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What is the optimal sequence of hydrogen development for heavy duty vehicle in Belgium?

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Table of contents

I. Glossary

BEV	Battery electric vehicle
COP	Conference of the parties
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CSP	Concentrating solar power
DAC	Direct air capture
EU	European Union
EU ETS	European Union Emissions Trading System
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gases
HDV	Heavy duty vehicles
ICEV	Internal combustion engine vehicle
LCV	Light commercial vehicle
LCOE	Levelized cost of electricity
LDV	Low duty vehicles
LNG	Liquefied natural gas
MSR	Market stability reserve
MWH	Megawatt hour
NREL	National Renewable Energy Laboratory
PNAS	Proceedings of the National Academy of Science
SMR	Steam methane reforming
TCO	Total cost of ownership
TSO	Transmission system operator
UN	United Nations

1. Introduction

In recent decades, the topic of global warming and the environment has emerged as a critical global issue. There is now widespread recognition that human actions play a significant role in these challenges, leading to adverse effects on biodiversity and the acceleration of global warming. Extensive research, such as a study conducted by PNAS involving more than 1300 climatologists, reveals a strong consensus among 97-98% of them, affirming that human activities are the primary drivers of global warming (Anderegg, Prall, Harold, Schneider, 2010).

Every year, 195 countries that have ratified the UN climate convention gather for a two-week conference, known as COP, to negotiate and make decisions towards addressing climate change. The last COP was held in November 2022 in Egypt. The agreements reached during these conferences include the Kyoto Protocol and the Paris Agreement (UNFCCC, 2023).

During the Paris Agreement, a commitment was made to continue efforts in order to limit global warming to 1.5°C above pre-industrial levels. The European Union initially set a target to reduce GHG emissions of 40% by 2030, compared to 1990 levels. However, in 2020, the EU revised its goal and now aims to achieve a 55% reduction in emissions by 2030 (United Nations, 2023).

The EU objective is to decrease GHG emissions across all economic sectors by 55% in 2030 and by 90% in 2050 compared to 1990 levels. To understand the contribution of each sector to these emissions, we can examine the share of responsibility of each sector in GHG emissions. It is found that the transport sector is responsible for the majority of these emissions with a percentage of emission of 25,8% (Olivier, 2022).

When looking specifically at CO2, which makes up 75% of GHG, it is observed that transportation is responsible for 30% of emissions.

Since 1990, only the transportation industry has had a significant increase in emissions. It is also worth noting that over 70% of CO2 emissions from transportation are generated by ground transportation (European Parliament, 2019).

To achieve the goals outlined in the Paris Agreement, the automotive sector faces two options for reducing its CO2 emissions. The first option involves optimizing engines to minimize fuel consumption, while the second option involves transitioning to alternative fuels. Currently, both approaches are being used. Automakers continuously refine traditional gasoline and diesel engines to enhance their environmental performance.

Simultaneously, the industry is increasingly embracing new, eco-friendly fuel types. At present, electricity appears to be the new energy for transportation. However, there are also barriers and limits to electricity and other alternative fuels are of interest for researchers. Hydrogen seems to be a potential solution to overcome some of the barriers of electric vehicles.

1.1 Goal, scope and expected contribution

The aim of the research is to determine what is the optimal sequence of hydrogen development in the future to substitute the conventional fuel, diesel, for long-haul heavy-duty trucks in the European and Belgian context. Therefore, different stakeholders active in the development of hydrogen network or heavy-duty vehicles (HDV) have been interviewed in order to have the best and up-to-date data on hydrogen development, especially for HDV. The study focuses as well on the production and procurement of hydrogen as on the development of the vehicle and network to be able to use hydrogen as a fuel in the future.

This research is also providing a comparative cost study of the battery electric trucks, hydrogen fuel cell electric trucks, LNG trucks and conventional diesel trucks in the Belgian context. It also includes a large panel of production and importation pathways for hydrogen, allowing to understand where it should be sourced from. Consequently, the findings can support companies, willing to switch to low-carbon fuels, to understand the impact of each solution.

1.2 Limitations

This work has several limitations. Firstly, due to the rapid acceleration of global warming and the climate change agreements, the evolution of this sector is highly dynamic, making it challenging to accurately predict future developments. The environmental landscape is highly sensitive and even minor changes can have significant impacts.

Furthermore, the sample size of individuals interviewed for this study is limited. A broader range of perspectives from multiple stakeholders would have provided a more comprehensive understanding. However, contacting relevant individuals proved to be difficult, resulting in a constrained sampling of participants.

Another limitation is that the numbers used in this analysis may not be universally precise in every situation. While averages are employed to provide a general overview of costs, prices, and quantities, they can vary based on location, specific circumstances, technologies, and other factors.

2. Literature review

In this section, we will start with a literature review. The transport sector as well as the different links between hydrogen and transportation will be studied.

2.1 Transportation sector in Belgium and its carbon footprint

Transportation is the only sector where GHG emissions have increased over the past three decades, rising of 33.5% between 1990 and 2019. Significantly reducing CO2 emissions from transport will not be easy, as the pace of emissions reduction has slowed. According to current projections, the reduction in emissions from the transport sector by 2050 would be only 22%, which is far from current ambitions (European Parliament, 2019). Road transport represents a total of 71,7% of the total emissions from transportation. Moreover, 37,1% of emissions are caused by trucks.

In Belgium, the evolution of freight transportation is analyzed through the number of ton-kilometers traveled on Belgian territory. This number increases between 2000 and 2030 with a projected growth higher than the historical observation. In 2021, 278 million tons of goods were transported by road with vehicles registered in Belgium (trucks and road tractors with a payload of at least one ton). This represents an increase of 1.4% compared to 2020 in terms of the number of tons transported, and 4.9% in terms of ton-kilometers performed (Statbel, 2022).

Freight transportation includes domestic transport, entries and exits from Belgian territory, as well as transit without transshipment. The increase in the number of ton-kilometers is linked to the changes in the total number of tons transported and the average distance traveled per ton of goods (Daubresse & Laine, 2017).

Historically, domestic freight transport has been dominant and will remain so by 2030, despite a growth rate lower than the ones of entries and exits. Two factors can explain this difference in growth. On one hand, the growth in tonnage transported to and from Belgium is stronger than the one of domestic transport between 2012 and 2030. These changes are directly related to the economic model change that occurred and continued during this period. Goods exchanges have experienced remarkable growth due to the increasing fragmentation of production and distribution chains, and the operation of the economy in just-in-time flows has favored road transport (Strale, 2011). On the other hand, the average distance per ton transported increases more significantly for entries and exits from Belgian territory than for domestic transport during the projection period (Daubresse & Laine, 2017).

Regarding the modal split of ton-kilometers traveled in Belgium, road transport is historically the dominant mode of transportation and remains so in the projection because it can meet the requirements of speed, cost and flexibility and provide an efficient solution for the transportation of smaller volumes. However, its share decreases slightly in favor of inland navigation and, to a lesser extent, rail transport (Strale, 2011).

2.2 Hydrogen types

Accounting for about 75% of the mass of all normal matter, hydrogen is the most abundant element in the universe. A minor amount is bound in other compounds, mainly hydrocarbons (Stolten & Emonts, 2016). Depending on the production process used, hydrogen is classified into three categories: "grey"; "blue"; "green". Clean hydrogen includes the types "green" and "blue" (Pflugmann and Blasio, 2020).

2.2.1 Grey Hydrogen

Grey hydrogen refers to hydrogen produced from fossil fuels and therefore emits greenhouse gases. Grey hydrogen is produced by reforming natural gas, a processing technique used to rearrange the molecular structure of hydrocarbons. In this process, methane, the primary element in natural gas is mixed with steam at a high temperature to yield hydrogen and carbon dioxide through a catalytic chemical reaction. However, due to its low production cost and the maturity of the technologies producing this type, about 96% of the hydrogen produced worldwide is currently "grey" (Shea Choksey, 2021).

2.2.2 Blue Hydrogen

The processes used to produce "grey" hydrogen primarily emit carbon dioxide. Therefore, it is possible to combine these production capacities with a carbon capture and storage unit (CCS) to make hydrogen production almost carbon neutral. Hydrogen produced from the combination of these two technologies is called "blue" hydrogen. Until recently, very few was produced because the cost of CCS units was not profitable. But since the quota price of carbon has increased within the EU ETS, blue hydrogen has become competitive compared to "grey" hydrogen (Cloete et al., 2022).

2.2.3 Green Hydrogen

Hydrogen can also be produced directly from electricity by performing water electrolysis. This chemical reaction forms hydrogen and oxygen without direct emissions of greenhouse gases. The necessary electricity can be supplied by any energy source. However, to produce carbon-neutral hydrogen and therefore "green" by name, this electricity must come from renewable energy sources. However, as in most countries the current electricity mix is not purely renewable, "green" hydrogen must be produced in a decentralized manner, that is, with electricity not from the electricity grid, but from a wind and/or solar photovoltaic installation directly coupled to an electrolyzer. The latter is the equipment that performs water electrolysis (Shea Choksey, 2021).

Green hydrogen has two advantages over other types. Firstly, unlike fossil fuels, all countries have access to renewable energy sources and to water (Pflugmann and Blasio, 2020). This allows each country, even if some have better resources than others, to become a producer of green hydrogen if the necessary infrastructure is put in place. These countries would become less dependent on energy imports. This advantage is even multiplied in Europe, given the gas energy crisis with Russia. Recently, the European Commission has launched a series of energy directives to reduce dependence on Russian fossil fuels in the short and long term (European Commission, 2022).

2.3 Hydrogen technology in transportation

Hydrogen provides a clean alternative to gasoline or other petroleum derivatives, especially when it is produced from renewable energy sources such as wind and solar (Stolten & Emonts, 2016). Considering the current context, where the European Union prioritizes the reduction of GHG emissions, it follows logically that if the production of hydrogen continues to generate significant GHG emissions, hydrogen cannot be employed as a viable "fuel" for transportation purposes. Different technologies already exist and have been developed in order to use hydrogen as a fuel for the transport sector.

2.3.1 Hydrogen motor

Having played a prominent role as a fuel for rockets in space agencies over the years, hydrogen is gradually making its way to civilian applications due to its beneficial properties in reducing vehicle emissions (Lanz, 2001). Similar to the transition from natural gas, our reliance on internal combustion engines persists as the means to convert energy into motion.

Here we have our classic 4-stroke engine. Notably, hydrogen can be used in both compression and ignition engines (Prasath et al., 2012). This implies that existing engines can be readily modified for compatibility with hydrogen as a fuel source. Of course, it has been modified and strengthened to be able to burn hydrogen or more precisely dihydrogen. The intense heat generated by the relatively clean combustion of hydrogen requires the reinforcement of valves, segments and other elements that are not lubricated by the residues of the past. For the same reason, the pistons must be equipped with internal cooling channels watered by jets of cold oil coming from nozzles located at the bottom of the sleeves, as for turbocharged sports engines. On the other hand, in hydrogen mode, the computer recalculates the fuel flow to ensure a stoichiometric mixture for proper engine operation (Stolten & Emonts, 2016).

2.3.2 Fuel cell technology

Hydrogen serves as a versatile energy source, capable of directly powering an internal combustion engine as we have seen, or generating electricity to drive an electric motor, which is made possible through the use of a fuel cell. The fuel cell operates by means of an electrochemical reaction involving oxygen from the surrounding air and hydrogen (Stolten & Emonts, 2016). This process looks like the one of a battery, but without the need for recharging or concerns of depletion, as long as a fuel supply is available, electricity and heat will be continuously produced. The fuel cell consists of two electrodes, an anode and a cathode, encapsulating a conductive chemical substance. Hydrogen, in our case, is supplied to the anode while oxygen is directed to the cathode. At the anode, the hydrogen molecules undergo a reaction that separates them into protons and electrons. The electrons are then channeled through a designated circuit, creating an electric current. Ultimately, the byproducts of this reaction are water and heat (Curtin & Gangi, 2016).

The hydrogen production required for this reaction follows similar methods used for hydrogen destined for combustion engines. When paired with sustainably produced hydrogen, the fuel cell presents an environmentally friendly transportation solution, as it only emits water. It holds promise for cleaner driving. Furthermore, when used in conjunction with sustainably produced hydrogen, the fuel cell offers comparable filling times and range to petrol-powered cars, ensuring that drivers do not face prolonged waiting periods during their journeys.

2.3.3 Internal combustion engine vehicle combined with e-fuel

Internal combustion engine can be considered as an integral part of the climate problem. E-fuels promise to break this link by allowing combustion technologies and fossil infrastructures to become part of the climate solution. E-fuels, also known as electrofuels, powerfuels, or electricity-based synthetic fuels, are hydrocarbon fuels synthesized from hydrogen and CO2, using carbon capture and utilization (CCU). In this process, hydrogen is produced through electrolysis, using electricity and water, while CO2 is captured from fossil sources (such as industrial plants) or from the atmosphere through biomass or direct air capture (DAC) methods. E-fuels leverage the low-cost and abundant global potential of low-carbon wind and solar photovoltaic power. These resulting gaseous and liquid fuels possess characteristics that make them excellent substitutes for traditional fossil fuels, including high energy density, storability, transportability, and combustibility. By incorporating carbon in a second step, the challenges associated with handling hydrogen can also be overcome (Ueckerdt et al., 2021).

2.4 Hydrogen network

Hydrogen delivery infrastructures are necessary only when hydrogen is produced at a central or semi-central locations away from locations where FCEVs are fueled. The delivery of hydrogen from the production plant to the vehicle tank includes packaging, transport and fueling operations. The packaging operation includes the compression of hydrogen into pipelines or tube trailers and the liquefaction of hydrogen for tank deliveries. Currently, hydrogen is delivered in two physical forms: gaseous or liquid (Stolten & Emonts, 2016).

The conditioning and transportation of hydrogen pose some obstacles to its widespread adoption in the automotive industry. In fact, these two aspects act as brakes that hinder the progress of hydrogen diffusion (McDowall & Eames, 2006).

As previously stated, hydrogen is the smallest element on the periodic table, making it the lightest gas in universe. To contain 1 kg of hydrogen at atmospheric pressure (the quantity required to travel 100 km) a volume of 11 m^3 would be needed. To achieve cost-effective transportation and storage of hydrogen, it becomes imperative to explore methods for minimizing its spatial requirements (Beeker, 2014; Cirid, 2020).

Currently, two primary approaches are used for hydrogen storage. The initial and more prevalent method involves storing it in a gaseous state under pressure at a consistent temperature. This entails compressing hydrogen to pressures ranging from 200 to 900 bars, depending on specific requirements. In its gaseous state, hydrogen can be conveyed through a network of pipelines rapidly.

The alternative approach involves converting hydrogen into a liquid state. In its liquid form, hydrogen attains its highest density (71 kg/m^3), which is twice as dense as compressed gaseous hydrogen at 700 bars (39 kg/m^3). However, this process requires the use of advanced cryogenic equipment. Additionally, alternative techniques like solid storage are under investigation, showing promising prospects (Eliasson et al., 2003; Malbrunot, 2019).

Another solution for hydrogen transportation, either liquid or gaseous, involves land-based methods. In this case, hydrogen is compressed and stored in tanks or cylinders before being transported to the intended destination. The compression process typically involves pressures ranging from 200 to 500 bar (Dhers, 2005). However, there are two significant challenges associated with this method.

The first issue pertains to the ratio between the mass of hydrogen carried by a truck and the amount of transported energy. Comparatively, a 40-tons truck transporting hydrogen will carry significantly less energy content when compared to methane (10 times less) or conventional fuels like petrol or diesel (80 times less). The second challenge relates to the compression of hydrogen gas. When hydrogen is compressed to pressures between 200 and 800 bars, there is a notable loss of available energy, estimated to be around 10 to 20% (Beeker, 2014; Boucher, 2016; Eliasson et al., 2003; Malbrunot, 2019).

A third way to transport hydrogen is by ship and has recently been introduced by Japan. This innovative system involves the liquefaction of hydrogen by subjecting it to extremely low temperatures of approximately -250°C, after which it is stored in appropriate tanks. While it is still premature to make definitive assessments regarding this mode of transportation, this approach holds promise as it enables the conveyance of larger quantities of hydrogen over extended distances (Stolten & Emonts, 2016).

To address these challenges in transportation, a potential solution is the decentralized production of hydrogen through the installation of small-scale electrolyzers adjacent to filling stations. This approach would enable the generation of hydrogen in a distributed manner, mitigating the need for extensive transport infrastructure (Beeker, 2014; Malbrunot, 2019).

2.5 Hydrogen infrastructures

It is important to note that the expense associated with a hydrogen filling station is exceptionally high (Koleva & Melaina, 2021). This substantial cost encompasses the installation of hydrogen storage tanks, dispensers, compressors, and other essential equipment for the secure and efficient distribution of hydrogen fuel. As a result, this cost introduces uncertainty and prompts a cautious approach towards potential widespread implementation (Beeker, 2014). On the other hand, the installation of a petrol or LPG station is much less costly and necessitates less space than a hydrogen station because it does not need as much equipment.

Moreover, hydrogen vehicles and refueling infrastructure are interconnected as complementary goods. Complementary goods refer to items that function as a system and need to be used together. This concept effectively illustrates the interdependence between hydrogen-powered vehicles and hydrogen refueling stations. In the absence of hydrogen or refueling stations, a hydrogen car cannot operate, similarly, a hydrogen station serves no purpose without consumer demand (Meyer & Winebrake, 2009).

Within this framework, individuals would refrain from purchasing a hydrogen car if they lack access to the requisite charging infrastructure. The issue lies in the fact that companies equipped to establish such infrastructures are moving to the opposite direction. The installation of hydrogen filling stations incurs significant expenses, and without a substantial demand for hydrogen, companies lack the incentive to deploy these stations on a large scale. Furthermore, the operational and maintenance costs of hydrogen filling stations remain exorbitant due to the limited industry expertise in this domain (Xu et al., 2020).

2.6 Hydrogen incentives

Governments and public entities in general have two main motivations for promoting hydrogen within their legislative frameworks. Firstly, there is a focus on reducing CO2 emissions and addressing environmental issues. This aspect can be seen as the "stick" approach, which involves measures such as limiting vehicle emissions and imposing quotas for zero-emission vehicle production (Trencher & Edianto, 2021). Secondly, there is an emphasis on promoting hydrogen as a preferred solution for environmental challenges, which can be seen as the "carrot" approach. This involves providing direct incentives to stimulate the development of the hydrogen vehicle market, including funding for research and development, information sharing networks, subsidies for refueling station setup, and consumer purchase initiatives (both monetary and non-monetary) (Trencher & Edianto, 2021).

The implementation of these initiatives depends largely on the extent to which governments adopt measures to promote hydrogen. Different approaches have been observed in the European Union, Belgium, France, and Germany, etc. Despite variations in their implementation, it is evident that governments are showing a clear inclination towards promoting hydrogen, with the EU taking the lead through an ambitious roadmap for 2050.

2.7 Synthesis

The analysis of freight transportation in Belgium shows an increase in the number of ton-kilometers traveled between 2000 and 2030, surpassing historical observations. This growth is attributed to changes in the total tonnage transported and the average distance traveled per ton of goods. Road transport has historically been dominant and will continue to be so. Moreover, transportation is the only sector where GHG emissions have increased over the past three decades, rising of 33.5% between 1990 and 2019. Hydrogen seems like a potential solution to decarbonize the transportation sector.

Hydrogen, the most abundant element in the universe, can be categorized into three types: grey, blue, and green. Grey hydrogen is produced from fossil fuels and emits GHGs. Blue hydrogen is produced using CCS technology, making it nearly carbon neutral. Green hydrogen is produced through water electrolysis using renewable energy sources, making it environmentally friendly.

Hydrogen can be used in transportation through two main technologies: hydrogen motors and fuel cells. Hydrogen motors can be used in existing internal combustion engines with modifications, while fuel cells generate electricity by combining hydrogen with oxygen. Fuel cells offer high efficiency and only emit water when powered by sustainably produced hydrogen. ICEV combined with e-fuels could also be a solution to substitute to traditional fossil fuels in the future.

Hydrogen transportation presents challenges due to its low density and the need for compression or liquefaction. Currently, gaseous and liquid forms are used for transportation. On the other hand, hydrogen infrastructures, including refueling stations, are costly to install and maintain. The lack of infrastructure and limited industry expertise hinders the widespread adoption of hydrogen vehicles. Governments provide incentives, both regulatory and financial, to promote hydrogen adoption, aiming to reduce CO2 emissions and support the development of the hydrogen vehicle market.

3. Method and sampling composition

For this analysis, we have interviewed several actors on specific questions in order to understand what is the optimal sequence of hydrogen development for heavy duty vehicles in Belgium.

The first person we interviewed is Mr Augustijn Van-Haasteren, who works at the European Commission's DG Energy. The European Commission plays a vital role in the advancement of hydrogen technology as they provide incentives and subsidies for various projects. Indirectly, they are at the forefront of hydrogen development in Europe because it is their role to fix climate objective and to put legislation on it.

The second person we interviewed is Mr Batiste Costa-Marini from Fluxys, which is the gas network manager in Belgium. They are responsible for all the underground gas pipelines in Belgium. They are also an important “actor” in hydrogen development because they are responsible for creating a network in order to provide hydrogen where it is needed in Belgium.

The third person is Mr Daniel Marenne working for Engie, which is a major actor in electric production in Belgium. He is responsible for the hydrogen development part. He is developing different projects in hydrogen, and he often makes different business models on the use of hydrogen for the transport sector.

The fourth interviewed person is Mr Pierre Joris from Jost Group. Jost Group is a reference partner in transport and logistics in Europe and they have an important number of HDV all over Europe. We could not have a physical interview, but he answered our questions by e-mail. It was important to have the vision from a big logistic company in order to have their point of view on the adoption of hydrogen vehicles for their companies in the future.

Finally, we tried to reach a truck manufacturing company. It would have been very interesting to have the vision from a company manufacturing hydrogen vehicle because it gives a very good insight of the complexities and incentives to manufacture such technological vehicles. Unfortunately, we could not reach anyone. However, Mr Paul Mandaiker, from Dhaimler truck, sent us some documentation on the development of hydrogen vehicles for their company.

4. Analysis

In order to clarify our research for this work, it is important to define the following categories:

- Light Duty Vehicle (LDV) are vehicles that are primarily used for personal transportation and have a relatively low weight and payload capacity. Examples of light duty vehicles include cars, vans, and pickups. This category can be subdivided in 2 other categories: the passenger cars and the light commercial vehicles.

- High Duty Vehicle (HDV) are vehicles that are primarily used for commercial or industrial purposes and have a much higher weight and payload capacity than light duty vehicles. Examples of heavy duty vehicles include trucks, buses and tractors (European Commission, 2014). They have a higher fuel consumption and emit more pollutants and greenhouse gases than light duty vehicles. The use of heavy duty vehicles can indeed be a major source of air pollution (Díaz, 2021).

Our analysis will be focused on the HDV category, and mainly on trucks because they constitute the majority of the HDV category. The study will concentrate on the Belgian market, but some European elements will be used to have a broader view of the subject.

4.1 Advantages of hydrogen in decarbonizing the HDV road transport sector

One proposed solution for decarbonizing the HDV road transport sector involves the electrification of vehicles, through the conversion of the fleet to battery electric vehicles (BEVs). However, manufacturers of trucks and LCV that produce BEVs are encountering several obstacles. Presently, these trucks and LCVs have a limited range of 80-280 km and require a charging time of 3-8 hours. This poses a significant challenge for many industries, impeding their investment in battery electric trucks. To address this issue, some BEVs are equipped with a range extender. It is a small combustion engine that charges the battery while driving. Additionally, due to their quiet operation, these trucks can pose safety concerns as they are not easily detected by cyclists and other vehicles. To mitigate this, external speakers can be installed on the trucks to emit artificial sounds, ensuring their presence is audibly recognized (EnergeTransitie Nederlands, 2021).

Given the former considerations, one frequently suggested alternative is the adoption of hydrogen fuel cell trucks, which are considered more suitable for sustainable long-distance transportation when compared to battery electric trucks. There are multiple factors supporting this assertion. Firstly, hydrogen fuel cell trucks are advantageous in terms of charging time. As previously mentioned, recharging an electric truck is a time-consuming process that can extend up to 8 hours, even with fast chargers (150 kWh) requiring approximately 1 hour. In contrast, refueling a hydrogen-based truck only takes between 10 to 20 minutes. Moreover, hydrogen trucks offer significantly longer ranges and shorter downtime when compared to battery electric trucks (Walker, 2021).

Furthermore, another compelling reason to favor hydrogen fuel cell trucks lies in their cargo capacity. In this aspect, there is a substantial weight disparity with battery electric trucks, as they necessitate a 1 MWh battery. Considering that the average weight of a battery is approximately 5 kg per kWh, the battery pack alone for a typical battery electric truck weighs around 5,000 kg. When adding the weight of the electric engine, inverter, and gearbox totaling 600 kg, the overall weight amounts to roughly 5,600 kg. In comparison, a diesel truck equipped with a conventional drivetrain and fuel tanks weights approximately 3,000 kg. Consequently, battery electric trucks sacrifice over 2,500 kg of cargo capacity compared to diesel trucks. Here is where the hydrogen fuel cell truck enters the picture, as it requires a much smaller battery, around 75 kWh, resulting in a cargo weight reduction of approximately 500 kg when compared to diesel trucks (Sharpe, 2019).

Moreover, hydrogen trucks provide significantly enhanced flexibility in comparison to battery electric trucks. Hydrogen trucks boast an extended range, making them well-suited for both regional and long-distance deliveries (Fedor, 2020). With the cryogenization of gaseous hydrogen, we can produce liquid hydrogen which is denser and who can fit in half the space of gaseous hydrogen for the same kilometric capacity (Air Liquide, 2022). This would enable to extend the distance range even more.

4.2 Cost and feasibility of green hydrogen usage for HDV transportation in Belgium

In this section, we will analyze through different points the feasibility of using green hydrogen as a fuel, including its commercial viability.

4.2.1 Hydrogen as a fuel

Currently, the fuel cost is mainly associated to the price of hydrogen. Green hydrogen is far more expensive than grey hydrogen, but the difference is decreasing slowly. Actually, the delocalization of green hydrogen production in countries where the price of renewable energy is lower and the economies of scales on the price of electrolyzers will tend to decrease the cost of hydrogen used as a fuel in the future.

Without considering the carbon market, the production cost of grey hydrogen is around 1.5 [e/kgH2] within the EU, while the one of green hydrogen varies between 2.5 to 5.5 [e/kgH2], two to three times more expensive (Taibi et al., 2020). However, thanks to technological improvements, cost reduction, carbon pricing, and strategies in place, green hydrogen could compete with grey and blue hydrogen.

Its production costs depend on three main costs: renewable electricity used, electrolyzers, and fixed operational costs. Among these, the most important is the electricity cost, so a significant cost reduction is necessary for "green" hydrogen to become competitive (Taibi et al., 2020). That is why countries with the best renewable resources are the more convenient for green hydrogen production because these countries will have low renewable electricity production costs. They can also export their surplus to countries with fewer resources, although transportation costs must be considered.

In Belgium, the potential for hydrogen production depends highly on our capacity to produce renewable energy. In 2022, the production of wind and solar energy amounts to 17.4 TWh, compared to 15.2 TWh in 2021. This is primarily due to the gradual increase in installed capacity for onshore wind energy and solar energy. Offshore wind production remains stable, with no planned increase in capacity for offshore wind farms before 2027-2028 (Elia, n.d.). However, we are still very dependent on nuclear energy as well as electricity produced from gas plant. They represent more than 50% of the electric production (Elia, n.d.).

The average cost of newly installed solar photovoltaic, onshore and offshore wind power projects worldwide decreased in 2021, despite increasing costs of materials and equipment. However, these rising costs have not yet fully translated into the total installed costs, leading to a decline in the global weighted average levelized cost of electricity (LCOE) (IRENA, 2022b).

The period from 2010 to 2021 has witnessed a significant improvement in the competitiveness of renewable energy sources. The global weighted average LCOE for utility-scale solar PV projects commissioned during this period decreased by 88%, while onshore wind projects experienced a 68% decline. Concentrating solar power (CSP) and offshore wind projects also saw substantial reductions of 68% and 60% respectively in their LCOE (IRENA, 2022b).

In 2021, the LCOE of new onshore wind projects dropped by 15% compared to the previous year, reaching $ 0.033/kWh. Similarly, the LCOE of new utility-scale solar PV projects decreased by 13% to $ 0.048/kWh, and offshore wind projects saw a 13% decline to $ 0.075/kWh. However, due to only one CSP plant being commissioned in 2021, the LCOE for CSP rose by 7% to $ 0.114/kWh (IRENA, 2022b).

The electrolyzers purchasing cost represents the second most important cost, meaning that cost reductions for this technology are also necessary for "green" hydrogen to become competitive (Taibi et al., 2020). Over the past decade, it has already decreased by nearly 60% (Pflugmann and Blasio, 2020) to reach an average cost of $1,120/kW in 2020 (Hydrogen Council, 2021). This cost could continue to decrease thanks to various improvement factors such as:

- Increasing the size of the stacks, meaning increasing the power from a few kW to several tens of MW. This would reduce electrolyzer costs by almost one-third and increase efficiency.
- Economies of scale in electrolyzer production. Currently, major electrolyzer manufacturers are building increasingly large production chains, reaching production capacities of 1 GW/year. These chains will be equipped with automation, and the production and design of electrolyzers will be increasingly standardized, reducing production costs.
- Technological improvements in terms of performance and durability. Increasing performance would reduce electricity consumption, while extending the lifespan of electrolyzers would spread the initial cost over a larger volume of hydrogen produced.
- Experience gained with each unit produced. This would reduce production time and improve and simplify manufacturing processes.
- Deployment and innovations in electrolyzer-adjacent technologies such as electrochemical batteries and fuel cells (Taibi et al., 2020).

Recently, Hysun, a Spanish company, has found another solution to produce hydrogen, with a method that does not use electricity, but just the heat of a resource that is abundant in Spain:

the sun. This company has adopted thermolysis. Clearly, new technologies make it possible to concentrate the heat of the sun, and to chemically break down water molecules. This produces 100% green hydrogen, without the need for electricity, which is more useful elsewhere. They have already plan to build 35 such solar power plants, for an annual output of 100,000 tons of H2. Their objective is moreover to obtain a commercial price of €1 per kilo by 2030, which could really compete economically with hydrogen produced from electrolysis. Another advantage is that the price of hydrogen would not depend on the price of electricity in this case (Lémeret, 2023).

4.2.2 Hydrogen technology for HDV

Hydrogen vehicles are still in the early stages of development and are generally more expensive than traditional gasoline or electric vehicles. The cost of a hydrogen vehicle is largely determined by the cost of the fuel cell system, which is the technology that converts hydrogen into electricity to power the vehicle.

Nowadays, the initial costs of fuel cell truck cost from roughly $200,000 to $600,000, depending on their size. The fuel cell propulsion system accounts for approximately 60% of the overall expenses and mainly encompasses the fuel cell stack and the balance of plant, encompassing the air compressor, fuel loop, high-temperature loop and sensors. Following closely in terms of cost is the gaseous hydrogen storage system, which incorporates high-pressure carbon fiber composite hydrogen tanks, hydrogen distribution components and structural support elements. Together, the fuel cell unit and hydrogen storage system are projected to account for approximately 80% of the total vehicle cost by 2025 (Ricardo Consulting, 2021).

In comparison with battery-electric technology, fuel cell technology is at an earlier stage of development in the trucking industry. As Daniel Marenne claims: "For hydrogen technology, we are currently at a stage comparable to Tesla and its electric vehicles in 2005 or even earlier."

Therefore, the cost estimates for 2025 are a reasonable approximation for the initial market of fuel cell trucks. Significant cost reductions in fuel cell technology (30% lower in 2030 compared to 2025) and hydrogen storage systems (21% lower in 2030 compared to 2025) are anticipated due to ample opportunities for manufacturers to learn and benefit from economies of scale. Alongside reductions in battery pack and electric drive unit costs, it is estimated that overall vehicle costs will decrease by 23% between 2025 and 2030 (Ricardo Consulting, 2021).

A big issue is that nowadays, there does not exist any industry to manufacture hydrogen trucks. All the hydrogen vehicles are manufactured mostly by engineer, piece by piece, which is increasing enormously their costs. When there will be an industry, economies of scale will reduce their costs. It is also important to note that the transport industry is very competitive and that the smallest increase in cost is not viable for companies.

4.2.3 Comparison of the viability of green hydrogen usage for HDV with other technologies

In this section, we will make a cost analysis of the different HDV that can be found on the market today. We divided our HDV in 4 different categories: ICEV gasoline, ICEV LNG, BEV and FCEV. The first and second category include the trucks running with diesel and liquefied natural gases with an internal combustion process, the third category includes the electric trucks, and the last category includes the hydrogen trucks with a fuel cell technology.

For this analysis, we made some hypothesis to simplify our calculations as maximum as possible. The hypotheses are the following ones:

- The total lifespan of a truck is 1,000,000 kilometers.
- The TCO includes mainly the purchase costs and the fuel costs. Maintenance, taxes costs and other small costs are considered as negligible.
- The fuel costs of a truck are estimated on a basis calculated per kilometers.
- The truck has a net null value at the end of his life.

We obtain the following TCO for the different categories of trucks considered:

Table 1: TCO of trucks according to their type

	ICEV gasoline	**ICEV LNG**	**BEV**	**FCEV**
Purchase cost	75 000 €	100 000 €	300 000 €	300 000 €
Fuel cost	510 000 €	450 000 €	585 000 €	600 000 €
TCO	585 000 €	550 000 €	885 000 €	900 000 €

In table 1, we see that the purchase costs of the vehicles are very different. In fact, FCEV and BE trucks cost approximately 4 to 5 times more than classic ICEV gasoline trucks (Piquard, 2022). On the other hand, ICEV LNG trucks also have a higher purchase cost compared to ICEV gasoline trucks. They are approximately 25% more expensive (GMobility, 2021).

To calculate the fuel cost, an average of 1,000,000 km of distance for the lifespan of a truck was considered. Then, it was multiplied by its fuel or kwh consumption per km and it was multiplied again by the actual price of the fuel or energy cost (France Hydrogène, 2022; Torregrossa, 2019; Totalenergies, n.d.).

In this analysis, maintenance costs are not considered. In fact, they are considered as negligible compared to other costs. However, they can be sometimes high. The change of batteries in BEV are a good example of maintenance costs that can be non-negligible.

On the other hand, we did not calculate a tax cost neither. When we see the different carbon markets like EU SEQUE and the price of carbon which is increasing, it could also become a considerable cost in the future for trucks which are emitting more GHG. This cost could increase the competitivity of BEV and FCEV compared to ICEV. Moreover, the LNG is approximately 25% less emitting GHG emissions than diesel, so it would also increase the competitivity of LNG compared to diesel (GMobility, 2021). ICEV could also be used in the future with synthetic fuels like liquefied methane or methanol. This would allow to keep the same vehicle technology but to decarbonize the fuel production.

Another element to consider is the stage of development of the technologies. FCEV and BEV are still in the early stage of development and economies of scale will tend to decrease their costs in the future (Curtin & Gangi, 2016). The hydrogen production cost also tends to decrease in the future as we have seen in the section above.

Unfortunately, JOST Group, a big actor in logistic and freight transportation cannot consider hydrogen as a viable short-term solution for transportation because they claim that there are still no infrastructures, no real solutions for vehicles, and they are very costly. Moreover, they say that the hydrogen currently produced is more polluting than LNG, and its price depends on the same LNG. JOST Group has decided to invest in LNG, which positions itself as a greener transitional energy compared to diesel. Their LNG project is a project worth tens of millions of euros, including a fleet of 500 vehicles, 3 LNG stations, and two tanker trucks for transferring LNG between the port of Zeebrugge and their various stations.

However, a possibility could be to use liquefied e-methane as a fuel with their new LNG vehicle. Doing so, they would be carbon neutral because the CO2 emitted during the combustion is the exact same CO2 that was captured during the e-methane production. As a result, this vehicle could be considered as net zero emissions vehicles.

4.2.4 Conditioning, storage and transport of hydrogen

European context

In Europe, there already exists an extensive pipeline network spanning over 1500 km, exclusively dedicated to hydrogen distribution. These pipelines facilitate the transportation of hydrogen at speeds of approximately 40 km/h. The hydrogen is compressed to a pressure ranging between ten and a hundred bars. It is important to note that this transportation system is primarily suitable for large quantities of hydrogen. Alternatively, it is feasible to use the existing natural gas pipeline network by blending hydrogen with a proportion of 80-20%. However, at the conclusion of the process, it becomes necessary to separate the two gases (Air Liquide, n.d.; Boucher, 2016; Dhers, 2005; Malbrunot, 2019).

Despite the initial high cost associated with establishing the pipeline infrastructure, this approach offers significant advantages, primarily due to its remarkably low energy loss during transportation, amounting to just 1.4% (Eliasson et al., 2003).

In 2021, 19 European natural gas operators devised a European hydrogen backbone plan. The European plan envisions initiating the network around 2025, connecting key European "hydrogen valleys" by 2030 through an approximately 11,600 km network. This network will be expanded to cover 40,000 km by 2040, with an estimated 69% of the hydrogen pipeline network comprising converted natural gas pipelines. The investment cost for this European hydrogen backbone is estimated to range between 54 and 81 billion euros. The transportation cost of hydrogen is projected to be between 0.1 and 0.2 euros per kg per 1000 km, indicating cost-efficient transport (Fluxys, 2022).

Belgian context

In Belgium there are several means and different places that seem optimal to import hydrogen:

The North Sea is one of the major renewable resources for Europe and benefits from favorable wind schemes which allow to produce renewable hydrogen at a low cost. The synchronized development of offshore electricity and hydrogen networks, coordinated with the other countries surrounding the North Sea, will allow to rapidly harness this energy (FPS Economy, 2022).

Piped imports from Southern Europe, mainly Iberia and North Africa are a promising long-term solution. It is known as the “South road”. It nevertheless requires the development of hydrogen transport networks through Europe and will therefore require more time before being ready. The shipping route may be a temporary solution here (FPS Economy, 2022).

The maritime road can be a solution too. It consists in importing H2-derivatives via ship. It is expected to become the most competitive and thus the preferred solution for supplying H2-derivatives to Belgium. H2 derivatives can either be directly used as is or be converted back to H2 molecules. The reverse conversion to H2-molecules enables to diversify their supply and to allow the constitution of strategic stocks that will soon be needed for the security of supply when H2-molecules gain in importance in the energy mix (FPS Economy, 2022).

The transport costs are negligible in the total price of hydrogen used as a fuel. It only represents between 0,3 and 1,5€/kg of hydrogen. The difference in price depends on the state of hydrogen, either liquid or solid and of the mean of transport. It also depends of the length of the transport. In fact, transport costs can be mainly equal to zero if we produce on site but are larger if we produce in other countries or on another continent. Economically, it can be interesting to import from other countries if the cheaper price of creating hydrogen in their countries more than compensate the higher costs of transport (Leonard, 2021).

In Belgium, there are two main approaches being explored to connect future sustainable green production facilities and potential import scenarios with pipelines: repurposing existing natural gas pipelines and constructing new infrastructure (Fluxys, 2022).

In 2021, Fluxys, the national transmission system operator (TSO) for natural gas, devised a rollout plan for hydrogen and CO2 infrastructure. This plan consists of two distinct phases, one short term and the second long term (Fluxys, 2022).

The first phase is about short-term options for establishing the initial decarbonization infrastructure. As it can be seen on Figure 1, it focuses on development starting from industrial clusters, utilization of a combination of repurposed natural gas pipelines and new infrastructure, progressive establishment of interconnections between clusters to facilitate transfers, enhance supply security, and provide flexibility. Another focus is put on the advancement of Zeebrugge's role as an energy entry gateway, shaping the hydrogen and carbon infrastructure for Belgium.

The estimated investment cost for this phase is around 1.1 billion euros. Following Baptiste Costa-Marini from Fluxys, the initial decarbonization infrastructure will be established within industrial clusters such as Antwerp, Ghent, the Albert Canal, Zeebrugge, Brussels, Charleroi/Bergen, and Liège. For instance, a local backbone spanning approximately 30 km is projected for the Port of Antwerp, while a hydrogen pipeline network of around 65 km (partially in the Netherlands) could connect several chemical companies in the North Sea Port. In the Port of Zeebrugge, a local network spanning 15-25 km is planned. These local pipelines will eventually be interconnected, using a mix of repurposed natural gas pipelines and new infrastructure. The connection between Zeebrugge, North Sea Port, and the Port of Antwerp is estimated to be approximately 100 km (Fluxys, 2022).

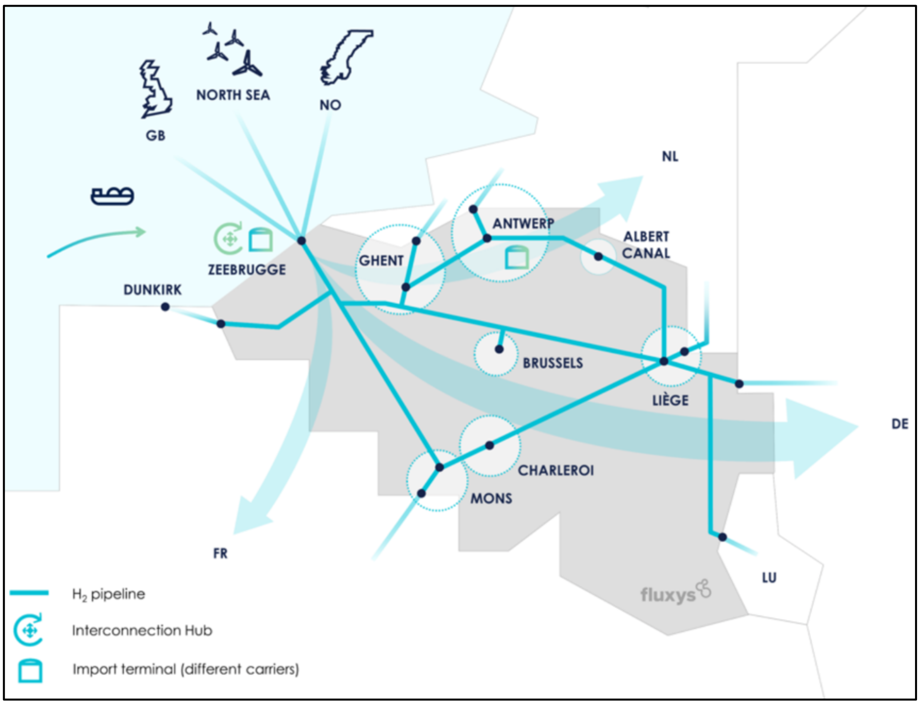

Figure 1: Map of the hydrogen network in Belgium (Fluxys, 2022)

The second phase consists in a long-term incremental development towards a fully carbon-neutral grid and focuses on additional interconnections between clusters to enhance flexibility, further interconnections with neighboring grids to ensure supply security and access to broader markets as well as importation of remotely produced green hydrogen via the Zeebrugge terminal, serving as an energy hub (Fluxys, 2022).

Finally, the storage costs of hydrogen are also considered as negligible. In fact, there are more and more promising technologies in the hydrogen storage that are being developed and that are able to produce hydrogen tank that have an illimited life period or that can store liquid hydrogen. These technologies, if deployed massively in the future, could become commercially viable (Air Liquide, 2022; NPROXX, 2023).

4.2.5 Hydrogen filling station

One of the primary obstacles confronting hydrogen usage in transportation is the lack of infrastructure to support its integration into the automotive sector. Presently, the availability of hydrogen charging stations is extremely limited. Indeed, in Belgium, there are only seven stations (Glpautogas, 2023), while Europe as a whole has a total of 254 stations (Autoplus, 2023). Although there have been some minor initiatives aimed at establishing additional refueling points, they pale in comparison to the extensive network of petrol stations (McDowall & Eames, 2006).

The expense associated with a hydrogen filling station is exceptionally high, between 1.2 and 3 million euros (Koleva & Melaina, 2021; Linde, n.d.). In contrast, establishing a diesel or petrol filling station necessitates an investment ranging from €50,000 to €200,000 (Demangeon, 2018). However, as the demand for hydrogen fueling infrastructure increases and technology advances, it is expected that the cost of building and operating hydrogen fueling stations will decrease.

The price of utilization of a hydrogen station can also be estimated. Modern infrastructure cost just €1/ kg of H2 dispensed based on a utilization level of 80% (Linde, n.d.). This cost depends on numerous factors and can fluctuate for each station depending on their size, complexity, etc.

It is possible to determine the optimal places for hydrogen filling station in Belgium if we want to maximize their utility for HDV. Trucks are using highways as much as they can in order to minimize their transport time as well as the complexity to go through small villages with large trucks or machines. In France, even with motorway tolls, trucks are using motorways at 76% (Rébillon, 2022).

We can see, on figure 2, a map of the principal road that we can find in Belgium. On the following figure, the motorways are the larger lines, and the other highways are represented by the thinner lines. The actual hydrogen filling stations are already represented on the map.

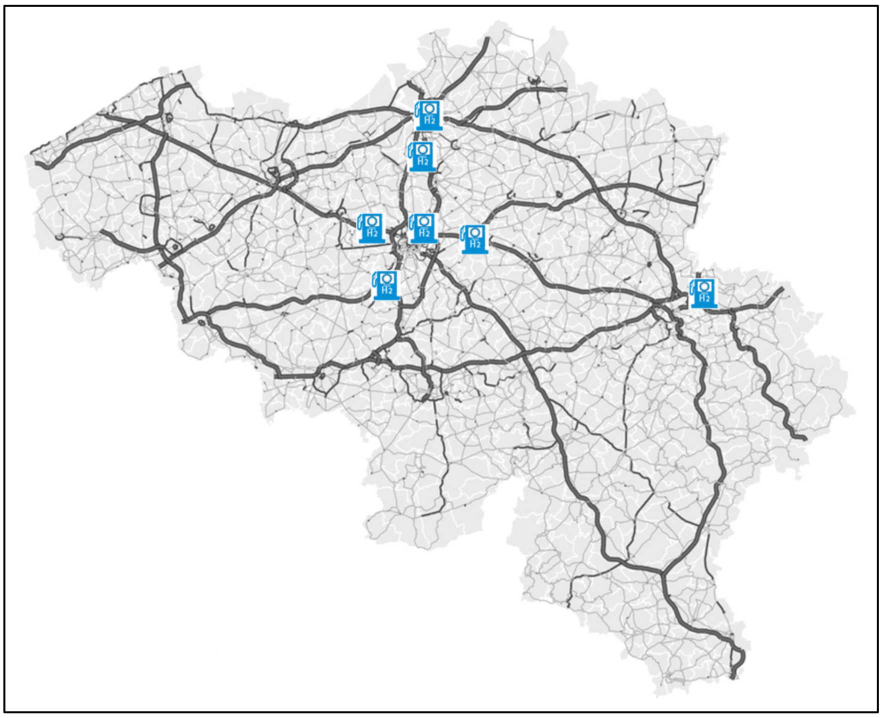

Figure 2: Principal highways in Belgium and actual hydrogen stations (Klein & Gerber, 2010)

As we have seen on the section above, the hydrogen network is mostly developed around the industrial clusters according to the map that we obtained from Fluxys. It is easier and less costly to develop a station somewhere where the hydrogen network will go through because the connection with the hydrogen filling station will be less costly, and the station will be more easily restocked.

Figure 3 shows again the map of the main highways in Belgium, and we added the potential future hydrogen network to the map to see where it would be the most optimal to add filling stations. Industrial clusters are circled in red. From this map, we can determine the best places to develop hydrogen filling stations. We obtain the following figure.

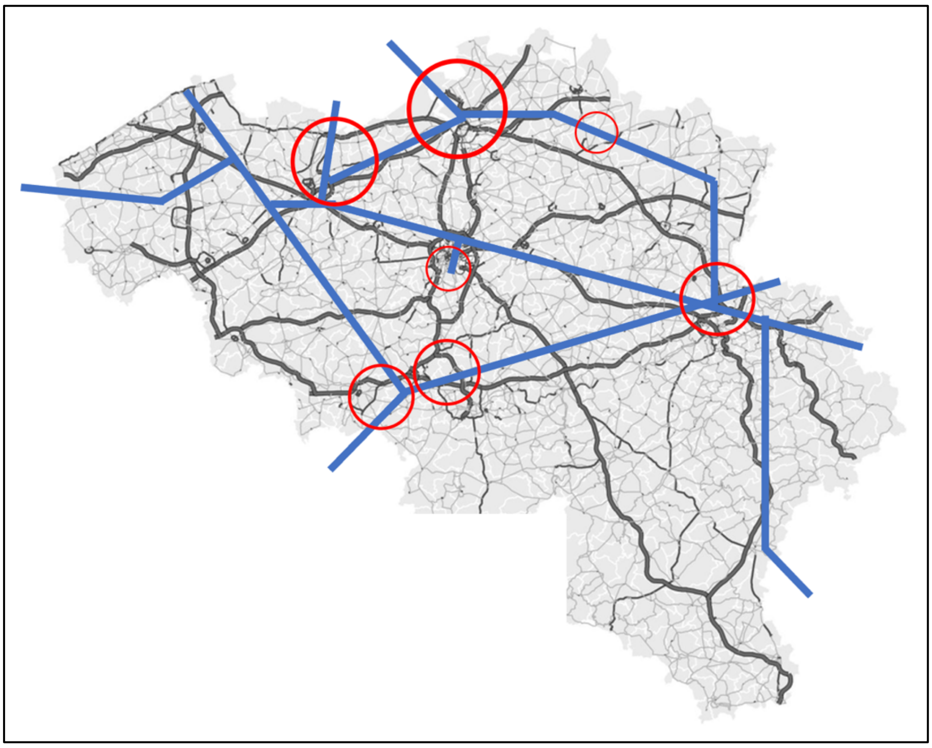

Figure 3: Map of main highways and hydrogen network in Belgium (adapted from Klein & Gerber, 2010)

On figure 4, the green triangles are the places that seem optimal for off-site hydrogen station. Off-site hydrogen stations are stations that do not have hydrogen production systems at site, and hydrogen is supplied either by tube trailer or by pipeline (Stolten & Emonts, 2016). We see that the places determined on the map are situated very close to the hydrogen network and on large roads, where the flow of HDV is the highest, so they are the optimal locations.

On the other hand, the yellow triangles on the figure are the places where on-site production seems the most appropriate. Hydrogen is directly produced at the filling station site and can be distributed directly (Stolten & Emonts, 2016). There are no transport costs and low storage costs. For these places, we could also imagine stations that are restocked by tube trailer with hydrogen either on the liquid or gas form.

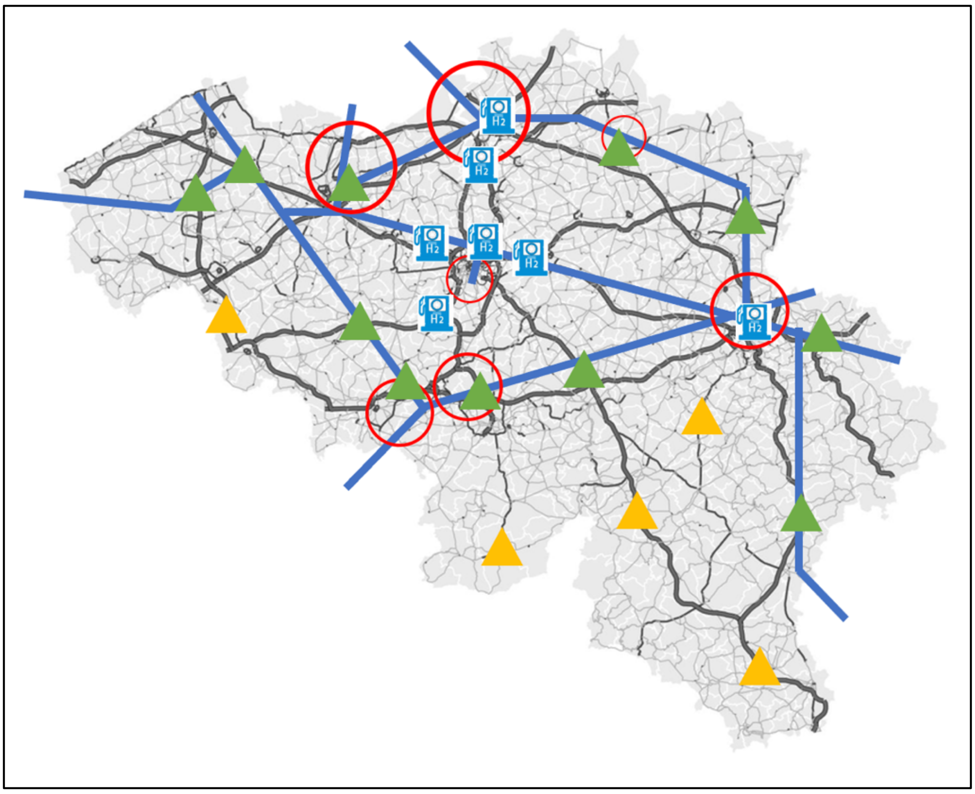

Figure 4: Map of the optimal location for hydrogen filling station (adapted from Klein & Gerber, 2010)

The challenge lies in striking a balance between minimizing the number of hydrogen stations, due to their high development costs, while ensuring that enough stations are available to create a viable market that can expand in the future. The initial stakeholders who are likely to show interest in hydrogen mobility are those who can accurately plan their itinerary and have assurance of finding hydrogen stations within close proximity for refueling when needed. Public buses and garbage trucks that follow fixed routes provide a good example of such actors. Similarly, companies operating within specific geographic zones where hydrogen stations exist could also find hydrogen mobility appealing. However, for international transportation, betting on hydrogen presents significantly greater complexity and challenges.

4.3 Policies and incentives related to hydrogen usage in transportation

In this section, the different incentives related to hydrogen will be developed. We have analyzed both incentives at the Belgian and European levels.

4.3.1 Hydrogen subsidies and incentives

European context

In its official communication on the topic published in 2020, the European Commission provides the context, ambition and roadmap for hydrogen in the European Union. The proposed measures include investments, initiatives to stimulate production and demand, the development of necessary infrastructure and the promotion of research and innovation in the field. The publication also explores the potential for international energy partnerships with neighboring countries and regions, offering incentives to achieve the goals outlined in the document. By outlining this plan and presenting a collection of 20 key actions for Europe, the Commission recognizes hydrogen as a crucial component of the broader clean energy transition and Green Deal, emphasizing the urgency of investing in it now (European Commission, 2022).

One of the objectives that the European Commission provided is to produce 10 Mt of hydrogen in the European Union and to import 10 Mt more in 2030. To produce 10 Mt of hydrogen, we need approximately 500 TWh of electricity and because we want to produce green hydrogen, the electricity used for hydrogen production should be green too. It seems a very ambitious plan, and it is very unlikely to happen when we see that 2030 is a near future and that we do not have yet the capacities to produce such a quantity of green electricity.

In different countries of Europe, hydrogen is at the center of the discussions. In France, hydrogen is recognized as a top priority for achieving environmental objectives, as emphasized in a joint study conducted by the French Ecological Transition Agency and EY in 2019. The study also highlights the intense global competition in the emerging hydrogen sector. To secure a leading position in this highly lucrative market, legislators are urged to swiftly promote hydrogen in France through a range of initiatives, with a particular focus on the automobile and transport sectors (ADEME, 2019).

The German context presents certain limitations for fuel cell electric vehicles, including high production costs, limited involvement of German automakers, inadequate refueling infrastructure and low overall demand (Trencher & Edianto, 2021). Given these challenges, policies and government support for hydrogen become crucial in driving its development.

Germany has placed significant emphasis on fostering innovation and production capabilities in the hydrogen sector. This includes the establishment of the National Innovation Programme for Hydrogen and Fuel Cell Technologies, which has allocated approximately 1.5 billion euros in funding over a decade (Trencher & Edianto, 2021).

It is important to highlight that the decarbonization initiatives include collective targets that the European Union must meet. These targets are accompanied by a governance regulation, which provides annual updates on the contribution of each EU Member State towards the given targets. If the trajectory is not on track to meet the targets, additional measures can be taken. The current objective aims to achieve the emission reduction target set for 2030 in the climate law. The governance system ensures that progress is monitored and, if necessary, additional actions can be implemented. This system is somewhat complex because targets are not specific to individual countries. Some countries may have varying costs and preferences for decarbonizing their economies using different methods, such as Fashion A or Fashion B. Therefore, it is a collective mechanism that ultimately seeks to achieve the 2030 target.

Regarding hydrogen decarbonization targets, imposing the same targets on all countries may not be appropriate. The benchmark for decarbonization should consider the existing technologies, such as SMR (Steam Methane Reforming), which has been highly recognized. The targets should be defined in a way that focuses on countries using these technologies. However, this does not mean that other countries cannot do anything. They would need to identify alternative areas for reducing their emissions in order to collectively reach the target. Flexibility and intelligent target setting are necessary because each Member State has a unique economic structure that should be taken into account when defining their targets.

There are various instruments to achieve the objectives set by the climate law. For example, in the negotiations related to duty transportation, an emission target is established. This target specifies the need to meet defined emission levels but does not dictate how it should be accomplished. The choice of electrification, hydrogen or other synthetic fuels is left to the sector. There is also a renewables target for that sector, acknowledging that hydrogen or its derivatives are the most efficient options. This approach encourages hydrogen production and consumption but allows economic incentives within the sector to determine the most cost-effective decarbonization methods. The sector itself decides on the technology choices rather than relying on technocrats to determine the most efficient technology. However, in sectors like heavy-duty transportation, where the prevailing technology or application is uncertain, setting specific targets may not automatically result in increased hydrogen consumption. The market dynamics play a significant role, where targets are set, and then the market determines the outcomes.

Regarding subsidies, the European Commission manages funds such as regional funds or recovery resilience funds, where a portion of the money is allocated for decarbonization purposes. While these funds are not solely dedicated to hydrogen production, member states are required to use the funds for decarbonization initiatives. This can include activities like funding for housing insulation, subsidizing the electrification of passenger cars, or establishing fuel and charging stations for electric vehicles.

Additionally, there is a new financing instrument called the Hydrogen Bank, which is a development-oriented subsidy auction system being implemented within the EU governance (European Commission, 2023). The funds for this initiative come from revenues generated by the Emission Trading Scheme. The Innovation Fund, a part of this program, has established an auctioning system to support projects focused on hydrogen and its derivatives. Although it is a new development, the first auction is being prepared and scheduled to take place before the end of the year. The objective is to allocate funds through a double-sided auction. While this funding will not cover the entire value chain, it represents a relatively new aspect of the subsidy landscape that is currently being developed and it is specifically used for hydrogen development.

Belgian context

In Belgium, the Federal Government is actively adapting its instruments and creating new ones to promote research and development in hydrogen technologies. This includes various initiatives:

The Energy Transition Fund, operational since 2017 and running until 2025, supports R&D projects related to hydrogen production, transportation, storage, and derivatives. It offers annual calls for projects with a funding range of 20 to 30 million euros (FPS Economy, 2022).

The Clean Hydrogen for Clean Industry calls for projects, part of Belgium's national recovery and resilience plan, focuses on mature technologies for hydrogen production and use. The aim is to stimulate investments that will accelerate the commercialization of hydrogen applications.

The first call, launched in April 2022, offers support of up to 50 million euros, and a second call with 10 million euros of support will be launched in 2023 (FPS Economy, 2022).

The H2ImportCall for projects, scheduled to be launched in early 2023 with a budget of 10 million euros, aims to develop and demonstrate technologies for importing hydrogen and integrating it into a hydrogen transport network (FPS Economy, 2022).

Additionally, the Federal Government is investing in VKHyLab, a testing infrastructure to facilitate the scaling up of hydrogen technologies for research institutes and companies. The government is providing 1.5 million euros for the acquisition of the site and an additional subsidy of 14.7 million euros to the Von Karman Institute of Fluid Dynamics for project development. VKHyLab is expected to be operational by 2025 (FPS Economy, 2022).

4.3.2 Carbon tax and quota

To further support innovation, the government can adapt taxes, excises or surtaxes. In the case of electrolysis, an essential process for hydrogen production, electricity excises are exempted to encourage the development of initial electrolysis capacities in Belgium and enable companies and research institutions to gain expertise in this area (FPS Economy, 2022).

There are also carbon markets that are emerging where quotas are decided in order to keep a control on the GHG emissions. Let's focus on the European carbon market, as it is the most mature emissions trading system. In fact, since the entry into force of the EU Emissions Trading Scheme in 2005, the European Commission launched the very first carbon market called the European Union Emissions Trading System (EU ETS) across its territory (ICAP, 2023b). It is the main instrument used by the EU to achieve its GHG emission reduction targets, specifically for CO2, N2O and fluorinated gases, in the various sectors involved.

The EU ETS covers the European economic area and includes three sectors: large-scale electricity and heat production, manufacturing industry and domestic aviation within the European Economic Area (European Commission, 2021). Over time, the EU ETS has expanded geographically to include Iceland, Liechtenstein and Norway. Since its launch, emissions in the covered sectors have decreased by nearly 43%. Currently, the EU ETS covers around 40% of total emissions within its member countries and approximately 5% of global greenhouse gas emissions (ICAP, 2021).

However, the functioning of the EU ETS has not always been optimal. In fact, the price of a carbon allowance on the secondary market remained consistently below €10 per ton of CO2 equivalent (ICAP, 2023a). This low price was due to the surplus of available allowances within the system, particularly as a result of the economic recession caused by the 2008 crisis. Despite the low prices, the EU objectives were still being met, as the economic recession had temporarily reduced greenhouse gas emissions (Eden et al., 2016). However, it was necessary to increase the price by removing a portion of the surplus allowances to make the trading system more efficient in the long term and improve its resilience. To achieve this, the European Commission introduced the Market Stability Reserve (MSR) mechanism in 2019. Its purpose is to address any imbalance between the supply and demand of allowances. Each year, the European Commission publishes the total number of allowances in circulation and adjusts the quantity based on that information. This mechanism allows market participants to have confidence in the carbon market by reducing price volatility and maintaining a sufficiently high allowance price to have an impact on emission reduction (Acworth et al., 2018). Through the application of the MSR in 2019 and 2020, the price of allowances increased to around €30 per tons of CO2 equivalent in 2020.

During the publication of the Green Deal and the Fit for 55 package in July 2021, the secondary market for the EU ETS experienced a favorable response. The prices of allowances increased to around 90 [€/tCO2e] before stabilizing at 80 [€/tCO2e] (ICAP, 2023a). With the war in Ukraine, it was destabilized with a decrease of the economy and went under 70 [€/tCO2e] for a short period. However, from February 2023, it had reached a new peak and it is now negotiated at more than 100 [€/tCO2e] (BNP Paribas, 2023).

This high pricing is important as it plays a determining role in achieving the necessary major changes in the European energy mix (Pietzcker et al., 2021). With such a high price, investments in low-carbon technologies such as renewable energy sources but also in currently underdeveloped technologies like hydrogen, biofuels, carbon capture, and storage, are facilitated (Acworth et al., 2018). Previously, carbon pricing was not high enough to promote rapid development of these technologies. However, with high allowance prices, there will be a growing interest in these technologies as they enable decarbonization in specific sectors. By achieving a well-balanced mix of all these technologies, it is possible to substitute fossil fuels, which is the primary objective. The second objective is to reduce overall energy consumption by improving energy efficiency and adopting a more frugal consumption pattern (IRENA, 2022a). However, following Augustijn van Haasteren, it is difficult to say to which extent the price of the EU ETS will influence the use of hydrogen and synthetic fuel.

In a carbon-neutral society, the two main energy vectors will be electricity and hydrogen (BP, 2022). Most sectors are expected to be electrified, but some sectors requiring specific characteristics of fossil fuels will use hydrogen or synthetic hydrocarbons derived from hydrogen. Therefore, it is necessary to support the development of the clean hydrogen industry.

Moreover, a new separate SCEQE II (Emissions Trading Scheme) for fuels used in road transport and buildings, which will set a price for emissions in these sectors, will be implemented by 2027 (European Parliament, 2022). However, there will be a maximum price of €45 per ton of carbon emitted until 2030.

4.4 Identification of challenges facing the development of hydrogen in transportation

In this section, the different challenges to develop hydrogen in the transport sector are listed and developed.

4.4.1 Efficiency

One of the major obstacles to the widespread use of hydrogen as a fuel is its efficiency. When producing green hydrogen, electricity is required and the conversion process yields approximately 65%. Moreover, if we aim to convert gaseous hydrogen into liquid hydrogen, nearly one-third of its calorific value is consumed in the process. Furthermore, the conversion of hydrogen into electric propulsion achieves a yield of approximately 60%. The total efficiency of a FCEV is of approximately 30%. In contrast, Battery Electric Vehicles (BEVs) directly use electricity without the need for additional conversions, resulting in an efficiency of approximately 85%. The various efficiencies can be summarized in the following Figure 5:

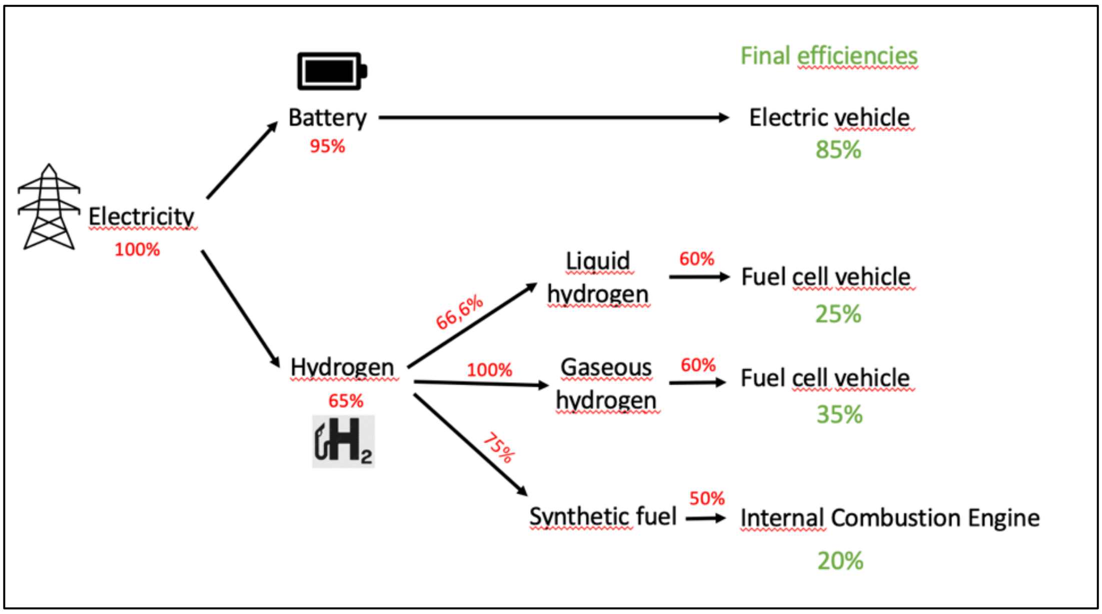

Figure 5: Hydrogen efficiency summary

4.4.2 Safety

The crash of the Hindenburg in 1937 still haunts the memories of many individuals, leaving lasting trauma. Despite the elapsed of time and the questioning of hydrogen's responsibility, there remains a prevalent perception among many people that hydrogen is dangerous and unsafe, contradicting the modern notion of vehicles being increasingly secure (Iskandar, 2020).

Furthermore, alongside this misconceived assessment of hydrogen, some potential adopters of the technology feel uneasy about carrying high-pressure tanks. Additionally, concerns arise regarding storing hydrogen-powered vehicles in confined spaces such as garages, as the highly flammable nature of hydrogen could impede its dissipation in the event of a leak (Hardman et al., 2017; O’Garra et al., 2005).

In 2008, INERIS highlighted the hazards associated with hydrogen usage. They emphasized its extreme flammability, capable of exploding upon contact with air. Hydrogen also possesses the propensity to leak even through the tiniest cracks. Presently, hydrogen finds its primary application in industrial and refining sectors, where it is handled by trained personnel under strict safety protocols. The concern arises from the potential release of hydrogen into the automotive industry, where unqualified individuals would handle it. Furthermore, meticulous attention must be paid to prevent any cracks that could lead to hydrogen leakage (Beeker, 2014; Malbrunot, 2019). Moreover, it is essential to acknowledge that even if hydrogen were eventually introduced to the general public, some accidents could hinder its widespread adoption.

Moreover, due to its dangerousness and high level of safety needed, hydrogen is also a risk for sabotage and terrorism. In fact, it could be used as a weapon by some individuals and an extended hydrogen network would necessitate a high level of precaution and security measures to prevent any kind of disaster.

4.4.3 Certification

Still, one of the most significant challenges faced by hydrogen today is the necessity to cultivate certainty among market participants via electrolyzer and green hydrogen standards and certification. Today, grey hydrogen produced from fossil fuels dominates the market (98%). This means that for green hydrogen to gain relevance, markets must incorporate tracking instruments that guarantee the origin of the hydrogen and distinguish green from grey hydrogen (IRENA, 2023).

A market for green hydrogen trade will rely on verifiable information, on production methods. A trustworthy certificate can ensure consumers that the purchased hydrogen (or its derivatives) has the renewable or low-carbon characteristics that the seller claims. As an example, ÜV Rheinland offers a Carbon-Neutral Hydrogen certification standard (H2.21), which allows manufacturers, distributors and users of carbon-neutral hydrogen to document its environmentally friendly production (IRENA, 2023).

Certificates can therefore enable the creation of low carbon, including green and blue, hydrogen markets by allowing the verification of low-carbon hydrogen use, as opposed to unabated use of fossil fuel-based hydrogen. Furthermore, hydrogen certificates can be used by downstream industries, such as those producing ammonia and steel, to market their products as having used green hydrogen. Certifying hydrogen is therefore an important step in creating markets for green hydrogen and industries using hydrogen as feedstock. Globally, there exists several certification systems for green hydrogen. Many of these focus on domestic trade (IRENA, 2023).

Having multiple certification systems presents a challenge: cross comparing the hydrogen certified by each individual system. However, several boundaries, labels and methodologies can render certificates inapplicable in different jurisdictions. Enabling an international hydrogen market, therefore, requires certificates to be harmonized globally. This means agreeing on taxonomies, accounting methodologies, boundaries, energy and fuel sources to ensure continuity in hydrogen certification (IRENA, 2023).

4.4.4 Other barriers

There are other barriers to hydrogen development. The price of green hydrogen is surely considerate as one of the biggest barriers. Currently, the cost of producing green hydrogen is not competitive compared to conventional fossil fuel options. This price disparity discourages industries from investing in technologies related to hydrogen. Consequently, there is a lack of manufacturing plans for hydrogen trucks and a limited number of hydrogen stations available.

The high cost of green hydrogen hinders its widespread adoption as industries are hesitant to take the financial risk associated with investing in hydrogen-related technologies. Without sufficient market demand and cost-competitiveness, the necessary infrastructure, such as manufacturing facilities for hydrogen trucks and an extensive network of hydrogen stations, remains limited.

To overcome this barrier, efforts are being made to reduce the cost of green hydrogen production through technological advancements, economies of scale, and supportive policies. Lowering the price of green hydrogen will stimulate market demand and encourage industries to invest in hydrogen technologies, leading to the expansion of hydrogen infrastructure and increased adoption in various sectors.

5. Conclusion

Green hydrogen as a fuel is still in its early stage of development and not suitable directly for the HDV in Belgium and Europa more largely. In fact, the first point in order to develop the market is to be able to produce green hydrogen at a competitive cost compared to grey hydrogen. To do so, the cost of green electricity production should decrease as well as the cost of electrolyzers. Moreover, incentives such as subsidies or taxes on grey hydrogen production should reduce the gap of price between green and grey hydrogen. Belgium does not have the capacity to produce green electricity as much as wanted in order to fulfill the hydrogen demand that will increase fast in the future. Importation of hydrogen from other countries will be needed. One possibility would be to import liquefied hydrogen from Norway to the Zeebrugge terminal, due to the high production of green electricity in Norway.

The development of the hydrogen network is a crucial aspect that requires attention. Fluxys has outlined an expansion plan to develop the hydrogen network in Belgium, but it will require a considerable amount of time. This plan is closely tied to various industrial stakeholders who have a future interest in hydrogen. The short-term objectives are set for 2025, while the long-term objectives are aimed towards the horizon of 2030. Initially, the focus of the green hydrogen network will encompass all industrial clusters such as Charleroi, Antwerp, Ghent, Liège, etc. Furthermore, there are plans to interconnect with neighboring countries to establish a European hydrogen network in the future.

As the network becomes more developed, hydrogen stations will first be installed in close proximity to it, aligning with the main transportation routes in Belgium. In more remote areas, hydrogen stations may be further away from the hydrogen pipeline network, which may necessitate on-site hydrogen production to minimize transportation costs. However, economies of scale will gradually reduce the price of hydrogen stations.

Additionally, the hydrogen HDV industry needs to be developed. Currently, the price of hydrogen vehicles remains high due to the absence of dedicated industrial factories worldwide.

Hydrogen will undoubtedly play a significant role in decarbonizing the transportation sector, with the aim of achieving carbon neutrality by 2050. However, we are still in the early stages of development, and rapid progress is unlikely. It will take time to establish a comprehensive network and ensure the economic viability of hydrogen solutions for transportation purposes.

In the near future, the emergence of e-fuels such as e-methane or e-methanol is more probable for decarbonizing the transport sector. These e-fuels offer the advantage of not requiring significant changes to vehicle technologies or the development of an extensive network. With slight adaptations, existing infrastructures can be suitable for e-fuels. The primary challenge lies in the production of e-fuels.

FCEV, on the other hand, are expected to initially find application in industries where the vehicles have well-defined routes and convenient access to refueling. Garbage trucks and public buses are prime examples of such industries. These vehicles operate on fixed itineraries, enabling them to accurately plan their refueling needs based on the availability of hydrogen fueling stations along their routes.

However, the situation becomes more challenging for international transport. The development of a widespread and evenly distributed network of hydrogen filling stations across different countries is a slow process. This non-uniform infrastructure development poses a hurdle for FCEVs used in international transportation. As the hydrogen infrastructure continues to evolve, efforts are being made to expand the network of hydrogen filling stations and improve their coverage across various regions. This will contribute to enhancing the viability of FCEVs for international transport by providing a more extensive and interconnected network of refueling options.

6. Critique

This work is based on a significant number of assumptions. Various quantities, prices and dates are provided to offer a comprehensive overview of the subject and identify important trends or discrepancies. Hydrogen is currently in the spotlight as a potential solution for decarbonizing the economy and it is often discussed by companies. However, there are numerous challenges that need to be addressed and their resolution will determine whether hydrogen becomes a major player in the future or remains a smaller part of our energy mix. We are still in the early stages of development and the objectives set for hydrogen may be overly optimistic.

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Appendices

A. Interview transcript Augustijn VAN HAASTEREN (FR&EN, original)

SPK_1: Bonjour, merci beaucoup de m'avoir rejoint lors de cet appel. J'ai une petite question, est-ce que cela vous dérange si j'enregistre l'interview ?

SPK_2: Si c'est uniquement pour votre mémoire.

SPK_1: Oui, c'est pour mon mémoire. Est-ce que c'est possible ?

SPK_2: Oui, vous pouvez enregistrer. Toutefois, si vous souhaitez publier l'enregistrement, c'est une autre histoire.

SPK_1: Non, non, bien sûr. En fait, c'est pour le retranscrire et l'inclure dans mon mémoire. Mais je peux vous renvoyer l'enregistrement.

SPK_2: pas de problème.

SPK_1: D'accord, merci. Donc, pour vous expliquer brièvement, je rédige mon mémoire sur le développement de l'hydrogène vert pour le secteur du transport lourd principalement. J'ai déjà interviewé le gestionnaire de réseau, ainsi qu'une personne de chez Engie. J'essaie également de contacter des constructeurs de poids lourds et de grandes entreprises de transport afin de voir comment l'hydrogène pourrait être introduit dans le secteur du transport lourd dans le futur. Et donc, je trouve cela très intéressant d'avoir aussi le point de vue de quelqu'un de la Commission qui soutient le développement de l'hydrogène.

SPK_1: Donc, voilà, comme première question, si je peux me permettre de vous demander
quel est votre poste au sein de la Commission européenne?

SPK_2: Mon rôle principal est le développement d'actes législatifs. En fait, l'amendement d'une législation existante sur les structures et le fonctionnement des réseaux gaziers, y compris leur extension. Cela concerne principalement, mais pas uniquement, l'hydrogène. Donc, tout ce qui concerne les règles et les infrastructures de l'hydrogène. Cela fait partie de mon domaine de responsabilité, mais ce sont aussi des questions traitées par les collègues chargés des critères de « sustainabilty ». Je m'excuse, j'utiliserai parfois des termes français avec un peu d'anglais, car je ne connais pas du tout les terme techniques en français. Donc, cela concerne principalement ce que signifie "vert" et aussi des questions internationales et liées à la production d'hydrogène. C’est principalement lié aux questions de réglementation. C'est là que j'interviens.

SPK_1: Pour le réseau d'hydrogène en Europe? Pas seulement le gaz, c'est ça ?

SPK_2: Surtout en ce qui concerne l'hydrogène, principalement l'hydrogène, mais cela fait partie d'une législation qui ne concerne pas uniquement l'hydrogène, mais aussi le gaz naturel. Il faut le comprendre ainsi, il faut le voir comme ça, mais moi, je suis responsable du côté hydrogène.

SPK_1: D'accord, merci. En lisant un peu sur le site de la Commission européenne, on voit que pour 2030, l'objectif est de produire 10 millions de tonnes d'hydrogène à partir d'énergies renouvelables, et qu'il faudrait environ 500 térawattheures d'électricité, si je ne me trompe pas. Quand on voit l'électricité qu'on consomme actuellement, est-ce vraiment un objectif réalisable selon vous de produire autant d'hydrogène d'ici 2030 ?

SPK_2: Disons que c'est très ambitieux, vraiment très, très ambitieux. En termes de soutien à la production d'hydrogène, il y a 4 actes pertinents. Il y a la « Energie » directive, qui n'est pas encore mise en œuvre, mais qui a été adoptée, et qui fixe des objectifs d'utilisation de l'hydrogène dans les transports et l'industrie. C'est une chose.
Il y a aussi deux actes qui ont été adoptés mais pas mis en oeuvre, le «REFUEL EU» pour le maritime et pour l'aviation. Donc, les trois instruments fixent des objectifs spécifiques pour l'utilisation de l'hydrogène ou de carburants synthétiques dans ces applications.

Donc, il y a des objectifs clairement définis qui constituent un minimum à atteindre d'ici 2030. On peut également ajouter que pour les règlements concernant le transport maritime et l'aviation, il y a des trajectoires au-delà de 2030, donc une trajectoire vers 2050 qui fixe un objectif. On peut discuter un petit peu du chiffre en termes de production d'hydrogène mais ça aussi on a dit que c'est loin des 10 Mt de production intérieure et des 10Mt à importer. Ce qui est un inconnu est l'effet de prix ETS sur la motivation d'utiliser de l'hydrogène ou des fiouls synthétiques. On ne sait pas dire dans quelle mesure l'ETS soutient ses usages dans les secteurs autres qui sont visés exclusivement par des objectifs, par des actes comme « REFUEL EU »

Il n'est pas évident d'évoluer dans quelle mesure ça soutient aussi l'usage de l'hydrogène, dans le secteur autre pour lequel il y a des objectifs

Je peux parler en anglais, ?

SPK_1: Evidemment !

SPK_2: There is at the beginning of the present Commission there was a climate law adopted which sets basically the obligation to EU to meet its 2050 Net 0 objective. And in this context, there was a 2030 objective in terms of reduction of emissions and there was also the obligation for the EU to set a point for 2040. So that the trajectory between 2013 and 2015 became clear. So these calculations are currently taking place and I don't know exactly when it will be published, but somewhere after the summer, this model exercise will also become available publicly and it will become clearer as to, let's say, what the role of various instruments and also the composition with results thereof in the energy mix, what the results will be. So this uncertainty as to whether we will achieve what will be by 2030, but also by 2040, will become clearer once we have calculated the impact of the current policy instruments which have been adopted over the quarter this year.

So it's not a very clear answer, but what I want is to qualify your question a little bit as to whether this is achievable. So I'm the first one to accept that it is very ambitious and maybe it will turn out to be too ambitious. Fair enough, but I gave you some other elements which allow you to benchmark the objective against the actual policy instruments which have been put in place now.

SPK_1: Thank you. Can you tell me also about the initiative that the European Commission takes in order to really push the countries to adopt hydrogen in industries? And you speak about the ETS, but are there also subsidies or incentives?

SPK_2: So there's no single answer to this question. But let me give you some relevance. First of all, under the "REFUEL EU" initiative which I mentioned earlier, there are targets which the EU collectively has to meet. And behind that is a governance regulation, which basically provides a yearly update on the contribution of Member States to a given target. And if we're not on the trajectory to meet this target, we can take additional measures. So the current objective should allow us to reach the emission reduction target of 2030 of the climate law. But this governance system ensures that we keep track of whether we're on the path to achieving it. And if we're not on track, additional measures can be taken. It is a bit of a complicated system, and the reason for that is that a target is not specific to a given country. Because some countries may find it very cheap to decarbonize their economy in fashion A, while other countries may find it more cost-effective to do it in a fashion, B. And so it is, it is a collective mechanism basically, which overall seeks to achieve this 2030 target. And there is a system around it, a peer review system maybe is the way to say it, to make sure that everybody does its own part of the job.

Just to be very concrete, for instance, one of the targets on the industry relates to the decarbonization of current hydrogen production. But the current hydrogen production is very much related to the structure of the chemical industry, which again each Member State has. And the other thing is, as most hydrogen production is focused in the Netherlands, Germany, and Poland. So, of course, every country has a little bit, but most of it is there.

Now, could we therefore impose the same hydrogen decarbonization targets on all countries? I would say no, the benchmark should be decarbonization existing in these SMR technologies which I have highly admitted. And therefore, the target should be defined in a way that focuses on those countries. But it doesn't mean that the other countries have to do nothing. It just means that they have to choose other areas where they will reduce their emissions in order to collectively reach the target. So there's a possibility of that. No Member State is the same, so it means that you have to leave some flexibility and do some intelligent target setting to make sure you reach the target, but everybody has a target that makes sense within the context of their own economic structure, basically. So this is a bit okay, it's a very short way of explaining a complex problem, yes.

SPK_1: About transport, mostly hydrogen usage in transport: Do you have any plans if we will use fuel cell technologies or more synthetic fuels for or other techonolgies, or you don't have any?

SPK_2: So there are various instruments. First of all, on the negotiations for the moment for having duty transportation, there is an emission target. That is one thing. An emission target says that you have to meet an emission target, but it doesn't say how you do that. So whether you electrify it or use hydrogen or another type of synthetic fuel, that is left to the sector. This is done deliberately because the same is true for the transportation target in the Renewables Directive as well. There is a renewables target for that sector, knowing that the most efficient way of doing that is using hydrogen or derivatives. So we know that it will push hydrogen production and consumption, but nonetheless, the means to decarbonize the fleet are left basically to the economic incentives of the operators. So the technology choices do not depend on technocrats who try to second guess what the most efficient technology is, but rather on the most cost-efficient means of decarbonization found within the sector itself. That's maybe the way to formulate it.

SPK_2: So the technology choices are not ours. It is about the objective of where you need to be in terms of decarbonization at a given moment in time.

SPK_1: Okay. And then it's, yes, more an economic question of cost-effectiveness.

SPK_2: Exactly.

SPK_2: So that doesn't mean that we're completely naive about what is going to be used because the targets, of course, are also set with the knowledge that we need a hydrogen value chain. There are targets where we know that one of the more cost-efficient ways of doing that is to use hydrogen or derivatives. But in the end, the choice is left to the sector. In some sectors, particularly in heavy-duty transportation, where it is not certain which technology will eventually prevail or what kind of applications will be used, whether synthetic fuels or electrification, it is not evident that setting such a target will automatically lead to higher consumption of hydrogen. It's the market. You set the targets, and then the market determines how it goes, okay, okay.

SPK_2: You were also asking about subsidies? It's a bit complicated. Traditionally, under such instruments, the Member States pay for the targets. But things are changing.

SPK_2: Okay, so already for a few years, there are funds that the Commission manages, like the regional funds or the recovery resilience funds, where part of the money is earmarked for decarbonization purposes. This doesn't mean it's dedicated solely to hydrogen production, but member states have to use this money for decarbonization purposes. This can include various things, such as funding for housing insulation, subsidizing electrification of passenger cars, or building fuel stations and charging stations for electric cars.

By the way, there's a new financing instrument called the Hydrogen Bank. I don't know if you've heard of it, but this is an instrument for development, and it's the first time there's a real subsidy auction-type of instrument being built on the EU governance. The funds for this come from ETS (Emission Trading Scheme) revenues. The Innovation Fund, which is part of this, has set up an auctioning system for projects focused on supporting hydrogen and its derivatives.

SPK_1: Okay, so this is very new.

SPK_2: Yes, it's brand new. The first auction is still in development and is supposed to take place before the end of the year, but you can find information on it. The idea is to use a double-sided auction to allocate the funds. This won't finance the entire value chain, but it's a relatively new part of the subsidy landscape being developed.

SPK_1: For the ETS, for now, it's about certain sectors like industries, electricity production, but in transportation, it's going to come in, right? I think in 2027. Is that possible?

SPK_2: That is correct, yes. The ETS is currently focused on certain sectors, including industries and electricity production. But if we talk about hydrogen in general, it has applications beyond transportation. The Innovation Fund seeks to support projects for hydrogen production in general, including industrial applications. It's true that the ETS doesn't currently cover transportation, but considering its support for the development of the hydrogen value chain, the Innovation Fund will play a role in ensuring that decarbonization in transportation occurs, either due to the ETS or the targets set for aviation, heavy-duty vehicles, or maritime transportation under the latest directives. These targets will apply starting from tomorrow, basically. Even if sectors don't fall under the ETS, it doesn't mean they have no targets or instruments pushing for decarbonization.

SPK_1: If I can ask one last question, what do you see as the biggest challenges for the development of the hydrogen value chain in Europe? More technical or economic aspects?

SPK_2: In terms of technology, there's uncertainty about which technology will dominate hydrogen production, but overall, the technologies have a high Technology Readiness Level (TRL). Europe is particularly strong in PEM electrolyzers. So, I'm not too concerned in that regard. The question is whether Europe is the most cost-effective place to produce hydrogen. To make it economically viable, you need to have sufficient renewable energy sources like solar and wind to support the electrolyzers and produce green hydrogen. Producing hydrogen is not so difficult, but producing green hydrogen is more challenging.

It's important to assess if the necessary conditions for green hydrogen production are met in Europe. Some parts of Europe are well-positioned, but there will likely be imports. The question is how much, by when, and through what means. Minimum infrastructure is needed for importation to be viable. Some Member States, like Germany and Ireland, already recognize that their industries require more hydrogen than they can produce domestically. In terms of transportation, it's not likely to be economical to transport hydrogen by pipeline for long distances. For shipping purposes, it's preferable to transport hydrogen derivatives like liquefied hydrogen or ammonia. Ammonia can be converted back into hydrogen, and the infrastructure for ammonia imports already exists. However, this method incurs efficiency losses, so it may not be the main form of importing hydrogen. If you're interested, you can find interesting information on this topic from organizations like the DOC and IRENA (International Renewable Energy Agency).

SPK_1: I'll check their website. It was very helpful. Thank you very much

B. Interview transcript Baptiste COSTA-MARINI (FR, original)

SPK_1
Bonjour, je vais vous présenter en quelques mots mon mémoire. Donc moi je fais un mémoire sur l'hydrogène, sur le déploiement de l'hydrogène vert pour le secteur du transport en Belgique. Et donc j'essaie vraiment en fait d'étudier un peu l'ordre dans le déploiement pour comprendre comment arriver à lier l'offre et la demande. Je m'intéresse surtout aux transports lourds. C'est pour ça que avoir une interview avec Fluxys gestionnaire du réseau, ça m'aide beaucoup et du coup, comme première question je voudrais vous demander juste d'expliquer quel est votre job chez Fluxys et de parler un peu de votre rôle en tant que gestionnaire du réseau ?

SPK_2
Je travaille depuis 5 ans chez Fluxys et j'ai travaillé avant chez Air Liquide, déjà dans l'hydrogène. Je travaille depuis 3 ans au développement des réseaux H2 et CO2. J'étais au début business analyst pour analyser différentes chaînes de valeurs d'hydrogène et ses dérives et de CCUS, pour voir ou est-ce qu'il serait le plus intéressant pour Fluxys de se positionner, et au développement commercial en charge de market intelligence et de fronting commercial. Je suis maintenant uniquement dédié au développement commercial, responsables sales et marketing de la partie francophone.

SPK_1
Ca va merci. Et donc exactement pour Fluxys, là c'est tout ce qui est plutôt vraiment sales, c'est ça ?

SPK_2
Oui, développement commercial des infrastructures principalement.

SPK_1
Dans ce qui est du réseau actuellement d'hydrogène en Belgique, vous savez quelles sont déjà les infrastructures existantes, ce qui est déjà développé, ce qui existe déjà ?

SPK_2
Ce qui existe déjà, c'est les pipelines d'Air Liquide, qui ne sont pas à fluxys.

SPK_1
Et ou passent-t-elles ? Il y a déjà beaucoup de kilomètres de développer en termes d'infrastructures ?

SPK_2
Vous pouvez regarder sur leur site, il y une carte de leur réseau, ils ont déjà pas mal de kilomètres.

SPK_1
Quels sont les projets en déploiement actuellement et quel est un peu le timing dans le déploiement ?

SPK_2
On développe des infrastructures, donc que vous trouverez également sur notre site web, mais donc on a un projet de développement des infrastructures. Je vais trouver un visuel sera sûrement plus simple.

Voici un processus commercial. Voilà un peu la carte de comment ce qu'on voit le développement des infrastructures. Alors de quoi fournir, enfin desservir les réseaux industriels, les clusters industriels de Gand, Anvers et au sud du pays, Liège Mons, Charleroi et Bruxelles.

En fait, comment est-ce qu'on voit ça ? Ce serait plutôt dans un premier temps, on va commencer 2026 avec les réseaux de Gand et Anvers et on développe un réseau international cross-border avec le cluster de Valenciennes en France, qui sera fait donc lui du côté français.
En fait, la stratégie fédérale hydrogène souhaite avoir dès 2028 une interconnexion avec les pays frontaliers qui sont l'Allemagne, les Pays-Bas et la France. Donc nous, on aura déjà une interconnexion avec les Pays-Bas à Gand, avec la France à Mons, donc ce qui est reste est l'Allemagne et donc pour ça on développe des infrastructures pour servir le canal Albert, Liège et donc là on peut interconnecter avec les clusters industriels de Chemelot et avec l'Allemagne.

Et ça, c'est la vision un peu 2028 et le reste viendra en 2030 et plus. Pour permettre l'approvisionnement, nous développons un projet de terminal à Anvers, on en développe un autre a Zeebrugge. On prévoit également à Zeebrugge l'approvisionnement avec des pipelines offshore, qui devraient pouvoir connecter les électrolyseurs qui seront en mer du Nord, la Norvège, le Royaume-Uni et surtout pouvoir alimenter principalement l'Allemagne. Enfin, la Belgique, bien sûr, mais principalement Allemagne et également le Luxembourg.

SPK_1
Oui OK, et pour développer tout ce réseau, vous vous basez plutôt sur la rénovation d'un réseau déjà ancien de gaz existant, ou c'est vraiment toutes des nouvelles pipelines ?

SPK_2
Alors on a un mélange au début, on va commencer par des nouvelles pipelines, tout simplement parce que les gens continuent d'utiliser du gaz naturel, donc on peut pas les déconnecter. Dans le futur, on envisage de réutiliser, on a le « repurposing » en fait.

En Belgique, on n'a pas qu'un seul réseau de gaz naturel, on en a 2, on a le bas calorifique qui est alimenté par le gaz néerlandais et on a le haut calorifique qui est alimenté à peu près par n'importe où, c'est-à-dire la Norvège, le gaz qatari, le gaz américain. Tout ça, c'est du gaz, dit haut calorifique.
Les Néerlandais sont en train d'arrêter leur production, du coup, on va passer tout le monde sur le gaz riche, donc ça va de libérer un petit peu de pipelines. On développe aussi des infrastructures CO2 donc après voilà, ce sera une optimisation entre est ce que c'est mieux de l'utiliser pour le gaz naturel, l'hydrogène ou le CO2.

Maintenant, il y a quand même eu l'impact de la guerre en Ukraine qui fait que tout le centre et l'Est de l'Europe, qui avant étaient alimenté par la Russie, maintenant est alimenté en grande partie en tout cas par l'Ouest de l'Europe, que ce soit par le gaz qui vient du Royaume-Uni, de Norvège par des terminaux LNG, donc ceux de Fluxys qui sont à Zeebrugge et à Dunkerque.

Et donc ça va de l'Ouest vers l'Est, là où avant les flux en Europe étaient plutôt de l'Est vers l'Ouest. Et donc du coup ça veut dire que toutes ces infrastructures sont utilisées pour l'instant à forte capacité, donc ça laisse pas tant de possibilités que ça pour le « repurposing ».

SPK_1
Quand on change comme ça des pipelines pour transporter différents gaz, ça demande beaucoup de changement ?

SPK_2
Principalement tout ce qui est valve. Tous les points d'attention, c'est les soudures aussi.
Techniquement, le tube marche, la plus grosse problématique, c'est comment est-ce qu'on continue d'alimenter les clients qui, sur un tube peuvent être connectés à différents endroits ? Donc c'est plus ça la problématique, la gestion des flux de gaz. Il y a aussi des problématiques techniques, mais elles sont résolues, ça veut pas dire que toutes les pipelines peuvent être réutilisés. Notre réseau, il n'est pas unique. Il a été construit sur 100 ans, avec des pipelines de qualité différentes, qui ont eu un usage différent, qui sont en plus ou moins bons états et à priori il n'y a pas de problème technique à réutiliser la grosse partie.

SPK_1
Pour ce qui est de la sécurité avec l'hydrogène, il faut plus se tracasser de ça dans l'exploitation, c'est plus contraignant ou ça va ?

SPK_2
Ce qui est plus problématique que sur le gaz naturel, c'est qu'on peut moins jouer sur les variations de pression donc par rapport au gaz naturel en fait, ce qui se passe, c'est que l'hydrogène va « rentrer » dans l'acier, quand on augmente la pression et en ressortir quand on baisse la pression. Ce phénomène peut fatiguer, user l'acier et donc on peut moins varier, ce qui offre moins de flexibilité qu'avec du méthane par exemple, là où on a une plus grande plage de flexibilité. On peut s'amuser à plus varier sur la pression pour jouer sur le volume de gaz et adapter les écarts entre le gaz qui est mis dans le réseau et ce qui est pris du réseau.

SPK_1
En termes de de capacité sinon pour des pipelines, qu'est-ce que ça donne ?

SPK_2
En capacité énergétique globalement, le rapport est que l'hydrogène étant moins dense que le gaz naturel à pression égale, on aura 3X moins d'énergie mais vu qu'il se déplace 3 fois plus vite, ça s'équivaut en flux. Pour les besoins en mobilité, c'est pas un problème.

SPK_1
En termes de de coût de développement du réseau, vous savez me donner une idée ?

SPK_2
C'est confidentiel.

SPK_1
Est-ce que le gouvernement belge, l'Europe soutiennent beaucoup le développement du réseau d'hydrogène ? Enfin, quelles sont les politiques mises en place ?

SPK_2
Il faut regarder la stratégie fédérale. L'Europe a donné de l'argent à la Belgique, la Belgique l'a donné en partie à Fluxys via le « recovery plan ». Après on calcule nos tarifs en fonction de l'amortissement de nos assets. Si on a des subventions, ça baisse le prix des assets, ça permet de baisser les tarifs pour une souscription de capacité similaire, mais pour nous ça change pas notre revenu.

Si on a pas de soutien public, on va construire pour les besoins actuels parce que aucune entreprise privée va investir à perte ou sans minimum de contrat commercial. Et du coup, on devra reconstruire ou augmenter les capacités d'une façon et ça aura un coût là où ça aurait été plus efficace de poser un pipeline de plus grosse capacité directement.

La Belgique a mis un peu de soutien mais n'a pas mis énormément comme nos voisins Néerlandais par exemple.

Ce qui manque surtout pour l'hydrogène, c'est des soutiens sur la molécule, hein. Le prix du transport, c'est quasiment rien dans l'équation par rapport au prix de la commodité. Quoi qu'on dise, l'équation est assez simple aujourd'hui, on utilise du gaz naturel pour faire de l'électricité, donc t'as un facteur, t'as un rendement, t'as quelqu'un qui prend une commission, t'as des CAPEX et des OPEX, donc ça coûte plus cher. Si tu transformes 60% de ton énergie de gaz naturel en électricité tu peux plus ou moins penser que ton prix de gaz naturel est 60% du prix de l'électricité. Ton électricité tu l'utilises pour faire de l'hydrogène. T'as probablement une efficacité qui est entre 60, 70% mais donc ça veut dire que ton prix d'électricité à peu près 60% du prix de l'hydrogène donc tu vois bien que t'arrives avec un prix de l'hydrogène qui est au-dessus du prix du gaz naturel.

Globalement, aujourd'hui, il n'y a pas de secret. Aujourd'hui, le gaz naturel est utilisé pour la flexibilité du réseau électrique, donc détermine les prix de marché électrique. Donc, l'hydrogène vert reste plus cher et pas compétitif.

SPK_1
Vous collaborez beaucoup avec des entreprises privées pour développer le réseau d'hydrogène ici en Belgique?

SPK_2
Tu dois différencier ce qui est partenariat et clients. De tout de façon, nous on ne fournit que l'infrastructure, faut qu'il y ait quelqu'un qui l'utilise, donc c'est oui, on parle bien avec les producteurs comme avec les consommateurs potentiels, on tire un peu le marché. On facilite, on est le seul acteur neutre sur le marché. Vu qu'on achète pas les molécules et qu'on vend pas les molécules, on est le seul acteur neutre comparé à un producteur ou un consommateur.
Donc on est un peu le point central qui parle avec tout le monde. On va pas construire un pipeline s'il y a pas de molécules qui sont produites par un acteur et qui sont achetées par un autre un peu plus loin.

SPK_1
Ok.

SPK_1
L'horizon de fluxys, c'est à 2030 ? il n'y a pas d'horizon plus loin ?

SPK_2
Tu peux t'amuser à faire des plans jusqu'à 2050, mais il y a encore beaucoup de facteurs différents qui vont influencer donc 2030 c'est déjà pas mal. C'est le marché qui va décider, c'est pas nous. On le sait, si un industriel veut de l'hydrogène, on posera un pipeline.
Les choses qui sont un peu plus top down on va dire que bottom up, c'est les interconnexions avec les autres pays. Clairement avec la Norvège, on aimerait bien développer des interconnexions, mais c'est vrai que au niveau fédéral, il y a pas un grand push pour ça ou avec le UK, donc là c'est des choses sur lesquelles tu vas rentrer dans des choses qui sont plus politiques. On sait qu'on a besoin de développer des terminaux parce qu'on sait qu'on va devoir importer l'hydrogène d'ailleurs qui sera produit moins cher. On sait que l'Allemagne a des besoins. On sait que la mer du Nord globalement et principalement le Royaume-Uni, et la Norvège sont des gros producteurs futurs, autant d'hydrogène bleu que d'hydrogène vert. C'est des choses qui peuvent un peu plus se décider où se prévoir. Mais derrière tu vois si c'est pour dire, « est-ce qu'on va aller sur la rive gauche ou la rive droite d'Anvers » ? C'est des clients qui vont signer les contrats qui vont décider.

SPK_1
Vous pensez qu'on va vraiment arriver à devenir fort développé en hydrogène en 2050 personnellement ou vous pensez que c'est pas quelque chose qui va prendre ?

SPK_2
Oui, ça va prendre. Il y a déjà un marché hydrogène, il y a déjà 15 TWh qui sont produits et consommés en Belgique aujourd'hui. Donc ça existe, mais aujourd'hui c'est un marché de niche. C'est pas une commodité comme le gaz naturel énergétique. Maintenant, est-ce que ce sera ce qu'on veut, c'est à dire le graal ? Non. Est-ce que ce sera plus qu'aujourd'hui ? Sûrement que ça arrivera quelque part entre les 2, on aura besoin dans tous les cas d'hydrocarbones, de chaînes avec de l'hydrogène.

Maintenant, est ce qu'il est plus efficace énergétiquement d'aller capturer du CO2d'un hydrocarbone qu'on casse et qu'on travaille, on va dire comme les produits pétroliers, ou est ce qu'il est plus efficace de les reconstruire soi-même à partir d'hydrogène et de CO2 ? Il y aura surement les deux.

On aura besoin aussi de molécules pour balancer les différences entre la production et la consommation électrique. C'est bien d'électrifier, mais aujourd'hui, la flexibilité du réseau électrique est assurée par les centrales au gaz. Ce sera encore le cas et ce sera encore plus le cas parce qu'on aura encore plus besoin dans le futur parce qu'on aura plus aucune unité qui est prévisible comme une centrale nucléaire, comme une centrale à charbon. A des moments il y aura trop de production et les batteries ne vont pas suffire pour l'absorber. Il y a des moments où il n'y aura pas cette production et on aura en plus électrifié beaucoup d'usage (chauffage, mobilité,…) donc on ne pourra pas dire aux gens « il y a 2 semaines ou il n'y a pas de production électrique. »

Donc voilà, il faudra des centrales à gaz qu'on va essayer de décarboniser, par exemple à l'hydrogène ou autre. De là à dire quel sera le vrai volume… Et puis, forcément, une fois qu'on aura ces centrales à gaz, oui, pourquoi pas les faire tourner un peu plus en important de l'hydrogène, qui est moins cher là-bas, parce qu'au final, qu'est ce qui est le plus efficace entre mettre un panneau solaire ici ou au milieu du Sahara… Il y a aussi une question de manque de place qui fait que pour nos besoins énergétiques actuels, la production renouvelable, en tout cas en Belgique ne va pas suffire. Il est plus facile de déplacer des molécules que des électrons.
L'hydrogène va beaucoup être transformé, c'est-à-dire que si on a besoin de molécules dérivés à partir d'hydrogène, on va sûrement produire ces molécules directement et en fait, on ne verra pas d'hydrogène en tant que tel. Si tu as besoin de bio kérosène, tu combines du CO2 ou du carbone avec de l'hydrogène pour fabriquer les hydrocarbones, tu le verras peut-être pas repasser en hydrogène. Là, aujourd'hui, on pense que tout ça, c'est des marchés hydrogènes. Ça sera des technologies hydrogène, mais ce que t'auras vraiment les infrastructures hydrogène ? Pour une partie, mais pas nécessairement pour tout…

SPK_1
Voulez-rajouter quelque chose sur l'hydrogène ?

SPK_2
Si, peut-être en fait, si tu veux, la question n'est pas, est-ce que c'est le meilleur outil ou pas ? C'est celui qu'on a choisi d'utiliser en combinaison de l'électrification. À partir du moment où tu as des milliards qui sont déployés en Chine, en Europe, aux États-Unis, pour construire les chaînes de valeur, pour développer les technologies, ça aura un rôle parce que simplement en fait, si tu déverses des centaines de milliards dans une technologie, tu vas finir par arriver sur des choses intéressantes, c'est mathématique. C'est de la politique industrielle. Et vu que le momentum que ça a, le fait que ce soit un buzz veut dire que ce sera une réalité en partie. Maintenant, c'est sûr que ça ne va pas répondre à toutes les attentes. Ca ne va pas être la panacée qu'on dit. On ne s'attend pas à ce que les réseaux d'hydrogène ressemblent au réseau de gaz naturel aujourd'hui, ça- ne va pas remplacer le gaz naturel. Maintenant, oui, il y aura des réseaux d'hydrogène qui seront interconnectés en Europe entre les pays, voilà et qui vont servir sûrement quelques clusters industriels où il y aura aussi les centrales à gaz qui seront connectées.

Maintenant pour le secteur de la mobilité, je ne suis pas sûr que la chaîne de distribution d'hydrogène passera par des pipelines. Ce sont des volumes qui sont trop petits. On ne va pas poser des pipelines pour une station-service qui prend 2 tonnes par jour, c'est trop petit pour la taille de nos réseaux. Si on passe, on la connecte si ils sont à 500 M du tracé…Maintenant si ils ne passent pas sur le tracé, on va pas le déplacer nous et de toute façon, tu dois comprimer, est-ce que tu serais pas mieux de le déplacer autrement ?
Donc t'auras les 2, parce que effectivement il y aura des clusters industriels qui sont aussi là où y a l'activité économique, qui sont aussi là où il y a les flux de poids lourds, trains et du coup ça fait des endroits où tu peux faire des stations connectées au réseau et ça ne sera pas cher et ça sera la meilleure option. Mais il n'est pas dit que la plupart des stations seront connectées à un pipeline.

SPK_1
Merci pour vos réponses !

C. Interview transcript Pierre JORIS (FR, original)

Merci d'avoir pris contact avec la société JOST.
Nous sommes honorés d'être un interlocuteur autour de la question de l'hydrogène.

Ensuite, pour répondre à votre thématique, à l'heure actuelle, nous ne pouvons pas envisager l'hydrogène comme solution viable à court terme pour le transport car :

1. Il n'existe pas encore de véritable solution pour les véhicules.
2. L'hydrogène actuellement produit est plus polluant que le LNG (Liquefied Natural Gas) et son prix est dépendant de ce même LNG.
3. Le réseau de distribution n'est pas encore développé. Faible nombre de stations de ravitaillement sur le territoire.
4. L'hydrogène reste instable.

5. Le prix élevé des véhicules et du carburant.
6. Etc.

JOST a pris la direction d’investir dans le LNG qui se positionne comme une énergie de transition plus verte que le diesel.
C’est un projet à plusieurs dizaines de millions d’euros comprenant une flotte de 500 véhicules, 3 stations LNG et deux camions-citernes pour effectuer le transfert de LNG entre le port de Zeebrugge et nos différentes stations.

L’hydrogène sera une solution pour le futur uniquement lorsqu’une issue sera trouvée pour décarboner sa production (avoir uniquement de l’hydrogène vert et non plus bleu ou gris) et avoir la possibilité de le stocker.

J’espère que ces éléments de réponse pourront vous aider dans la rédaction de votre mémoire.

D. Interview transcript Daniel MARENNE (FR, original)

SPK_2 : Quel est votre parcours chez Engie ?

SPK_1 : Voilà, alors en fait, j'ai commencé en 2000, donc je travaillais chez Engie Electrabel. À l'époque, en 2009, on m'a attribué comme mission, si tu veux, de développer la mobilité électrique. C'était en 2009, il n'y avait pas de voitures électriques qui roulaient donc et je commençais à regarder si c'était possible. Le business aujourd'hui, tout ça, tu vois ? En 2013, 2014, je me suis intéressé à l'hydrogène, mais pas pour la mobilité. Parce qu'à l'époque, quand tu travailles sur la mobilité électrique, tu te dis que la mobilité hydrogène, ça n'a tout simplement aucun sens. Ouais, en termes de rendement et tout ce que tu veux, ça n'a aucun sens. Et j'ai commencé à m'intéresser à l'hydrogène vers 2016 on va dire. Un peu plus, et pour faire des projets en gros. À l'époque, le seul business model qui semblait tenir la route pour de l'hydrogène vert, c'était la mobilité.

Et donc on a commencé à regarder comment produire de l'hydrogène le moins cher possible. Et se connecter le plus près possible d'une source électrique, parce que sinon tu as tous les frais de réseau distribution et tout qui vont faire augmenter les coûts de l'hydrogène. Alors que tu peux les éviter si tu te connectes directement à une centrale électrique. Mais il faut que cette source soit verte et qu'elle fonctionne en continu, c'est-à-dire 8000 heures par an. Et il n'y en a qu'une seule qui le fait au niveau de la production d'énergie, ce sont les incinérateurs de déchets qui produisent beaucoup en continu, car en fait, lorsque tu produis en continu, le coût de ton investissement initial (capex) est amorti sur les 8000 heures de fonctionnement.

Comment amortir sur les 8 milles heures de fonctionnement si tu te branches, par exemple, sur ce que tout le monde rêve, des panneaux solaires ou des éoliennes ? Eh bien, les panneaux solaires ne fonctionnent que 1000 heures par an, soit 1000 heures comparées à 8000 heures. Donc en gros, le coût de l'investissement initial sera plus de 8 fois plus cher. Et si tu fais ça avec une éolienne, qui fonctionne 2000 heures par an, cela signifie que tu auras un coût 4 fois plus cher pour la partie capex, c'est-à-dire l'investissement, qui aujourd'hui encore, coûte très cher. Donc si tu peux réduire au maximum le coût initial (capex) en travaillant 8000 heures par an, c'est mieux. Donc l'idée était de se mettre près d'un incinérateur de déchets, avant qu'il ne se connecte au réseau, et de produire là de l'hydrogène, principalement pour la mobilité lourde, plutôt que la mobilité légère, c'est-à-dire les voitures.

Pour moi, cela n'a aucun sens de produire de l'hydrogène pour la mobilité légère, pour des raisons de rendement. Même maintenant, je pense que ça n'aura jamais aucun sens, mais c'est mon avis. En fait, avec une voiture électrique, quand tu charges une batterie et que tu utilises ensuite l'électricité pour les roues, tu as une perte de rendement de 15%. Donc en gros, 80% de l'électricité, tu peux l'utiliser pour la mobilité. Si tu fais de l'hydrogène, tu vas d'abord perdre 30% ou 35% pour produire de l'hydrogène, et tu perds encore 50% pour utiliser... Tu vois le ratio entre l'énergie électrique produite par une source renouvelable et celle que tu utilises pour la mobilité c'est 30%.

SPK_1 : Mais alors, dans ce cas-là, l'électricité produite par un incinérateur de déchets, elle n'est pas verte ?

SPK_1 : En fait, dans un incinérateur de déchets, une partie des déchets provient de la biomasse, et cela est considéré comme vert au niveau européen. À l'époque, c'était considéré comme vert, car ils recevaient des garanties d'origine d'électricité verte pour 50%.

SPK_1 : Donc l'idée était de mettre des électrolyseurs qui n'utilisaient pas plus de 50% de la capacité électrique de l'incinérateur, de manière à pouvoir dire que je n'utilise que de l'électricité verte pour produire. Depuis lors, les régulations ont changé, et l'utilisation de l'électricité provenant de ce type d'installation n'est plus autorisée dans le cadre de la mobilité. C'est bien dommage, car honnêtement, c'était ce qu'il y avait de moins cher, mais l'Europe ne favorise pas du tout le pragmatisme et le moins cher, voilà.

Alors du coup, j'ai commencé par faire ces électrolyseurs pour la mobilité, mais je me suis très vite rendu compte aussi d'un point, c'est que la mobilité hydrogène, tout le monde en parle, mais personne ne le fait. En ce qui concerne les voitures, il y a royalement, peut-être 10 voitures qui roulent à l'hydrogène en Belgique, sur 6 000 000 de voitures, ça fait pas beaucoup. Comme il n'y a pas de pompes, rien du tout. De toute façon, il n'y a pas de raison qu'il y en ait plus, puisque je ne sais pas comment les gens pourraient avoir ça. L'idée était plutôt de regarder les mobilités où on n'avait pas vraiment besoin d'infrastructures de chargement.

Donc, typiquement, ce qu'on appelle les « Milk run », c'est-à-dire le style de livreur qui fait son tour et revient toujours au même point. Et donc, dans ce cas-là, tu avais 2 types de mobilité à l'hydrogène. Ceux qui avait quand même un intérêt, c'étaient les bus, typiquement les bus des villes où il y a un dépôt. Ils reviennent toujours au même dépôt. Et les camions poubelles, parce que les camions poubelles, ils reviennent d'office d'un incinérateur ou du traitement des déchets. Donc, c'est pour ça qu'on a visé cette technologie-là. Seul problème, c'est qu'on a fait un projet pour donner un ordre de grandeur, environ 10 bus dans la région de Charleroi qui fonctionnaient de manière très importante, 60 000 km par an, ce qui n'arrive normalement pas, la moyenne des bus c'est 30 000 km, mais certains bus pouvaient faire plus. Le besoin en électrolyseur, c'est 500 kilowatts d'électrolyse. Or, maintenant on me demande de développer des projets où on parle de plus de 100 mégawatts. Donc, la mobilité, ce n'est juste pas possible… J'ai essayé de dire oui, mais peut-être qu'on peut acheter plus de bus ? Sauf que lorsque tu demandes ça aux fabricants, ils disent qu'ils n'ont pas les usines. Donc aujourd'hui, tout ce qui concerne la mobilité à l'hydrogène est réalisé par des ingénieurs dans les ateliers. Il n'y a pas du tout de ligne de production prévue. Donc ça va arriver, mais au mieux en 2030. Donc si tu veux accélérer la transition vers l'hydrogène, tu te dis que tu ne peux pas rester uniquement sur l'utilisation directe de l'hydrogène pour la mobilité.

SPK_1: Donc j'ai commencé à explorer une autre forme d'utilisation de l'hydrogène pour la mobilité, qui consiste à produire des carburants synthétiques.

SPK_2: D'accord.

SPK_1: C'était comme au niveau européen en 2018, il y a un texte qui est sorti, qui était la RED II (Directive sur les Énergies Renouvelables II). Alors, on a mis beaucoup de temps à le voir et même les actes délégués, c'est-à-dire les règles de fonctionnement, ne sont pas encore complètement définis. Donc RED II a défini un concept qui était les RFNBO (Raffineries de Carburants Néosynthétiques à Base d'Origine Logique). En gros, cela concerne tout ce qui ne provient pas de la biomasse, et dans cette définition, on peut utiliser du CO2 capturé quelque part et de l'hydrogène qui doit être vert.

Donc, si on combine les deux pour produire des carburants synthétiques, cela peut être du méthane, du méthanol ou du diesel. Cela entre dans des catégories considérées comme renouvelables et qui peuvent être incluses dans les quotas que les raffineurs doivent atteindre pour leurs carburants actuels. En fait, il faut savoir que dans le cadre de la décarbonisation de l'économie, l'Europe fixe des quotas. Par exemple, actuellement, il y a une obligation d'ajouter 10% de bioéthanol dans l'essence (le B10) et 7% de biodiesel dans le diesel (le B7). Ces quotas vont doubler d'ici à 2030. Et maintenant, c'est même plus. L'objectif est de doubler ces quotas, sachant qu'au départ, nous avions déjà, plus ou moins, exploité toutes les options simples, c'est-à-dire les carburants de première génération.

Pour passer à des carburants plus complexes, cela sera plus cher et plus compliqué, et les règles de durabilité pour les carburants se renforcent. Par exemple, les diesels ont été largement produits avec de l'huile de palme soi-disant issue de forêts durablement gérées en Indonésie. Mais il faut savoir que les certifications de durabilité en Indonésie sont plutôt douteuses. On peut obtenir un certificat de durabilité pour à peu près n'importe quoi, même si ça n'a aucun sens. C'est juste du papier. Au pire, ils utiliseront ce qui n'a pas été déforesté avant 2009, où il y avait déjà des plantations de palmiers à huile, et ils l'utiliseront pour les marchés européens, tout en développant le reste. Donc, cela n'a aucun sens. L'Europe s'est rendu compte qu'elle avait fait une erreur dans cette histoire, donc il y a toute une partie de la politique qui va réduire les biocarburants à l'utilisation exclusive des déchets. Donc, cela rend le défi beaucoup plus complexe. C'est là que le marché pour l'hydrogène associé au CO2 pour produire des carburants synthétiques entre en jeu. Et là, on parle d'installations de taille énorme, de l'ordre de plusieurs centaines de mégawatts. Ce sont de gros projets. Et comme nous avons des centrales électriques où nous avons la possibilité de disposer de ces connexions électriques, nous avons un avantage concurrentiel par rapport à d'autres qui démarrent au milieu des champs. Donc, il était intéressant pour nous de développer ce type de projet.

Voilà, depuis 2019, je travaille exclusivement sur de grands projets liés à l'hydrogène, mais pour la mobilité lourde, comme les camions, avec potentiellement du méthane ou du méthanol. Si nous commençons à utiliser des moteurs au méthanol pour les camions, depuis l'année dernière, en 2021, sont également venus s'ajouter les secteurs de l'aviation et du fioul maritime. Donc, pour les gros navires, le fioul lourd. Pour remplacer le fioul lourd actuel, nous avons les mêmes options, le méthanol ou le méthane.

Ces applications peuvent jouer un rôle majeur. Si l'on parle de projets d'énorme envergure, les besoins d'ici à 2030 sont gigantesques. Par exemple, une entreprise de transport comme Merck, qui possède de nombreux navires, parle de 6 millions de tonnes dont ils auront besoin d'ici à 2030, alors qu'aujourd'hui ils n'utilisent rien.

Et avec 100 mégawatts, qui fonctionnent pendant 8 000 heures par an, vous pouvez avoir une idée de la situation. Le sourcing reste de l'électricité renouvelable, vous devez donc jouer avec un peu de solaire, un peu d'éolien pour obtenir un taux de charge correct. Et cela représente une énorme quantité. De plus, ils savent que pour utiliser des biocarburants, il faudra changer de moteur. Par exemple, si nous passons au méthane, ils ont déjà adapté les moteurs au gaz naturel, que ce soit du biométhane ou du méthane, c'est la même chose. Ce n'est pas une adaptation très compliquée par rapport au moteur actuel, et c'est surtout un système dual fuel, ce qui leur permet de passer de l'un à l'autre et de revenir à chaque fois. Donc, ils peuvent encore utiliser ce qui est déjà sur le marché. C'est une situation moins risquée pour eux, moins coûteuse en termes d'investissement, car il s'agit simplement de changer les moteurs et d'ajouter un peu de stockage si nécessaire, mais sous forme liquide, ce qui n'est pas un grand défi pour eux de le mettre sur leurs navires. Donc, cela revient beaucoup moins cher en termes d'adaptation. Maintenant, sur le marché maritime, cela fait moins d'un an, la plupart des grandes entreprises de transport qui n'avaient pas encore adopté le GNL commencent à acheter des moteurs dual fuel. Donc, nous savons que le marché va devenir énorme, car les motoristes, ceux qui vendent les moteurs pour les navires, achètent tous des moteurs pour le méthanol. Donc, on voit arriver le mur de la demande, et c'est du méthanol durable, c'est-à-dire que nous prenons de l'hydrogène et du CO_2 et nous en faisons du méthanol.

SPK_1: Donc, tu as un petit cours de chimie, c'est très simple. C'est CO_2 plus H_2 donne CH_4 si tu fais du méthane, et pour cela, tu as besoin de $4H_2$, sinon tu n'y arrives pas. Donc, c'est $2H_2$ plus CO_2 qui donne CH_3OH, ou CH_3OH plus $2H_2$.

SPK_2 : Donc, dans ce qui concerne la mobilité lourde pour les camions, on se tourne davantage vers les biocarburants que vers l'hydrogène qu'on utilise avec une pile à combustible par exemple ?

SPK_1: Alors oui et non. Certains s'intéressent quand même à l'hydrogène car c'est un effet de mode et cela fait bien d'avoir des camions à hydrogène, voire des trains à hydrogène. Les trains à hydrogène seront probablement plus simples, car tu connais Les lignes et donc tu peux mettre des stations de chargement d'hydrogène aux endroits le long de la ligne. Si tu fais des camions hydrogène, bah t'as le problème que l'infrastructure d'hydrogène n'existe pas et donc où est-ce que tu vas aller ? Enfin, quelles sont les premiers business models que tu vas pouvoir mettre en place sur de la mobilité lourde ?

Pour développer l'hydrogène, tu dois viser une certaine mobilité. Par exemple, si t'es en Belgique ne vise pas du transit international, ça marchera jamais parce que tu sais une fois que tu sors de la Belgique, tu rentres dans un autre monde dont tu connais pas les infrastructures… par contre tu as quand même une partie de la mobilité des containers ou des trucs qui arrivent en Belgique à destination de la Belgique, et donc du coup ils reviennent tous à Zeebruges ou à Anvers donc oui va là-bas éventuellement …

Certains entendent investir dans quelques camions, à des fins purement marketing pour des entreprises privées. Mais économiquement, pour l'instant, ça ne correspond pas au modèle commercial, ce n'est pas réalisable. Certains peuvent penser qu'il est préférable d'essayer un ou deux camions pour avoir une certaine expérience. Mais quand ils disent que c'est impossible d'essayer un camion, ils voient cela en fonction de certains aspects. Tu dois vraiment aller vers des niches où le client final est prêt à payer pour une mobilité complètement décarbonée. Si ton client final te dit : peu importe le coût, je paie. Alors, forcément, on trouvera une solution, sachant que normalement, le prix du carburant et le coût d'achat du camion ne représentent jamais plus de 15 à 20 % du coût total de la mobilité. Parce que le coût principal, c'est le chauffeur.

Le principal coût, c'est le chauffeur. Oui, OK, mais voilà, le problème du transport, c'est que c'est un marché très concurrentiel. Et donc, ce n'est pas pour rien qu'on recrute des chauffeurs dans les pays de l'Est. Euh, c'est vrai qu'en fait, ils sont, entre guillemets, en esclavage perpétuel, parce que dès qu'il y a le moindre surcoût, on ne l'a plus. Donc, on ne peut pas se permettre d'avoir que des chauffeurs belges, car avec toutes les lois sociales et le coût du travail en Belgique.

C'est le chauffeur qui coûte le plus cher. Maintenant, si tu doubles le coût de ton camion et que, en plus, tu as besoin d'hydrogène, eh bien, tous les modèles économiques sont impossibles... mais en même temps, en 2050, du point de vue européen, nous devons être neutres. Fondamentalement neutres. Donc, mon problème, c'est qu'en 2050, tout le monde est d'accord mais personne ne veut être le premier à faire le pas, tout le monde veut que ce soit ton voisin qui le fasse. Ensuite, il y a des économies d'échelle, bien sûr, car une fois que la filière est lancée, le prix des camions devrait baisser, mais pour cela il faut qu'il y ait des camions et il faut de l'infrastructure. Et en fait, c'est un problème. Nous l'avons vu avec les voitures électriques, il était très difficile d'avoir des infrastructures de recharge. Mais alors, pour la voiture électrique, tu pouvais charger 90 % à la maison, tu t'en fichais presque de l'infrastructure, alors que pour l'hydrogène, si tu n'as pas d'infrastructure, tu ne roules pas, n'est-ce pas ?

SPK_2 : Engie développe aussi des projets d'infrastructure de recharge ?

SPK_1 : En France, on le fait, OK, mais c'est à 100 % subventionné, il n'y a pratiquement rien. Si quelque part, nous sommes prestataires de services pour des communautés. En gros, s'il y a une communauté urbaine qui dit qu'elle veut de l'hydrogène ou une mobilité hydrogène, nous y allons. On le fait en France parce qu'on a une image à défendre. En France, on est un groupe français.

On l'aurait fait en Belgique si les politiques avaient un tout petit peu suivi. Mais comme ni à Bruxelles, ni en Wallonie, ni même en Flandre, il y a eu un seul politique qui s'est bougé pour nous....

SPK_2 : Et en Belgique, c'est surtout de la production d'hydrogène, alors des projets de production des « méga-factory ou quoi » ?

SPK_1 : Oui et non, parce qu'on a 2 projets mégas. Donc on a un projet à Charleroi, qui a un projet Colombus, donc qui sera en partie pour l'industrie et en partie pour la mobilité. Ça, c'est 100 mégawatts, et puis on a un gros projet dans le port de Gand pour faire du méthanol normalement, qui sera normalement plutôt pour la maritime. Il pourrait être utilisé aussi pour les camions, il pourrait, mais les moteurs dual fuel n'existent pas encore dans les camions, mais ça pourrait venir.

Le problème en Belgique, c'est qu'en fait, on n'a pas d'électricité, on n'en a pas assez. On a beaucoup trop peu d'électricité, d'électricité verte, quoi. Donc on veut arrêter les centrales nucléaires, on va arrêter la centrale à gaz, on veut mettre que du renouvelable sur les centrales à gaz. Mas on fait quoi après ?

L'hydrogène de l'Europe aujourd'hui, c'est un peu du n'importe quoi. En fait, ils ont des objectifs qui sont irréalistes. Leur objectif, oui, c'était énorme ce qu'ils veulent faire, mais c'est juste pas possible. Pour te donner un exemple assez facile à comprendre, on doit atteindre l'objectif de production d'hydrogène en Europe d'ici à 2030. En 7 ans, c'est 10 millions de tonnes d'hydrogène. Donc 10 millions de tonnes d'hydrogène produites avec de l'électricité renouvelable, si tu prends le pouvoir calorifique de l'hydrogène, c'est 330 térawattheures d'hydrogène dont tu as besoin, c'est ça.

La consommation totale de la Belgique en énergie, c'est 400 térawattheures, donc ça te donne une idée. Pour 330 térawattheures d'hydrogène, tu as besoin de 500 térawattheures d'électricité verte, , c'est ce que l'Europe des 27 a produite en énergie éolienne et solaire en 2019.

Ça, c'est déjà un premier problème, c'est où est-ce que tu vas aller chercher ton électricité verte ? Parce que oui, même 10 millions doivent être produits en dehors de l'Europe en plus de la production intérieur. Il y a déjà un problème, déjà là tu te dis, ah ouais quand même. Ensuite, tu te dis, OK, les électrolyseurs. Aujourd'hui, il n'y a pas d'usine. Les électrolyseurs, y en a pas de grandes à part en Chine. Oui, mais tu peux pas les amener en Europe parce qu'ils ne sont pas du tout aux normes, donc par exemple John Cockerill, qui est un fabricant belge, était en train de construire une usine pour adapter des modèles chinois au marché européen. Mais il construit seulement l'usine, maintenant elle sera opérationnelle au mieux en 2024. Et tu dois en sortir, si tu veux suivre ces électrolyseurs, à peu près 200 gigawatts. Un électrolyseur, c'est 5 mégawatts… c'est gigantesque. Et ça, ça doit être fait avant 2030. Alors que les usines n'existent pas. C'est une équation impossible.

Et donc, c'est trop loin. Comment fais-tu dans les cinq prochaines années pour modifier le truc et qu'est-ce qui est réaliste ? Ce qui est réaliste, c'est surtout la mobilité à l'hydrogène, oui, c'est réaliste pour certains... Certains secteurs, comme le transport lourd. Il y a des boucles, voilà, c'est ça le train. Si ce n'est pas électrifié, mais la question est de savoir s'il ne serait pas préférable de l'électrifier à la fin, car c'est nettement meilleur en termes de rendement.

SPK_2 : Et les camions électriques, ça a un avenir ?

SPK_1 : Oui, si tu redéfinis le modèle de la mobilité…Si tu arrives à avoir de grandes lignes, imagine de grandes voies ferrées qui transportent beaucoup, donc de conteneurs, tu arrives aux dépôts et ensuite tu distribues sur de courtes distances en camion électrique, ça fonctionne très bien.

Par contre si tu as besoin de faire beaucoup de rotations et que le plein pose un problème, pourquoi pas l'hydrogène ? Mais c'est une redéfinition complète, ça change tout.

Le tout est que si tu as une vision commerciale à ce sujet, ce que tout le monde a, je sais ce que j'ai aujourd'hui et je ne dois pas trop m'éloigner de ce que j'ai. Ce qui me rapporte des revenus, je sais comment les obtenir. Si je sors de ma zone de confort, je rentre dans quelque chose qui est complètement inconnu, n'est-ce pas ? C'est l'inconnu, l'industrie, le lien vers l'inconnu de l'après, tout ça.

SPK_2 : Quel est le prix de l’hydrogène actuellement?

SPK_1: Donc le rendement d'un électrolyseur, c'est 65%. Donc tu as 35% de perte. Avec un mégawattheure d'électricité, tu fais 650 kilowattheure d’hydrogène. Donc tu perds 35% et les pertes c'est de la chaleur à basse température donc en gros c'est rien en fait ça tu laisses tomber. Avec ça, tu sais que si tu as un mégawattheure à 50€ ou 100€ du mégawattheure et que tu veux faire 650 kilowattheures d'hydrogène, tu peux calculer ton côut de l’hydrogène, c’est une simple division. Après tu as le capex qui est aujourd'hui alors normalement c'est censé être 1000€ par kilowatt installé. En réalité avec après la crise et tout on est plutôt en 1600-1700€ du kilowatt aujourd'hui. Ça, tu dois l'amortir sur 20 ans, 15 ans. Et ça, ça a un coût. Tu dois générer plus de revenus pour payer ton coût capital. Si tu utilises 8000 heures par an ton électrolyseur, tu vas mieux amortir que si tu ne l’utilises que 1000 heures par an. Et puis après t'as ce qu'on appelle les opex donc c'est en gros la maintenance du truc. On va dire que dans un premier temps tu le négliges c'est pas ça qui est le plus gros coup, donc tu rajoutes quelques euros en plus, mais c'est négligeable.

Le prix par kilo d'hydrogène en fait, ensuite, tu as un prix par an. Donc si tu investis de l’argent, finalement, tu empruntes de l'argent à une banque, tu sais que tu dois le rembourser, et donc tu sais quel est le montant à rembourser en fonction de ton intérêt. Alors ça, tu le divises par la consommation, enfin par la production d'hydrogène, et voilà, il faut que j'aie, par exemple, 5 000 000 euros à rembourser par an. Ben, je produis 30 000 tonnes d'hydrogène, voilà, c'est un calcul quoi, mais ça a l'avantage que très rapidement, tu peux dire, Ah oui, bah OK, donc si j'utilise mon électroménager 6000 heures par an ou 2000 heures par an, ben je vois tout de suite que mon coup capital il va exploser quoi. Et par rapport au coût de l'hydrogène, le prix pour l'instant, actuellement, à une station d'hydrogène, c'est exact, on disait qu'on était à 10€, 10,00€ du kilo.

SPK_1 : Ce qui honnêtement, et du coup, on va être plus ou moins 5 fois, alors c'est plus ou moins fois 2.

SPK_1 : Non, parce qu'en fait, le prix aujourd'hui que tu vas payer sur une station, c'est là où le, l'endroit où il va produire son hydrogène. C'est important parce que si tu produis à une centrale électrique, tu produis au coût du marché de l'électricité. Ouais, si tu produis sur le réseau de transport, tu dois rajouter les primes, les coûts de transport qui sont de l'ordre de 15, 20€ du mégawattheure en plus du prix de l'électricité, sur votre distribution, tu rajoutes encore 30, 40€ du mégawattheure.

Ça donne au moins 10€ du kilo, plus tu dois rajouter le capex. Je te parle de l'électrolyseur, mais si tu rajoutes la captation de chargement, là tu doubles ton côut. Si tu augmentes le stockage d'hydrogène, , ça augmente encore. Si tu as comprimé, ça coûte très cher, pas tellement en énergie, mais en capex.Et pour l’hydrogène liquide, c'est facile, donc le pouvoir calorifique inférieur de l'hydrogène, c'est 33,33. Et pour arriver à liquéfier de l'hydrogène, il faut 10 kilowattheures par kilo d'hydrogène, et donc le rendement. Donc en fait, tu perds en gros 1/3 de ton énergie à liquéfier.

SPK_2 : Ah oui, c'est énorme.

SPK_1 : C'est énorme et c'est pas envisageable. Il y en a qui y pensent, moi personnellement je trouve que ça n'a aucun sens. Mais bon, c'est mon avis ça. C'est quand même, à -252° l'hydrogène liquide. Je ne devrais pas te faire un dessin pour te dire que la molécule n'a pas envie de rester à 252° quand il fait 40° dehors, même quand il fait moins 5, elle a pas du tout envie de rester à 12, et donc tu as des fuites. Et donc c'est ce qu'on appelle le boil-off, c'est qu'en fait, l'hydrogène va repasser en phase gazeuse et puis se remettre en phase liquide, ce qui est couteux énergétiquement.

Sur la mobilité hydrogène, perso, je vois 0 jusqu'en 2030, à minima 0 pourcent. Peut-être un peu plus, mais, si je prends l'analogie par rapport à l'électrique, Tesla a commencé en mieux des années 2000. Il a mis un paquet incroyable de pognon dedans pour arriver à sortir les premières Tesla un peu et à faire que maintenant il a des usines qui sont productives, mais il a mis 20 ans. L'hydrogène, c'est au niveau de Tesla, au début de Tesla, et tu as besoin de une bonne comparaison. Tu as besoin de 3 fois plus d'argent parce que tu as besoin de créer des infrastructures en plus importantes. C'est juste pour te donner une idée de pourquoi, personnellement, en tant que travailleur dans le domaine de l'électrique, je constate qu'en 2010 tout le monde disait que l'électrique c'était pour demain. Aujourd'hui, on est pas encore demain. On a encore beaucoup de chemin à parcourir avec l'hydrogène, on est au niveau de 2005 par rapport à la voiture électrique.

L'hydrogène est beaucoup plus impressionnant, l'hydrogène, déjà, tu as certainement des problèmes avec les stations et tout ça, et tu te bats aussi avec des éléments, à un moment donné tu peux te poser la vraie question de savoir si on devrait faire de l'hydrogène ou si on peut rester à l'électrique. Ou alors, est-ce que les biocarburants offrent un service similaire à l'hydrogène ? C'est limité, on le sait, parce que la biomasse n'est pas infinie, on n'aura pas plus de biomasse que ce dont on a besoin, et on a encore besoin de carbone dans le sol, sinon ça aura un impact sur l'agriculture. J'ai appris ça en discutant avec des agriculteurs, sur le cycle global du carbone. Comme on a besoin de CO2 biogénique, mais en gros, on a besoin du CO2 qui vient de la biomasse. Oui, enfin si tu prends le CO2 de la biomasse, ça pose un problème parce qu'à la fin il faut quand même que le sol contienne aussi du carbone.

Abstract :

The transportation of heavy-duty vehicles plays a significant role in the emission of greenhouse gases. To address this issue and make the high-duty transportation sector more environmentally friendly, hydrogen has emerged as a promising solution that aligns with climate agreements.

Hydrogen possesses the remarkable advantage of being producible from renewable green energy sources and can be utilized in various forms. This research delves into the optimal strategy for developing hydrogen to be effectively employed in heavy-duty transportation.

At its outset, this paper provides a concise overview of the current situation. Subsequently, it conducts an in-depth examination of diverse approaches to produce green hydrogen, exploring viable technologies and the requisite network and infrastructure development to establish a sustainable business model for hydrogen as a fuel in this context. Lastly, the study also sheds light on the various limitations and challenges associated with the advancement of hydrogen technologies.

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