-Gas projects could benefit from these feed-in-tariffs in Belgium, it would be a sufficient incentive to have a business case for the direct injection of hydrogen in gas grids.

If we want to convert hydrogen (H_2) to synthetic methane (CH_4) by using carbon dioxide (CO_2), we have additional costs and efficiencies which bring the costs in the range of 150-200 €/MWh, which makes it difficult to justify today. But if we want to decarbonise fully the gas distributed and transported in our grids in the future, this is definitely an option to be considered, taking into account the limitation of existing gas grids for hydrogen (Altfeld & Pinchbeck)**.**

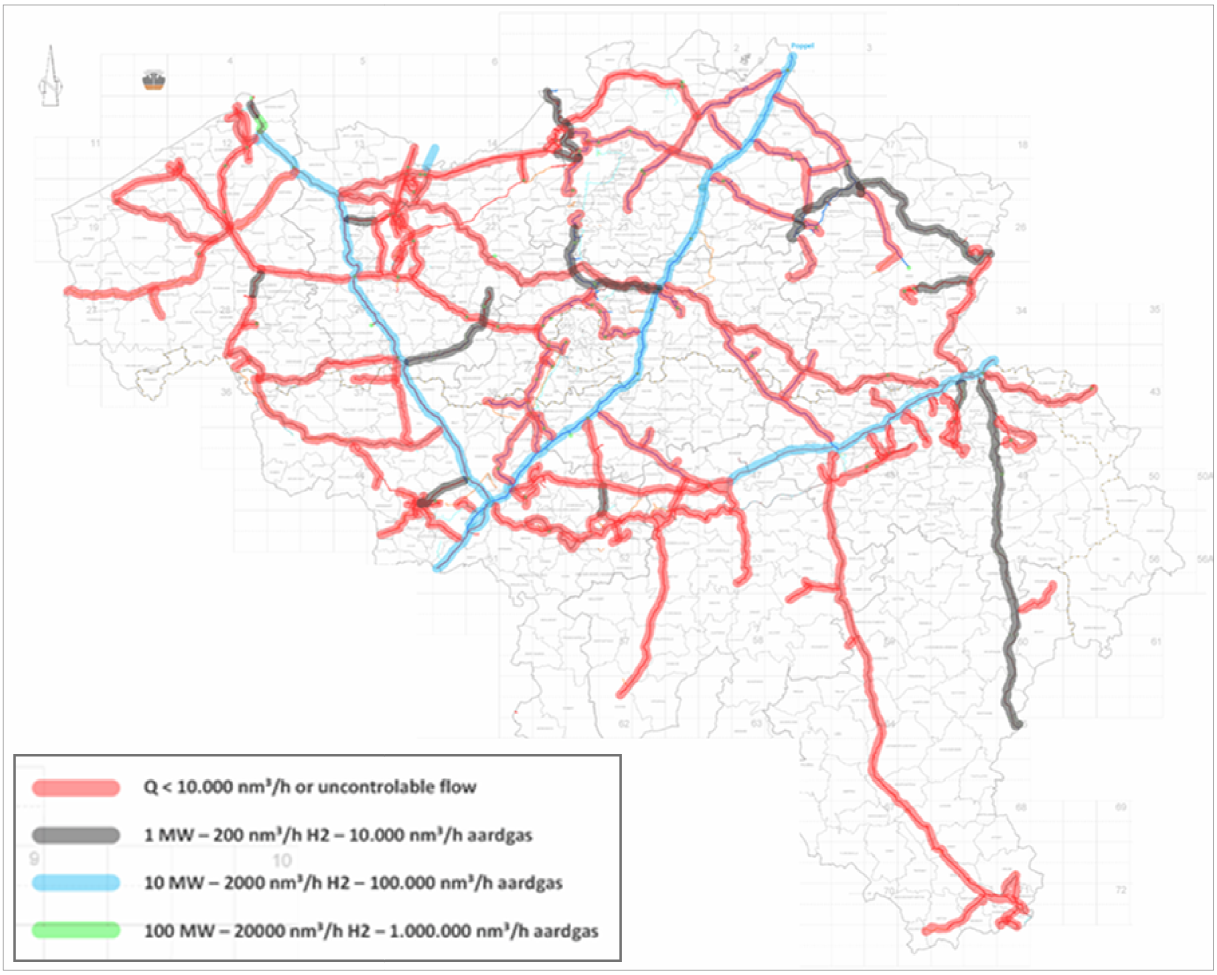
[3] The top of the colored bar represents LCmax at full load operation; the bottom of the colored bar represents LCmin with optimized number of operating hours, and the bottom of the grey bar finally represents LCsoc (again with optimized number of operating hours). For biomethane, the bottom of the colored bar represents the low scenario (75 €/MWh HHV) and the top the high scenario (125 €/MWh HHV).

[4] There is today nor feed-in-tariff for biomethane injection in gas grids in Belgium

A study[5] on the Admissible hydrogen concentrations in natural gas systems showed that if an admixture of up to 10 % by volume of hydrogen to natural gas is possible in some parts of the systems, issues remain in some other important areas. Therefore a 10%vol concentration cannot be applied blindly and a case by case approach is recommended as not only the gas transport and distribution infrastructures but also downstream infrastructures using natural gas as a fuel (gas turbines…) or in contact with natural gas should be considered. In particular, the presence of underground porous rock storages and the UN ECE R110 specification used for steel tanks in natural gas vehicles lead to the adoption of a cautious approach with concentrations limited to 2%vol. For these reasons, in Belgium, it is generally accepted that a 2%vol is currently the maximum concentration to be allowed in gas grids.

Fluxys has analysed the potential of direct injection of hydrogen in the natural gas grid in Belgium based on this $2\%_{vol}$ limitation (see Figure 9) and has identified one spot on its transportation gas grid close to Zeebrugge for a potential 100 MW Power-to-Gas project, several spots with a potential of 10 MW and a dozen spots with a potential of 1 MW. The Power-to-Gas potential would obviously increase accordingly if higher concentration of hydrogen would be allowed in gas grids.

Figure 9: Potential of direct hydrogen injection in the Belgian transport gas infrastructure [6]



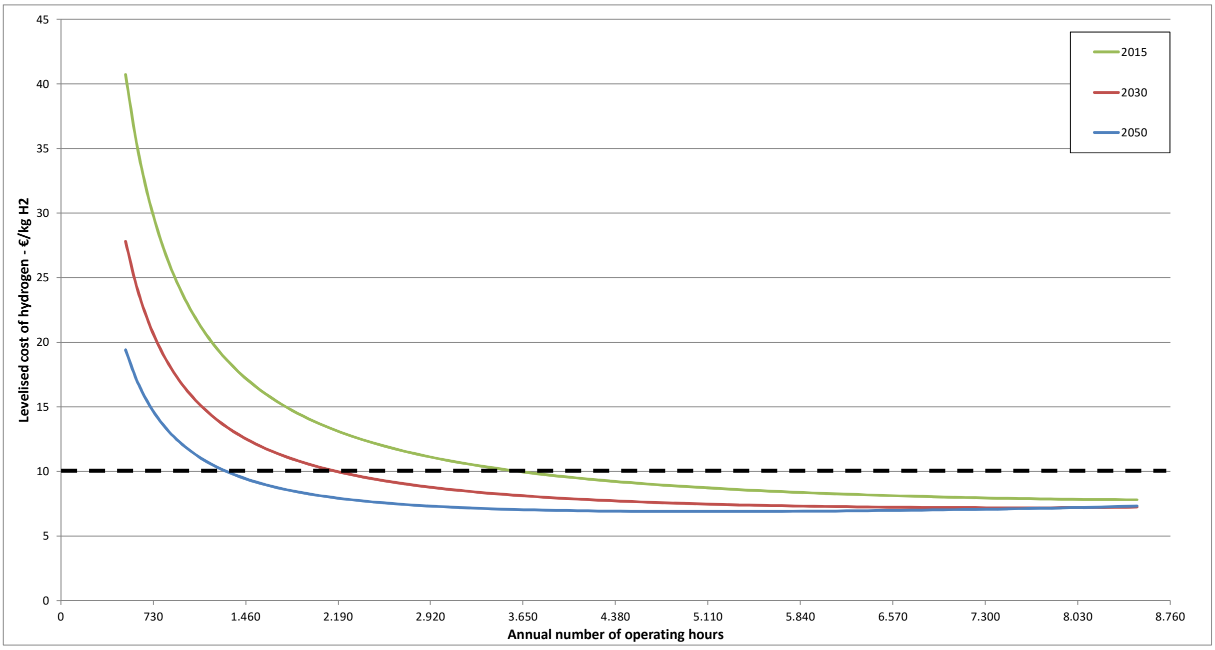
[5] (Altfeld & Pinchbeck)

[6] source: Fluxys Belgium, indicative information based on a $2\%_{vol}$ limitation

4.3. Power-to-Mobility and Power-to-Fuel

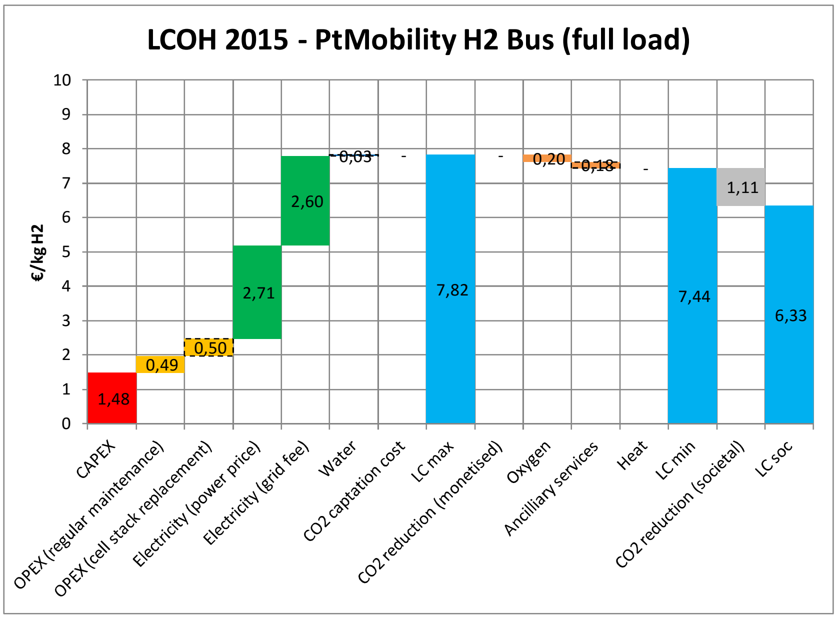
For the Power-to-Mobility cases, we have considered the case a Hydrogen Refuelling Station sized for a fleet of 25 buses refuelling daily (2.2 MW electrolyser, 900 kg/day, 450 bar). Considering the same methodology for the business case, it is expected that the LCmax for the HRS can fall below the 10€/kg landmark if the utilization of the HRS (and electrolyser) is generally above 25% (see Figure 10). If the utilization is lower, then LCmax is increasing drastically to high numbers.

Figure 10: Levelized cost of hydrogen (LCmax) vs. operating time (HRS for buses)



Analysing the waterfall graph, we notice the overall high impact of the electricity grid fees on the LCmax, representing 2.60 €/kg in this specific example. If these fees could be removed, the LCmax would be in the range of 5.2 €/kg.

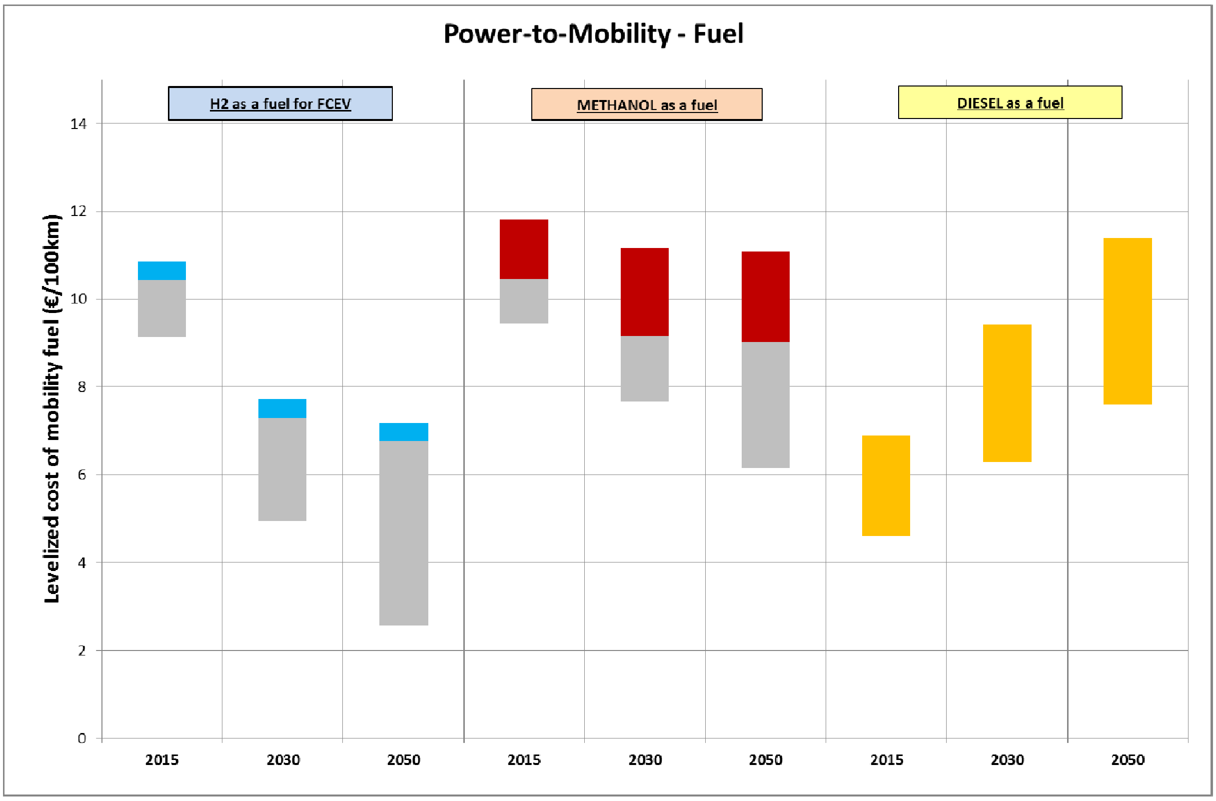
Figure 11: Waterfall graph 2015 HRS for buses (full load operation)



A similar case has been realized for a small HRS for cars, giving results in the same range.

Taking into account a general improvement of the hydrogen consumption of FCEV over time and the cost decrease of hydrogen production in HRS, we expect that the direct use of hydrogen in FCEV will become more competitive than diesel on the medium term (2030) already on a fuel cost basis for a 100 km distance (see Figure 12).

Figure 12: Fuel cost comparison for 100km between FCEV, methanol and diesel cars until 2050



For the Power-to-Fuel application, even if several alternatives are available, only the partial substitution of diesel with bio-methanol produced from the combination of electrolytic hydrogen and carbon dioxide in a methanolisation process has been considered. In this case, a large scale Power-to-Methanol project has been considered. The methanol would be blended with diesel. We expect methanol to become competitive with diesel around 2030 already.

4.4. Power-to-Power

For the Power-to-Power applications, a small-scale and a large scale hydrogen energy storage system have been considered comprising an electrolyser, hydrogen storage and a fuel cell to re-electrify the hydrogen to power. For all time horizons, we expect this application to be more expensive than the alternatives (mainly batteries). Nevertheless, we expect some very specific applications which require long term energy storage and high reliability in remote areas would demonstrate business cases close to profitability. These have not been calculated here as these are not really expected to be found in Belgium. However, it is still important to develop the technology for this specific application for export possibilities.

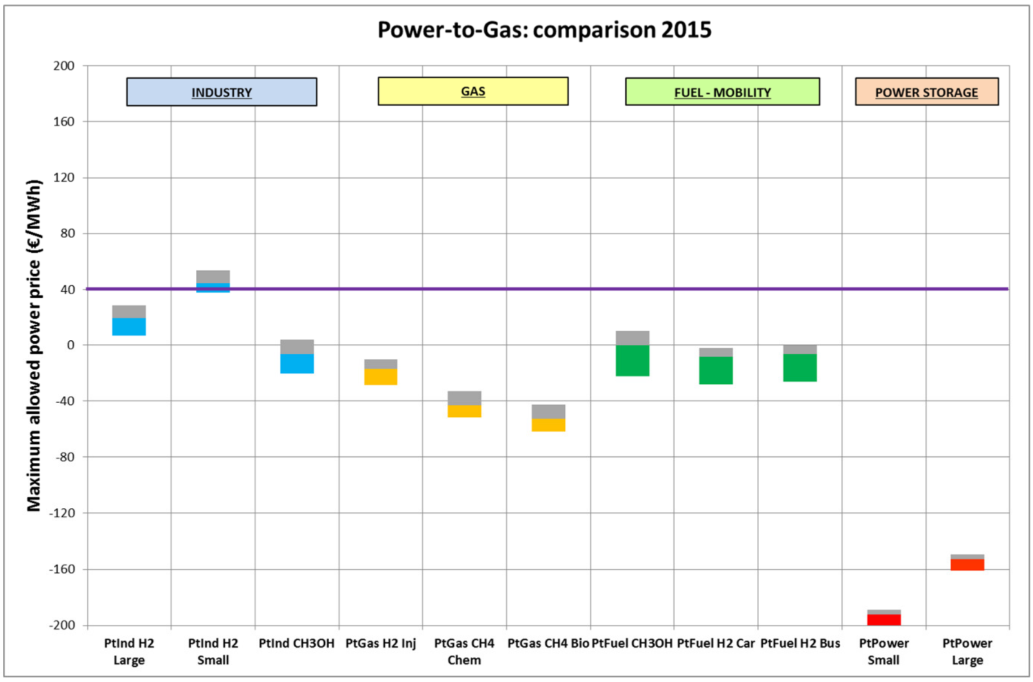
4.5. General comment and comparison

All of the calculated results for 2030 and 2050 depend on the correctness of the assumptions used in the calculations, and therefore have to be interpreted as indicative figures. As power price, operating time and initial investment have been identified as the main cost drivers in most cases, the calculated results will only be valid if these conditions are met in 2030 and 2050. The evolution of power prices is the most sensitive parameter, and it has been assumed that no dramatic changes would occur on the electricity market (electricity pricing, structure of grid costs, installed storage capacity, price duration curve). Of course, regulatory aspects and market development of hydrogen technologies will have significant impacts on the results. If fundamental changes in the structure of these markets, costs, technologies or regulatory framework will occur, updates of the business-cases will be required in order to calculate the actual economic feasibility of Power-to-Gas concepts

An interesting way to compare economic feasibility of the various valorisation pathways is to calculate the required commodity price for electricity to bring the levelized cost of the end product in line with the expected value of that same end product. As all of the described pathways use electricity as a starting point, this is a common point that can serve as a comparison. Required commodity price is calculated for continuous operation (97% availability), which means the maximum allowed market price for baseload electricity, excluding grid costs, taxes and levies.

Results are shown in the Figure 13. The bottom of the coloured bar represents the maximum allowed power price for the base case, thus excluding revenues from oxygen production, heat recovery, providing ancillary services, and CO_2 emission allowances. The top of the coloured bar represents the maximum allowed power price if revenues from oxygen production, heat recovery, providing ancillary services, and CO_2 emission allowances were included. The top of the grey bar represents the maximum allowed power price if all societal costs of CO_2 emission could be monetised when avoiding the emission. Finally, the purple line represents actual baseload power price (excluding grid costs, taxes and levies).

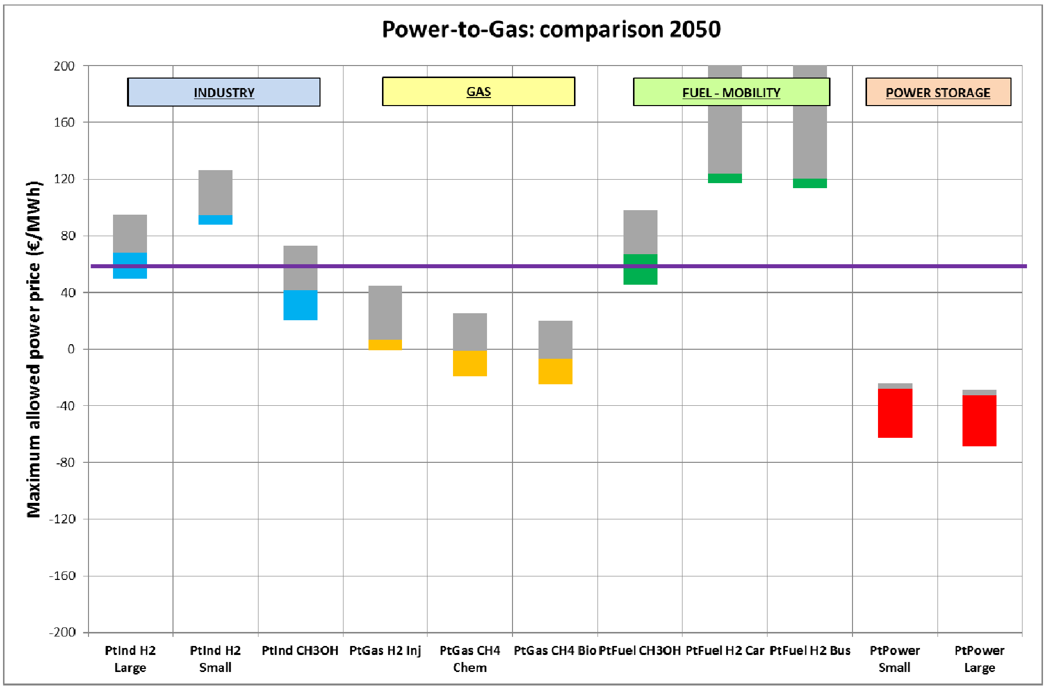
Figure 13: Comparison of Power-to-Gas business cases - Maximum allowed power price for profitable case in 2015, compared to estimated average power price in 2015



For 2015, only the small scale industry valorisation pathway shows a maximum allowed power price close to the actual baseload power price (excluding grid costs, taxes and levies). In some cases, where additional benefits from oxygen production and ancillary services supply and the avoided societal cost of CO_2 emissions can (partially or fully) be taken into account, the maximum allowed power price might even exceed the actual baseload power price. So, already from 2015, the small scale industry valorisation pathway can reach break-even, at least when some additional revenues can be taken into account. Other Power-to-Industry pathways and some Power-to-Mobility pathways have a maximum allowed baseload power price above zero, where certainly the power storage (Power-to-Power pathways) but also the hydrogen or methane injection in the gas grid (Power-to-Gas pathways) require negative power price all over the year to turn profitable.

As shown in Figure 14, in 2050, the expected baseload power price is below the maximum allowed power price for the small scale industry pathway and both mobility pathways for cars (hydrogen and methanol as a fuel for cars), and in most cases also for the large scale industry pathway (if some additional benefits can be realised). The industrial methanol pathway and the mobility pathway for buses require that avoided societal costs for CO_2 emissions are monetised, whereas all Power-to-Gas pathways and certainly the power storage pathways require baseload power prices that are far below the expected price (for methanation and power storage even below 0 €/MWh).

Figure 14: Comparison of Power-to-Gas business cases - Maximum allowed power price for profitable case in 2050, compared to estimated average power price in 2050



4.6. Main conclusions from the economical feasibility study

The following global conclusions can be drawn for the different valorisation pathways in Power-to-Gas concepts:

<u>Power-to-Mobility:</u>

Mobility represents the most promising economic application for the use of renewable hydrogen and there is a political momentum in Europe/Flanders on this topic. The deployment of Hydrogen Refuelling Stations (HRS) is starting up in larger quantities now (especially in Japan and California), but is challenging from an economic point of view for the moment. Therefore grants and other incentives are necessary. Beside this, it is key to link the development of HRS to the development of FCEV vehicles (for all vehicle segments) to generate enough hydrogen demand and reasonable prices.

<u>Power-to-Industry:</u>

For small scale applications using hydrogen delivered on site by tube trailers, green hydrogen locally produced from electrolysis is already competitive under specific circumstances in 2015. For large scale applications, opportunities to generate cheaper hydrogen from electrolysis compared to Steam Methane Reforming (SMR) will emerge after 2030, taking advantage of the lowest electricity prices.

<u>Power-to-Fuel</u>

Power-to-Methanol, as a partial substitute in diesel could represent an interesting alterative already in 2030 and should be further explored.

<u>Power-to-Power</u>

Hydrogen energy storage is expected to be less attractive than other Electrical Energy Storage (EES) technologies such as batteries for a few hours or days due to a relatively higher cost and lower round-trip efficiency. However, when electrical energy storage is needed for longer periods (weeks, months) of larger energy quantities, hydrogen represents a very attractive solution. In all cases, electrolysis offers the possibility to balance the power grid with more renewables, which could be further remunerated in the future grid balancing market.

Power-to-Gas:

The technical potential for Power-to-Gas (direct injection of hydrogen or injection of synthetic methane) in Belgium is significant. On the short term, direct injection of hydrogen in natural gas grids (up to 2% in volume) seems the most promising option, with competitiveness close to biomethane already in 2015, completely in 2030 and onwards. Methanation routes combining hydrogen from electrolysis and CO_2 show much higher cost structures but have the advantage to better exploit the actual natural gas grids without limitation on the maximum allowed concentration. Transport of either hydrogen or synthetic methane over the natural gas grid could also be studied as an alternative to electricity transport over high voltage lines.

5. SOCIETAL IMPACT

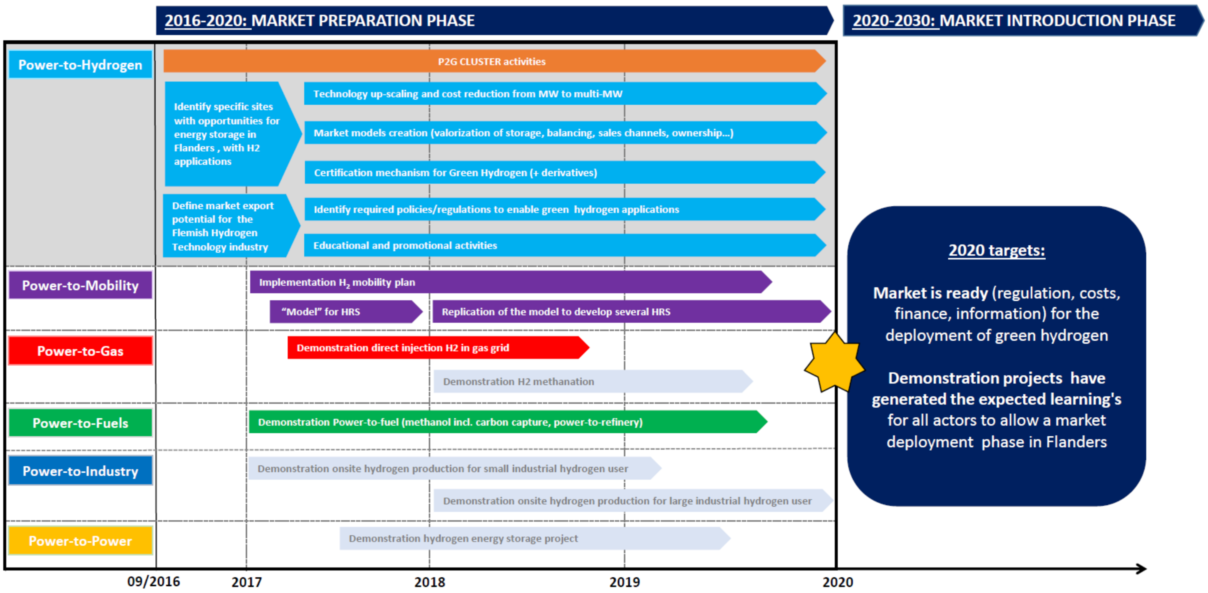
No detailed quantitative societal impact study could be performed within the Power-to-Gas roadmap study for Flanders. Nevertheless, societal benefits of deploying Power-to-Gas/hydrogen in Flanders are numerous and comprise among others:

- Improved energy security of supply in Belgium by maximizing the use of renewable power across the various energy sectors (power, gas, mobility, fuel and industry)
- Improved air quality : no CO_2 or NO_X emissions for FCEV
- Climate change mitigation: Reduction of GHG emissions
- Additional grid flexibility sources : electrolysers providing grid balancing services
- Technology leadership of companies active on Power-to-Gas/hydrogen in Flanders
- Job creation and increased economic activity in Flanders

6. IMPLEMENTATION PLAN: THE ROADMAP UNTIL 2030

Figure 15 shows the general timeline with different actions on the different valorisation pathways of hydrogen in Flanders.

Figure 15: Power-to-Gas Roadmap for Flanders until 2030



The most important short term action resulting from the roadmap is the creation of a **Power-to-Gas Cluster** that will become the vehicle for the implementation of the roadmap. This action is already on good tracks seeing *Agentschap Innoveren en Ondernemen (VLAIO)* has confirmed on 20 July 2016 the Power-to-Gas cluster as one of the regional clusters.

Considering **Power-to-Mobility** has been identified as one of the most attractive applications for Power-to-Gas/hydrogen, on the medium and long term, we suggest the creation of an appropriate regulatory framework for vehicles and HRS (including a market support mechanism) as soon as possible. In parallel, the 20 HRS in Flanders by 2020 should be clearly determined; their business case should be carefully prepared in order to determine the appropriate level of support these HRS will require from authorities and potential early costumers for FCEV (cars, buses, trucks, material handling vehicles) should be identified. This market preparation phase (2015-2020) should result in the creation of a network of 20 HRS in Flanders with a fleet of about 1000 FCEV and 50 buses in Flanders operating on hydrogen. This should allow the starting of an early market introduction phase (2020-2025) of new FCEV generating an additional demand in existing HRS, improving their profitability and generating a demand for additional HRS. By 2025, the market in Flanders should be ready for a full market introduction phase (2025-...) with sufficiently dense HRS network, a wide FCEV offer from car/buses OEM's and a competitive total cost of ownership for FCEV in comparison with clean mobility alternatives.

For **Power-to-Gas**, we suggest to focus the actions of the cluster on the realisation of a Power-to-Gas (direct injection) demonstration project. This project should be initiated in 2017 with a consortium comprising the most relevant companies and be in operation in 2019. This consortium should lead the efforts to create the necessary regularly framework applicable for such a project, in particular the possibility to inject at least $2\%_{vol}$ of hydrogen in gas grids and the possibility to benefit for feed-in tariffs similar to the ones applicable for biomethane in neighbouring countries. Considering methanation is a medium to long-term solution, a demonstration project including the production of synthetic methane could be initiated afterwards. In parallel, a clear political and strategic vision (including targets) on decarbonisation and specifically on the injection and transport of green gases (biomethane, synthetic methane and hydrogen) in existing gas grids should be defined in collaboration with the competent authorities, industry partners and the government.

For **Power-to-Industry**, we suggest to initiate the realisation of a demonstration project with a consortium of companies in Flanders. This project should serve as a reference to validate the economical aspects of such project and should help to identify the regulatory framework improvements required to decarbonise the hydrogen production/consumption in Flanders on the medium to long term.

For the **Power-to-Fuel** applications, we suggest to focus our actions on the possibility to use green hydrogen from electrolysis in refineries in partial replacement of fossil based hydrogen. The actions should comprise the constitution of a consortium around a specific project in the Port of Antwerp and should look in particular at getting the appropriate regulation in place in Belgium (mainly transposition of the European legislation such as the FQD and the REDI). In parallel, a power-to-methanol project should be envisaged.

Between 2025 and 2030, all these actions should lead to the creation of general regulatory framework in our energy system allowing Power-to-Gas/hydrogen to play a significant role by bridging the power sector including more and more renewables with the mobility, gas and industrial sectors. By 2030, Flanders should be ready to deploy a hydrogen society model in which hydrogen is becoming an energy vector as important as electricity.

7. REINFORCEMENT OF THE INDUSTRY IN A POWER-TO-GAS CLUSTER

To accompany all these actions, there is a need for a vehicle for the implementation of the roadmap and the organization of the follow-up activities that have been identified.

Therefore, a Power-to-Gas cluster has been formed in 2016 with a group of 20 companies active at various levels in the value chain: from energy production (wind, solar) over hydrogen technology (electrolysis, compressors), transport and distribution, to end users (transport, chemistry).

Figure 16: Representation of the Power-to-Gas value chain

Given the high diversity of the companies in the cluster, the added value of the cluster as an organisation that facilitates joint knowledge building is very high. Most of the partners have their expertise in only a small part of the chain, such cooperation with other companies is absolutely necessary to obtain a stronger position in the Power-to-Gas market worldwide.

Table 2: Power-to-Gas cluster members

RES producers	Electrolysis	Hydrogen compression, storage and transport	Grid operators	System integrators	Hydrogen users
Aspiravi Polders Inv.Fonds NPG Energy/Enevos Terranova Solar Colruyt/Eoly	Hydrogenics Umicore	Atlas Copco Air Liquide	Eandis Fluxys Belgium	Deme Van Wingen Port Antwerp	Hyundai Belux Toyota Motor Europe VDL PitPoint E-Trucks Colruyt Group Shipit

Additional players in Flanders and potential future new cluster members have been identified and will further be approached.

This study will serve as the building stone of the cluster and it is expected that the roadmap will be regularly updated according to the latest situation.

8. FINAL COMMENTS

It seems quite clear from the present study that hydrogen has a strong potential to decarbonize the energy market in Belgium, especially in the mobility, gas, fuel and industrial sectors. However, the pre-condition is a massive development of renewable power in Flanders which will create more opportunities to generate green hydrogen. The evolution of power prices is very uncertain, but will be determinant for the future of hydrogen.

To ensure an accelerated adoption of hydrogen technologies in the energy market, demonstration projects will play a key role in showing the technical benefits of the various solutions, in getting the appropriate regulation in place and in raising the general among all stakeholders groups (energy sector, political sector, general public).

Flanders has strong industrial actors active in the field of hydrogen and renewables forming potentially a strong value chain, representing export possibilities and additional new jobs in Flanders. Good cooperation between these companies will be key to establish collaboration with federal and regional authorities and realizing successful demonstration projects. To achieve this, the creation of a Power-to-Gas cluster in Flanders is essential as a vehicle to implement this Power-to-Gas roadmap and update it when periodically.

The challenges ahead of hydrogen and Power-to-Gas are important but the potential for the decarbonisation of our energy system are immense. First actions need to start now, if we want to be ready in time for the real market deployment of hydrogen technologies and Power-to-Gas projects, and benefit from this global opportunity.

Political leadership and financial support will be needed in the coming years to establish hydrogen and Power-to-Gas sustainably in the future energy system.

The full report is available on: www.power-to-gas.be