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Green hydrogen multi-market optimisation: real complementarities or temporary transaction costs?

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Abstract

The French strategy on hydrogen deployment shows good perspectives at 2050, yet at short term, the economics of clean hydrogen remains ambiguous, and locally inhibits investments. This study evaluates wind-hydrogen project applications at different milestones, following a roadmap of hydrogen industry maturity built over the entire supply chain. Simple linear interpolations are assumed to draw the path of deployment and pave the way for the H2 ecosystem. Hydrogen is here obtained from a dedicated far-offshore wind farm and targets primarily the use in transportation, following policy agenda priorities of maritime transport which could also trigger the H2 demand in industry, gas and power sector. By means of an optimization algorithm, the operation of hybrid wind-hydrogen is simulated to set the size of the necessary infrastructure, under the constraint of H2 delivery timeline (daily or weekly). For instance, the harbor of Saint-Nazaire will distribute at least 4 t H2 per day in 2050 for maritime and road transport, needing the installation of 60 MW of wind energy capacity. Residually it could supply 1,880 t H2 for industry and energy sector, yet, the sectors' coupling hinders business ecosystem building that remains essential to economies of scale and industry establishment. These orders of magnitudes are crucial for the hydrogen industry planning and highly needed by policy makers to set commitments and build regional hydrogen roadmaps for next decades.

Keywords

Wind-hydrogen, power-to-X optimization, business ecosystem, transactions costs, regulatory frame.

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1. Introduction

A growing number of reports, initiatives and energy scenarios designate the hydrogen vector as one of the few solutions to achieve the Paris Agreement target, which is to limit the rise in the average global temperature to well below 2°C by 2100 (IAE, 2019). To that, deep transformations of the energy production and consumption need to occur such as to curb emissions well before 2050, by means of continuous investments starting today. Hydrogen industry is well established and industry sectors use hydrogen since decades, yet the economics of clean hydrogen, i.e. from renewable energies, remains ambiguous. Sustainable hydrogen can fuel technologies in multiple sectors and could contribute to the decarbonization of the world economy, yet its uptake has been slow despite initiatives and efforts worldwide.

Most of the current hydrogen production is fossil-fuel based, by steam-methane reforming, and by oil and coal gasification, but the focus next will be on clean or green hydrogen produced from renewable electricity via electrolysis. The largest share of the current demand for hydrogen comes from the chemicals sector for the production of ammonia, refinery for hydrocracking and desulphurization of fuels, and industry such as producers of iron and steel, glass, electronics, etc. The highest future potential is estimated to be in transport, industry (mainly steel and chemicals), and energy (gas and electricity). The hydrogen global market demand is estimated at 61 Mt H₂ in 2015 and is projected double by 2050 due to new usages (IRENA, 2018) and to rise to 650 Mt H₂ (or 18% of the world's final energy demand) following the optimistic scenarios of the Hydrogen Council (2017).

In Europe, there is a great concern into the potential for hydrogen such as to reduce dependence on fossil fuels and to cut carbon emissions, i.e. by 40% by 2030 below 1990 levels. The European Union has adopted in 2018 the “Hydrogen Initiative”⁶, a non-binding commitment of member states to pool efforts of cooperation on research in support of sustainable hydrogen for the decarbonization of the transport, power and heating sectors. Over the past years, the European Fuel Cells and Hydrogen Joint Undertaking has contributed to funding more than €100 million, which shows the political support to materialize the potential of hydrogen and to reduce costs.

Projections of the European hydrogen demand shows estimates of 2,250 TWh in 2050 (67 Mt H₂), or 25% of the final energy demand, following the European Hydrogen Roadmap (FCH-JU, 2019). The market is split across sectors as follows: 60% in transport, 21% in building heating and power demand, and 19% in industry. However this ambitious scenario requires massive efforts to scale-up the industry by 2030, with an annual investment rate of EUR 8 billion.

In France, the hydrogen demand represents almost 1 Mt in industry and emerges in other selected sectors triggered by the policy support and industrial and research consortia. The national strategy sets targets for clean hydrogen at 10% of the total hydrogen production by 2023 and at 20-40% by 2028, with a focus on the major current production source, the industry sector (MTES, 2018). Regulation is provided with investments (EUR 100 million per year) such as to bust low TRL⁷ innovative projects and to create synergies among already well established H₂ equipment providers (ADEME, 2018).

⁶ <https://hydrogeneurope.eu/sites/default/files/2018-09/The%20Hydrogen%20Initiative.pdf>

⁷ https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Yet, most of the national investments target low maturity H2 projects (TRL < 3) up to demonstration stages, but no specific tool is provided for (mass-) deployment of the industry. Among regulatory measures designing the frame of clean H2 production are next labeling clean hydrogen if renewable-based, by means of European directives on renewables and carbon footprint databases; establishment of a certification center for high pressure hydrogen for all transportation means; clear detailed targets on the type and the number of H2 driven vehicles at medium and long-run along with the deployment of the refueling infrastructure under H2 specific safety regulation and risk prevention rules.

According to estimates, the H2 market size in France could attain EUR 40 billion in 2050 and employ some 150,000 people, while avoiding 55 Mt of CO2 emissions and expanding the national industry strength through exports (Afhypac, 2018).

A number of projects emerge in France for various applications, aiming at first to remove the remaining technological barriers and to anticipate the technical obstacles which need clarification such as the social acceptability, the legislation, the administrative steps, and the business model. A short selection is made next based on the application type in order to demonstrate that the industry is well established and widely spread across regions in France, however synergies among operators and applications are not reached yet.

- For the Power-to-Mobility vector, several projects are ongoing such as railway applications (by Alstom), *Febus* fueling a bus fleet with hydrogen from solar panels, *Zéro Emission Valley* combining clean H2 refueling stations with light vehicles, *Hype* taxi fleet in Paris, and *Navibus* with Jules Vernes 2 hydrogen urban river shuttle, etc.
- For Power-to-Power application, Myrte project combines a complex system of solar panels and electrolyzer and injects power into grid.
- For Power-to-Industry, the project Vabhyogaz3 (Albhyon – Hera industrial) produces hydrogen from biogas.
- For Power-to-Gas, projects such as *Grhyd* and *Jupiter 1000* test hydrogen blending into the natural gas network, at low concentration rates, 0.5-1% of the energy delivered to the buildings, without modifying the initial distribution infrastructure. However, a double usage is designed, such as bus refueling station (hythan). Next step is to capture carbon from heavy local industry emissions and produce through methanation synthetic natural gas (syngas).

This diversity of projects shows large heterogeneity in terms of H2 production size (bulk H2 for industry versus retail production for power storage), demand type (high compression level in transport versus low levels for power and heat), the frequency of delivery (daily station refueling versus non-stop operation of steel factories). The hydrogen is almost a different product by market segment and alternative regulations apply, in particular for H2 storage, transport and distribution. The only element in common would be the electrolyser, upstream of the system, while downstream, the process follows completely different specifications, contractual provisions and legal, administrative, economic and social constraints. For instance, the production of hydrogen legal frame is set by the European directive Seveso III (2012/18/EU)⁸ transposed into national legislation. The national frame concerning licenses of classified facilities for

⁸ Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances (Official Journal of the European Union).

environment protection (ICPE 4715)⁹ mentions that no particular industrial site regulation applies for storing less than 100 kg of H₂, but a *declaration* is necessary for storing H₂ in the range of 100-1000 kg, while storing more than 1 t of H₂ requires permit or *authorization*¹⁰ and an impact study of dangers, and storing more than 50 t of H₂ needs *authorization with public utility*¹¹.

The variety of procedures explains the initial use of the current projects for one market only, e.g. gas or transport or power, but not all of them in a first stage. For one use only, the administrative task seems already complex and this led the government to commit guiding H₂ operators on their legislative procedures to comply with. In time, this is aiming at creating and reinforcing the H₂ ecosystem necessary to ensure synergies among applications, and be able to provide multiple sectors by the same H₂ production operator (ADEME, 2018). Regional projects are already ongoing, such as the hydrogen economy demonstrator EHD 2020 (Energy Hydro-Data, in Normandia), aiming at reinforcing first of all the business ecosystem of hydrogen by identifying actors, bringing together stakeholders (politicians, industry, energy producers, social public), creating the demand, and ultimately the necessary governance for hydrogen industry mass-development.

This study argues that the regional development of hydrogen necessarily follows gradual steps, triggered simultaneously by renewable mass-deployment, on the generation side, and by massive usages like transportation, on the demand side. It further tries building a roadmap with timelines and orders of magnitude, such as to help projecting the horizon when the hydrogen production can capture revenues from multiple markets. Meanwhile, for full potential of hydrogen to materialize, policy and financial support and significant cost reductions are required.

2. Case study

The infrastructure consists of an off-shore wind farm, an electrolyzer, a compressor, a regular vessel transporting cylinders of compressed hydrogen, and two storage facilities with tanks located off-shore near the farm and on-shore in the harbor area. Additional transport and distribution infrastructure will next be necessary, depending on the demand type and location, on the cost of H₂ and its competitiveness. However, this study looks only at the wind-electrolyzer-storage size such as to support the upstream H₂ chain planning.

Wind power potential. The study case considers an off-shore wind farm installed in the Atlantic Ocean, far along the coast of Pays de la Loire, a French region with large off-shore wind potential and no grid interconnections to other countries. The suitable areas for H₂ delivery could be harbors of Saint-Nazaire, Turballe and Fromentine, with different sizes in terms of population, industrial activity and maritime traffic flow. The wind farm is located far off-shore, has no interconnection to the mainland, and is entirely dedicated to hydrogen production. This implies that the power which is not used to produce hydrogen due to the saturation of the H₂ infrastructure (transport or storage) is lost or curtailed.

⁹ ICPE is the French acronym for facilities classified for environmental protection, and covers any depot, yard, workshop and facility involving hazards or inconvenience for the neighbourhood, health, safety, agriculture, or the protection of nature.

¹⁰ For more details, see <https://www.inventec.dehon.com/en/p/site-regulation/19.html>

¹¹ https://aida.ineris.fr/consultation_document/10461

The study assumes floating wind turbines with a similar design to the currently on-test turbines in France¹² and elsewhere in Europe¹³, and assumes that by 2025 a robust fleet could consist of tens of turbines of 10 MW each, based on the successful French demonstration project, Floatgen, with respect to the ecosystem of the same area of our hypothetical project. A far-shore location assumes that near-shore is saturated, which could solve to some extent the issue of conflict of interests in the French harbors which are under the pressure of coastal multi-use such as fishing, navigation, aquaculture and recreational activities (Lacroix & Pioch, 2011). The size of the farm will be next calibrated triggered by the H2 demand volume.

The electrolyzer. There are several technological options for providing electrolytic hydrogen, such as the alkaline electrolysis, the polymer electrolyte membrane electrolysis, the alkaline polymer electrolyte water electrolysis, or the solid oxide electrolysis. They each have advantages and drawbacks making the integration of large scale off-shore wind energy challenging (IRENA, 2018). For instance, the alkaline electrolyte is a well mature technology and the most extended at a commercial level worldwide, while the polymer electrolysis would respond more quickly to the power input and have a higher efficiency when operated below nominal load, thus being suitable to support intermittent energy integration. However more research is needed to develop these technologies, to enhance their durability and to further reduce costs.

Next it is assumed that a polymer electrolyte is coupled with the off-shore wind energy source. The time step being one hour, the electrolyzer could quickly shut-down and start-up in front of intermittency, even if additional equipment to store the electricity and smooth the input to the electrolyzer could be envisaged. An additional constraint will add: the energy inflow should be at least 5% of the electrolyzer rated power to make the process work. The size of the electrolyzer will be endogenously set, knowing that currently demonstration projects have been proved successful at small scale (<1MW) and are ongoing for larger scale, i.e. up to 10 MW (JCH-JU, 2019).

A compressor of 100 bars is next used before storing hydrogen in gas cylinders. It has to be noted that the compression higher than 100 bars could change the size of the electrolyzer due to losses and the storage infrastructure and the choice of the transport means, i.e. the number of tanks and the vessel type. The H2 low pressure instead is here suggested for the sake of usage simplification: in the gas sector (100 bars), in the electricity sector (200 bars), for on-board storage in automotive applications (700 bars). Further transformation is therefore necessary after delivering the H2 to the harbor at 100 bars.

Demand for hydrogen. The demand follows the power-to-X concept elaborated in authors' previous study (Loisel et al., 2015), where hydrogen can be used to produce electricity (power-to-power), can be injected into a natural gas pipeline network (power-to-gas), can fuel natural gas power plants or produce second generation biofuels (power-to-fuel), or can fuel transportation (power-to-mobility) and industry (power-to-industry).

However, the approach is different now, starting from the finding that sectors coupling beforehand could enhance additional transaction costs. Rather the demand is split in primary and secondary target markets, where the primary demand is for transportation, and the secondary market for other selected sectors. The first demand type meets the constraints from transport in

¹² <https://floatgen.eu/>

¹³ <https://www.windpowerengineering.com/business-news-projects/worlds-first-floating-wind-farm-delivers-promising-results/>

terms of delivery volume and timing, while the second type is residually obtained. This means that the secondary demand would allow fully exploiting the H2 infrastructure and would avoid wasting both wind and H2 asset market opportunities. Yet, this demand should next be identified on the territory.

Transport is the first market target from economic and policy perspectives, and the best-performing option to meet climate targets complying with local emissions regulations. It covers heavy-duty transport like medium- to large-passenger vehicles and commercial vehicles, large fleets of buses, trucks, trains, ships, and aviation. Economic evaluations show that the cost of a refueling station could be covered more quickly with regular provision of large-scale needs from various customers, with at least 80 kg H2 per day, for a cost of EUR 10 per kg H2 (Ademe, 2018).

- By transportation type, the maritime sector is the first target, triggered by the international shipping strategy to reduce CO2 emissions, i.e. by 50% by 2050 compared to 2008, and local pollutants (NOx, SOx and particulate matter)¹⁴. Hydrogen fuel cells can also avoid the water pollution and the noise generated with diesel fueled engines and can replace the onshore power supply installations in harbors for boats electrical connection (IRENA, 2018). Fuel cell ships are at different development stages for ferries, shuttles, long-run ships with liquefied hydrogen and fuel cells and cruise ships requiring longer autonomy.
- Other transportation means make the object of the policy regulation such as the replacement of trains fueled with diesel, and road fleets of buses and light commercial vehicles and heavy trucks. The French H2 strategy mentions targets of 5,000 light vehicles for professional use by 2023 and 200 heavy vehicles and an infrastructure of 100 refueling stations. These targets increase up to 50,000 light vehicles and 2,000 heavy vehicles by 2028 (MTES, 2018).
- In aviation, hydrogen and synthetic fuels based on H2 are presented as the only large-scale solution to decarbonize the sector, and H2 meets criteria of high energy density for lightweight energy storage, short refueling time, and long driving ranges and autonomy.

Secondary demand is the residual demand where other large-scale applications need to be found, like large-scale industry: in decreasing order of importance, oil for refinery and petrochemicals, ammonia, iron & steel, chemicals, and chlorine. By 2030, expectations in France show an increasing trend in the oil industry hydrogen production, and a decline in the production of ammonia, for a total demand in the range of 1 - 2 Mt H2/year (Le Duigou et al, 2011). Other usages are in the power sector, where hydrogen could supply long-lasting large-scale storage to large centers of demand; and in the heating sector for residential and commercial buildings, as H2 is estimated to replace 7.5% the natural gas by volume into the French gas grid by 2030 while some cities could switch to 100% pure hydrogen networks (FCH-JU, 2019). Additionally, the forklift market based on fuel cells is emerging in warehouse at harbors and large companies, and is already a commercial solution, with thousands of units already deployed across the United States (Coca Cola, BMW, Amazon; IRENA, 2018).

The secondary demand should be considered in areas of less than 300 km (Babarit et al., 2018), or less than 100 km in other estimates (Ademe, 2018). Longer this distance, the transport and distribution of H2 by road could limit the carbon free advantage of clean hydrogen; while H2

¹⁴ <http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx>

delivery by pipelines would reduce the economic attractiveness due to high installation costs, which would be justified for large volumes in range of 0.5-1.5 t H₂ /day.

Cost issues. This hypothetical project makes no price projection and is focused on volumes only, on the equipment sizing that maximizes the use of assets while meeting the fuel transport demand. By the time the off-shore floating wind farm is installed, costs are expected to drop, by 70% from the current levels in some estimates, with however a high cost over the entire chain of production-transport-distribution (in the range of EUR 10-20 /kg H₂ by 2030; IRENA, 2018). Reports show also that the production cost could be less than EUR 5 /kg H₂ in 2035 (Ademe, 2018) provided that renewables massively penetrate the French energy mix and make the price of the electricity used for electrolysis dropping to some EUR 40/ MWh.

Three times lines are next designed based on the assumption that the policy commitments will trigger the development of the hydrogen industry and the demand expansion. For a big harbor like Saint-Nazaire, in 2030, maritime and road transportation with captive fleet would need about 1 t H₂/day, it would double by 2040 and attain 4 t H₂/day in 2050. At lower scale, for smaller harbors like Turballe and Fromentine, only half of the demand could be expected (see Fig.1). This demand will determine the size of the infrastructure made of wind-electrolyzer-storage-vessel capacity. For meeting a fixed demand at a given delivery time, the production will necessarily be locally oversized, meaning that more wind or H₂ assets will be available over the year and could generate levels above the fixed demand. In addition to maritime and road transport, other usages could be identified from the industry (forklifts, ammonia), energy (gas and electricity) and buildings (heat). This is changing the perspective of the storage size, according to the optimal trade-off between the frequency of delivery and the storage platform size, but would let the wind and the electrolyzer unchanged.

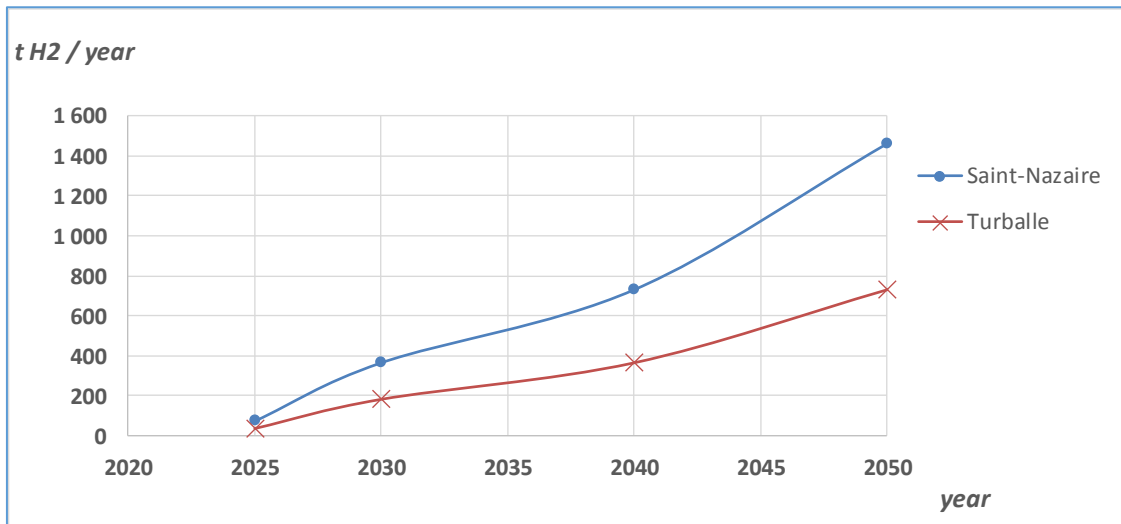


Fig 1. Hydrogen demand for maritime transport, by harbor (t H₂ / year)

This vision of hydrogen potential in the regional economy is built assuming the right circumstances in terms of policies, regulations, codes and standards, which will accelerate the investment in the development and the commercialization of hydrogen and fuel cells. Another prior condition for H₂ supply and demand to be effective, the renewable potential should be high. According to Ademe (2018), the current H₂ consumption in France could be obtained from renewables if their share in the electricity mix attains at least 60%, which is foreseeable by 2035.

From a risk management perspective, wind-H2 partnership could be based on forms of long-term contracts or take-or-pay provisions, such as to cover the heavy infrastructure of both wind-H2 projects. However, the specificities of the hydrogen will lock-in consumers, which could guarantee the long-term relationship between producers and costumers. The nature of the demand would be centralized consumers such as H2 filling centers for heavy-industry, large boats, trains or planes, to medium-sized demand from industry, natural gas grid and power sector, down to small local consumers as refueling stations for river ferries, trucks, buses and commercial vehicles.

3. Methodology

A dynamic optimization model is built to simulate the operation of the wind farm dedicated to the production of hydrogen, and is implemented in GAMS, using the solver Cplex¹⁵. The model assumes perfect information on the wind profile and on the hydrogen demand for transport usage, and gives orders of magnitudes of each location-specific supply and demand.

The database of the wind power potential consists of data collected in the region Pays de la Loire in 2013, at an altitude of 35 m. The data is collected at 10 minutes time step and adjusted at model hourly step. Under physical limitations of wind availability, energy conversion, component efficiencies and mechanical losses, a total capacity factor of 42% is obtained.

Hydrogen is compressed at 100 bars and stored in tanks, which are hold in the area of the wind farm and transported by vessel to the harbor for any further transformation and use. The size of the reserve in the off-shore area depends on the frequency of the vessel (every day or weekly transportation) and depends also on the harbor planning to store hydrogen on the site or to distribute it without storage to end-users or to traders.

In a first step, the model returns the size of the wind farm necessary to meet the demand of H2 at a given time-step, while minimizing the waste or curtailment of wind resource. Secondly, constraints set on the frequency of the delivery will optimally return the electrolyzer and the storage capacity. Another sizing driver is the distribution of the deposit, off-shore or on-shore, and ultimately the vessel represents the adjustment sizing variable. Put it differently, the model optimizes the wind farm, the electrolyzer and the storage of H2, and pass on the economics of the vessel any suboptimality of the cargo capacity use. This residual demand will absorb the excess of the wind which would otherwise be lost, and can punctually solve the issue of oversizing H2 storage capacity, but the externality of the wind intermittency is now passed on secondary demand itself.

Eq 1: Resource waste minimization (objective function):

$$Excess_s = \sum_1^{B_s} Min_{d,h} \sum_{d=1}^{d=t_s} \sum_{h=24}^{h=24} Wind_{d,h} - WindH2_{d,h}$$

¹⁵ The General Algebraic Modeling System (GAMS) is suitable for modelling linear optimisation problems, being especially useful with large database (<https://www.gams.com>). The GAMS solver Cplex is designed to solve large, difficult problems quickly. These advantages are fully exploited here to solve the power system problem in a short execution time (less than one minute).

Eq 2. Dynamics of the storage reservoir dedicated to the primary H2 supply:

$$RP_{d,h} = RP_{d,h-1} + PS_H2_{d,h} - D1_H2_{d,h}$$

Eq 3. Wind energy balance:

$$ExcessH_{d,h} = Wind_{d,h} - WindH2_{d,h}$$

Eq 4. Hydrogen production:

$$PS_H2_{d,h} = WindH2_{d,h} \cdot eff$$

Eq 5. Supply of residual hydrogen production potential:

$$SS_H2_{d,h} = ExcessH_{d,h} \cdot eff$$

Eq 6. The residual hydrogen is stored in the same facility as the primary hydrogen production or it needs additional storage:

$$SS_H2_{d,h} = ST1_SS_H2_{d,h} + ST2_SS_H2_{d,h}$$

Eq 7. Supply of residual hydrogen is using reservoirs dedicated to primary hydrogen:

$$ST1_SS_H2_{d,h} = SS_H2_{d,h} - (K_{RP} - RP_{d,h}) \text{ if } SS_H2_{d,h} > RP_{d,h}$$
$$0, \text{ if } R_{d,h} = K_{stor}$$

Eq 8. Dynamics of the storage reservoir dedicated to the secondary H2 supply:

$$RS_{d,h} = RS_{d,h-1} + ST2_SS_H2_{d,h} - D2_H2_{d,h}$$

Eq 9. Secondary H2 demand needing distribution infrastructure is the residual cargo capacity after filing-in to meet the primary H2 demand:

$$D2_H2_{d,h} = K_c - D1_H2_{d,h}$$

Eq 10. The capacity of storage for primary H2 supply:

$$K_{RP} = Max_{d,h} (RP_{d,h})$$

Eq 11. The capacity of the cargo:

$$K_c = Max_{d,h} (D1_H2_{d,h})$$

Eq 12. Need of additional storage infrastructure to use the residual hydrogen:

$$K_{RS} = Max_{d,h} (RS_{d,h})$$

Eq 13. The electrolyzer capacity:

$$K_{El} = Max_{d,h} (PS_H2_{d,h})$$

Eq 14. The wind farm capacity:

$$K_W = Max_{d,h} (WindH2_{d,h})$$

Eq 15. Conditions that reservoirs are filled-in up to their capacity:

$$RP_{d,h} \leq K_{RP}$$

$$RS_{d,h} \leq K_{RS}$$

Eq 16. H2 compressed over the year is lower than the demand of H2 over the year:

$$\sum_{d=1}^{B_s} \sum_{h=1}^{d=t_s} H2_{d,h} \leq \sum_{d=1}^{B_s} \sum_{h=1}^{d=t_s} D1_H2_{d,h}$$

Eq 17. The electrolyzer works in the range [0.05 – 1] of its rated power. Hence the wind energy necessary to produce hydrogen should be at least the 5% of the electrolyzer capacity net of losses:

$$WindH2_{d,h} > \frac{0.05 \cdot K_{El}}{eff}$$

Index

d – day (1, 365)

h – hour (1, 24)

s – optimization strategy: daily or weekly optimization ($s = \{“day”, “week”\}$)

t_s – time interval by optimization strategy: daily ($t_{“day”} = 1$) or weekly optimization ($t_{“week”} = 7$).

B_s – the number of recursive blocks over the year, by strategy: daily optimization ($B_{“day”} = 365$); weekly optimization ($B_{“week”} = 52$).

Parameters

eff – round-trip efficiency of producing the hydrogen and compressing it ($eff = 50\%$)

Exogenous Variables (Inputs)

D1_H2_{d,h} – the demand of hydrogen for transportation at hour h , day d (in MWh)

Endogenous Variables (Outputs)

Excess_s – yearly wind energy in excess by strategy ($Excess_{day}, Excess_{week}$) (in MWh)

WindH2_{d,h} – hourly wind energy used to produce hydrogen (in MWh)

D2_H2_{d,h} – residual demand of hydrogen at hour h , day d (in MWh)

ExcessH_{d,h} – hourly wind energy in excess (in MWh)

PS_H2_{d,h} – primary supply of H2 produced at hour h , day d (in MWh)

SS_H2_{d,h} – secondary supply of H2 produced at hour h , day d (in MWh)

RP_{d,h} – the state of storage of the primary energy at hour h , day d (MWh)

RS_{d,h} – the state of storage of the secondary energy at hour h , day d (MWh)

ST1_SS_H2_{d,h} – secondary H2 supply produced at hour h , day d and stored in the same facility as the primary H2 supply (in MWh)

ST2_SS_H2_{d,h} – secondary H2 supply which would need additional storage capacity at hour h , day d (in MWh)

K_{RP} – capacity of reservoir for primary H2 supply (in MWh)

K_{RS} – capacity of reservoir for secondary H2 supply (in MWh)

K_{El} – capacity of the electrolyzer (in MW)

K_W – capacity of the wind farm (in MW)

K_c – capacity of the cargo vessel (in MW)

Wind_{d,h} – hourly wind potential at capacity Kw (in MWh)

4. Results

4.1. Scenario *Daily H2 delivery in 2050*

Infrastructure sizing. The model returns the capacities of the wind farm and the hydrogen infrastructure (electrolyzer, H2 storage, and H2 transport vessel) for fixed demand and for a given wind profile. The choice of the wind farm capacity is a function of the H2 storage capacity, and of the willingness of the wind energy investor to accept losing energy in case of low market opportunities. Market with low hydrogen demand would imply curtailing wind energy, which would lower the business attractiveness of the energy operator. Fig 2 shows the way the wind farm capacity is decreasing with increased H2 storage size, and the wind curtailment which is decreasing but generally remains high (more than 30%).

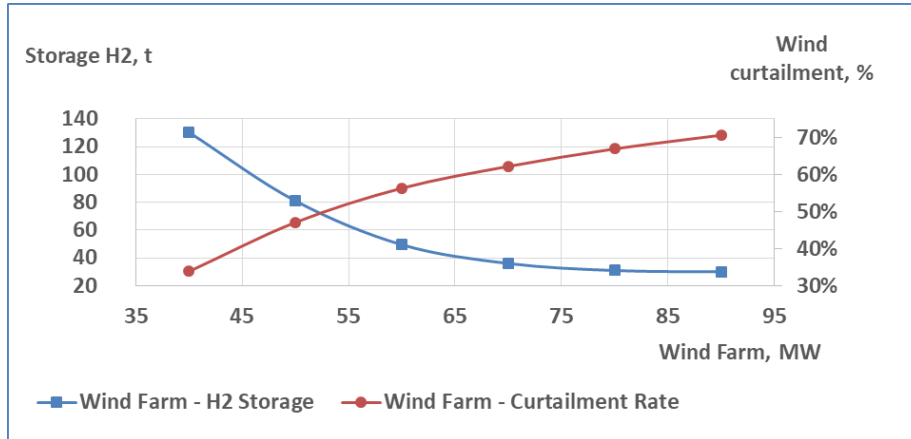


Fig 2. Wind farm capacity to the H2 storage capacity (left axis) and Wind farm to the Curtailment rate (right axis) in the scenario *Daily supply in 2050*

For either wind or H2 storage, the higher is the capacity, the lower is its usage rate, or the higher is the unutilized capacity rate. A wind farm of 40 MW requires a large storage capacity of 130 t H2/ day, and records high usage rate of the wind farm capacity (66%), but lower usage rate of the storage reservoirs (24%). By contrast, a wind farm of 90 MW would need 30 t H2 a day of storage to meet the daily hydrogen-to-mobility demand, recording low wind utilization rate (29%) and high storage use (56%). The trade-off between installing more wind turbines or more storage tanks depends on the rate of curtailment which is admitted socially and economically, and on the management of the ocean area.

Results for milestones by harbor show capacities needed for a curtailment rate of the wind energy of 51% which is extremely high but could be employed for other usages as it will be assessed next. Fig. 3 shows that for producing 2 t H2 a day in 2040 at the harbor of Saint Nazaire, a wind farm of 30 MW (or 3 turbines of 10 MW each) would be necessary; while only half would be needed at smaller sites like Turballe. It should be noted that installing far off-shore turbines should be seen as a lumpy investment, with no additional capacity in between milestones. Furthermore, the wind farm capacity and the hydrogen demand should be foreseen beforehand, since marginal investment like installing one wind turbine more is highly cost-inefficient and technically unforeseeable.

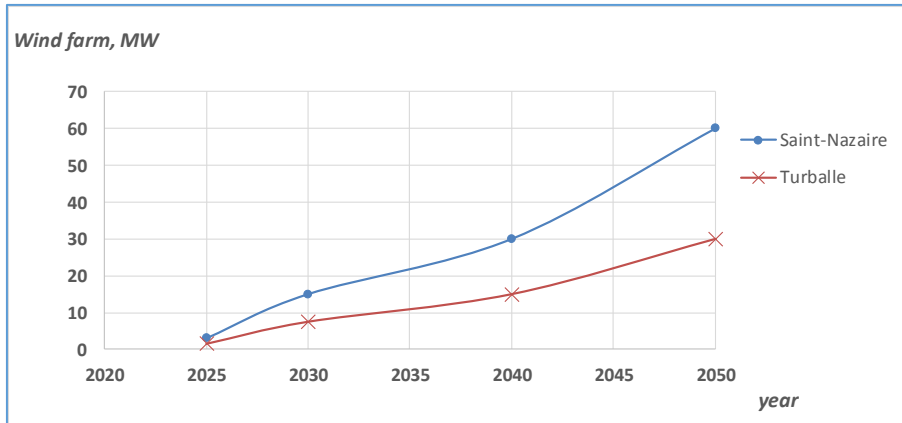


Fig 3. Wind farm capacity installed by harbor, triggered by local H2 demand, by year

System operation. An hourly representation of the above aggregated results is made for an intermediate scenario consisting of a wind farm of 60 MW and a storage capacity of 50 t H2 (1,650 MWh energy equivalent).

Fig. 4 shows the distribution of the wind energy between the production of hydrogen-to-mobility and the residual demand of hydrogen, priority being given to the former one. Hydrogen-to-mobility is produced by an electrolyzer of 10 MW capacity, as the minimum size necessary to meet the demand in time: in Fig. 4 the wind energy dedicated to hydrogen-to-mobility production is capped at the electrolyzer capacity times its efficiency (=50%).

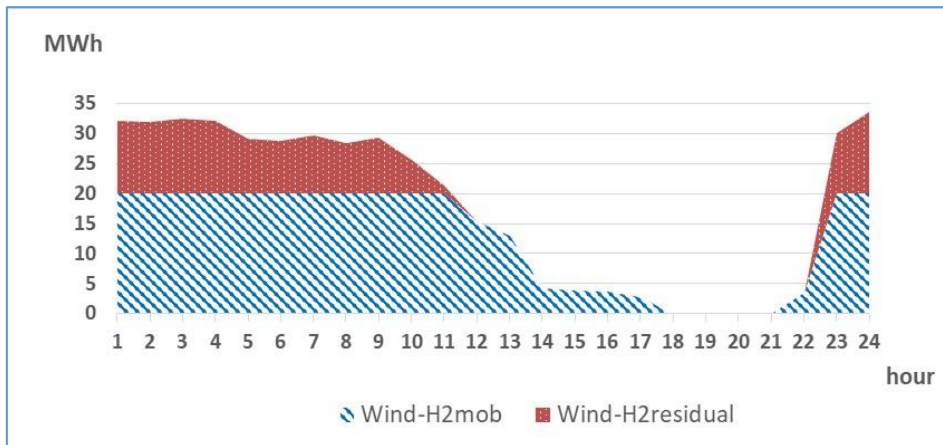


Fig 4. Hydrogen production from wind energy, by use (primary and secondary), during one day

Avoiding the wind energy curtailment would need additional infrastructure for the electrolyzer, storage and transportation.

The size of **additional electrolyzer** capacity needed to meet the residual demand for hydrogen is selected based on statistics of the frequency and the amplitude of potential hydrogen production. Table 1 shows that the number of events where the production of hydrogen is lower than 10 MWh, concentrates the largest share of the electrolyzer activity over the year (70% of the total number of hours in operation), and records also the highest H2 production (63%). For clarifying the table reading: the production of hydrogen in the range of (10 – 20) MWh arises during 2,098 of hours over the year and cumulates 469 t H2, which means that installing 10 MW more

capacity of electrolyzer would add 469 t H₂ to the residual supply. The frequency is lower for an hourly production higher than 20 MWh, i.e. 608 hours of activity, adding 158 t H₂ more.

Table 1. Residual hydrogen production over the year, by range of production

H2 Production, MWh	Number of events	t H ₂ / year
(0, 10)	6 030	1 071
(10, 20)	2 098	469
(20, 30)	608	158

To summarize scenarios for electrolyzer sizing, 10 MW of installed capacity would optimally meet the hydrogen-to-mobility demand. Adding 10 MW to this capacity would avoid curtailing 1,071 t H₂, and the usage rate will pass from 56% for 10 MW electrolyzer, to 48% for 20 MW electrolyzer. The maximum size of the electrolyzer would be 40 MW of capacity which would totally avoid curtailing the wind energy, and would have a usage rate of 32%. The criteria of selection would depend on the wind curtailment rate admitted socially by the regulator if sustained by any feed-in tariffs or by the wind energy investor if subject to the market; on the cost-efficiency targets of the hydrogen investor, such as the cost of the electrolyzer and the usage rate target; on the maritime spatial planning, and last but not least, on the residual demand market opportunities.

The size of the **additional storage** depends on three factors: the wind energy potential at each hour, the state of the storage installed for hydrogen-to-mobility, adjusted with withdrawals for meeting the daily primary H₂ demand, and the size and the frequency of the transportation vessel.

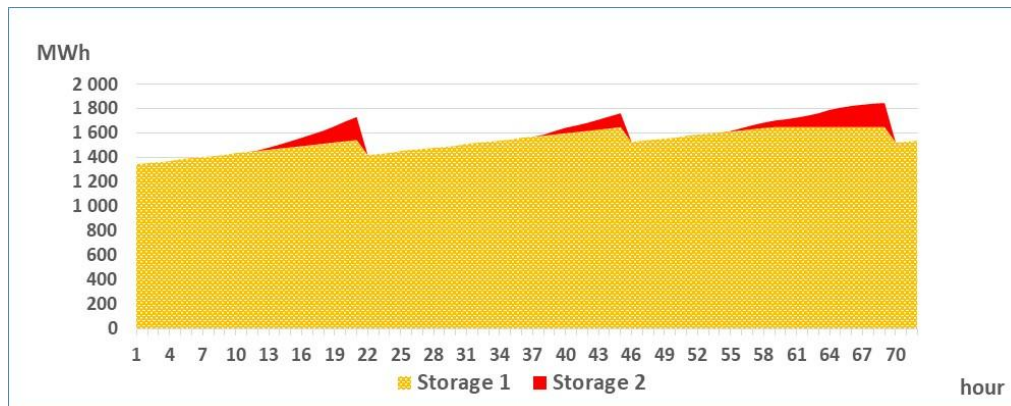


Fig 5. Dynamics of storage for primary H₂ demand (Storage 1) and the additional storage capacity (Storage 2)

The storage initially installed to optimally support the production of hydrogen-to-mobility from 60 MW wind farm has a capacity of 50 t H₂ and an annual capacity factor of 51%. Using the remaining share to store hydrogen-to-X residual demand would optimize the use of the assets. Fig. 5 shows the dynamics over three days of this functional optimization, which aggregated over the year gives a new capacity factor of 90%. The dynamics of the storage filled with both primary and secondary demand is regular such as to give a constant schedule to the vessel, but this could be optimized as well in line with the wind intermittency. Based on the regularity assumption, a new storage infrastructure would be necessary such as to recover the entire residual hydrogen production, i.e. 1,880 t H₂ over the year. The already installed storage capacity could punctually store most of this production, and the additional storage would amount to 400 MWh (13 t H₂) to

store some 314 t H₂ over the year. The usage rate is very weak, 0.34%, so the economic interest to install more storage could balance in favor to energy curtailment, i.e. 64 t H₂ or 4 GWh of wind energy lost.

The capacity of **transportation by vessel** would fit exactly the daily H₂ demand level, 4 t H₂ per day (or 133 MWh equivalent). Yet, doubling the transportation vessel capacity or the frequency of the delivery (twice a day) would decrease the size of the storage needed to recover the secondary hydrogen production. The intermittency of hydrogen generation is reflected in the cargo use for secondary H₂ which adds to the primary H₂, as represented in Fig. 6.

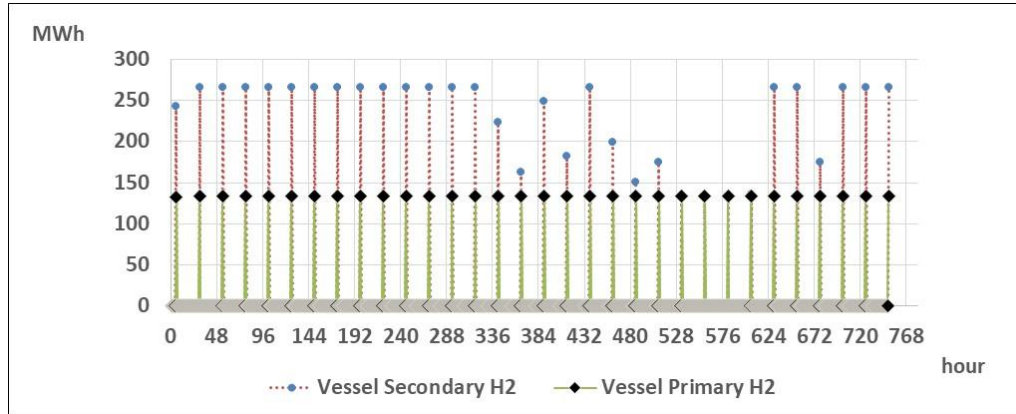


Fig 6. Daily traffic of the vessel for hydrogen-to-mobility (Vessel Primary H₂) and for hydrogen-to-X residual hydrogen production (Vessel Secondary H₂), over one month

If the vessel is dedicated to only primary hydrogen transportation, i.e. 4 t H₂/day, its usage rate would attain 4.1% over the year, while assuming that the same formula could apply as for energy assets. By doubling the capacity to carry the residual hydrogen production would make decrease its capacity rate to 3.3%. Or keeping constant its capacity but doubling the frequency would naturally double the rate, 6.6%.

This optimal sizing approach is a trial to handle the intermittency of the wind energy which is passed on the electrolyzer, on the H₂ storage and the use of the vessel. These assets could increase their market value by supporting the market for hydrogen-to-X which is ultimately the last chain to bear the intermittency, and appears in this study as the adjustment variable that optimizes the economics of the wind farm and the hydrogen infrastructure.

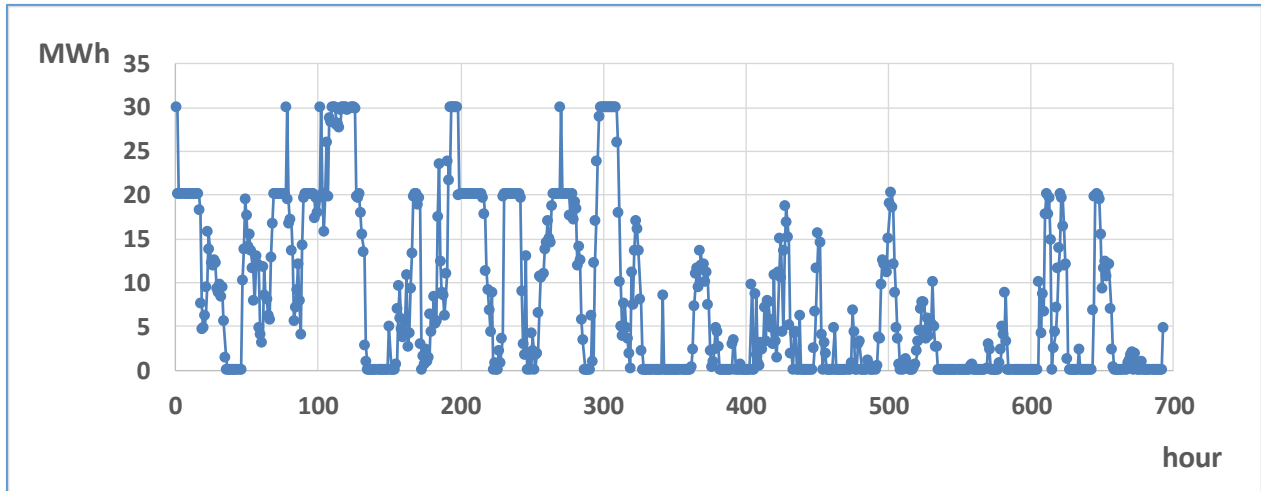


Fig 7. Hourly residual hydrogen production over one month

Fig. 7 shows the variability of this production within the range (0-30) MWh or (0-900) kg H₂ per hour, and this raises next the issue of the identification of those customers who might adjust to the delivery time and volume returned by the model. Or to install on-shore storage such as to regulate the flow over one day or over few days.

4.2. Scenario Weekly H₂ delivery in 2050

This section analyses the infrastructure of the same wind farm of 60 MW endowed with an electrolyzer of 10 MW, such as to compare economic indicators of storage and transportation with longer delivery time. Implicitly it is assumed that the contract terms are suitable for both producer and consumer, i.e. that the demand has an weekly consumption due to some on-shore storage facilities, and that the supply can be stored off-shore for one week following an administrative procedure that makes scenarios at 4.1 and 4.2 comparable.

Similar results among scenarios are obtained for the production of primary hydrogen, wind curtailment rate, and the usage rates for the electrolyzer and the wind farm. Differences are in terms of storage capacity which is larger for a weekly delivery (94 t H₂ versus 50 t H₂ in Daily H₂ case) and has a higher usage rate due to longer storage provision (60% versus 51%). The overall cost could increase due to higher storage capacity with yet some economies of scale, but it could probably decrease by using less the transportation vessel, once a week, yet its capacity should be seven times larger. One of the main advantages of the weekly delivery is the use of newly over-sized storage capacity to handle the residual hydrogen demand. The usage rate of storage by storing both primary and most of the secondary hydrogen will almost be 1 (98%). The need for additional storage infrastructure will be lower (8 t H₂ of capacity) to avoid the curtailment of some 14 t H₂ over the year 2050, which could be better to curtail.

5. Policy implications

Prior conditions to these scenarios are the supply chain and the geographic distribution of H2 infrastructure, and the nature of the H2 demand. Both should be considered simultaneously to overcome the chicken-and-egg dilemma, where the consumer does not invest if there is no distribution infrastructure, and conversely, there is no investment from suppliers as long as the demand is non-existent in fact.

The supply chain. H2 suppliers cover a large area of interests (H2 component manufacturers, infrastructure operators, car manufacturers, intermediates of H2 distribution). They all are reluctant to invest in mass H2 deployment before hydrogen becomes commercial, as they would face several years before any return on investment. Despite government support to R&D projects, private investment is critical to H2 development (some EUR 8 Bln per year during the scale-up phase, FCH-JU, 2019); to that, short-term bankability is key for investment to be in line with the long-term vision of the hydrogen in the energy transition. For commercial viability, some forms of long-term contracts are needed to secure revenues, or large scale is necessary, i.e. gigawatts, to reduce costs, improve power density, lifetime and balance-of-plant efficiency.

The long-term vision of the market is assessed in terms of turnover, exports, know-how and jobs. In Europe by 2050, the H2 market could represent EUR 820 Bln for the fuel cells industry and H2 equipment, and 4.4 million of jobs. The actor dynamics in France is ongoing, as for instance the joint-venture between the H2 producer (Air Liquid), car manufacturer (Toyota) and car fleet user (taxi company Hype); R&D specialization (EDF-Hynamics dedicated to H2 production, Peugeot with bus and clean car projects) and R&D cooperation (Symbio-Michelin-Faurecia).

The nature of **the H2 demand** concerns first of all the scale of consumption due to early development of the H2 industry, and targets local large customers, such as large industry and large-scale mobility deployment. Regionally, scales could be restrained, for instance in non-interconnected islands where hydrogen could already be economically viable (Ademe, 2018).

By usage, priority seems to be given to sectors able to rapidly generate economies of scale with minimal infrastructure requirements such as refineries, steel, chemistry, methanol production, buildings, and heavy-duty transport such as ships, buses, trucks, trains. As the technology type is not the same among users, strategic prioritization of segments is necessary and hydrogen adoption could come in waves, with transportation leading the way (IRENA, 2018).

Hydrogen-to-maritime-mobility will be triggered by the political pressure to implement clean alternatives to fuel the marine sector by banning ships with high local pollutants and CO2 emissions (FCH-JU, 2019). The refueling infrastructure and services of maintenance needs to develop such as to send investment signals to ship builders, vehicle industry, and to consumers (individual drivers, services, administration). In France, regions are involved in H2 development (Normandia with fishing boat development, Occitania with off-shore projects in harbors and on-shore on airport and roads, Pays de la Loire with H2 boat and bus projects).

In a number of countries, **governments** support the hydrogen industry by providing direct investment as subsidies to reduce the capex, but probably the most effective in de-risking investments is the regulatory framework which would trigger both supply and demand in a structural way. Specific instruments are emission restrictions, carbon pricing, mandates for clean fuels in industry and targeted sectors, and more particularly certification of clean hydrogen when produced from renewables (IRENA, 2018). Ultimately the coordination among stakeholders (policymakers, industry and investors) needs to emerge to ramp-up the hydrogen segment and to meet decarbonization targets.

Conclusion

This research has investigated the infrastructure of a hybrid wind-hydrogen project located in the French region Pays de la Loire. The hybrid scheme means that an off-shore wind farm is dedicated to the hydrogen production which should meet a fixed transportation fuel demand. Volume projections by decade until 2050 allow building scenarios for H2 deployment and planning the design of the project by component (number of wind generators – electrolyzer capacity – storage size – vessel frequency and capacity). An optimisation model has been built to optimize the operation of the plant such as to minimize the wind-H2 capacity installed.

Optimal sizing shows the inverse relationship between the wind farm and the storage capacity (the larger the wind farm, the lower the storage capacity to deal with both intermittency and volume issues). The ratio wind to storage that would be selected by an operator will depend on the acceptable wind curtailment rate and the cost of the off-shore storage tanks. The comparison between a daily delivery and a weekly delivery shows higher storage capacity (almost the double in our study case) with yet lower delivery needs.

The study allowed confirming that any fixed contract provisions in terms of volume and delivery time enhance necessarily oversizing the infrastructure in front of the wind intermittency. The main remaining issue is the wind energy lost, which in all sizing scenarios is very high, more than 30% of the wind potential. The study suggested a further recovery of the residual wind energy for any hydrogen-to-X usage, which could also improve the economics of the other assets, e.g. the electrolyzer use and the storage fill-in, but would have an irregular profile due to the wind intermittency.

As an open problem remain the nature of the **market**, which could further address the residual intermittency, and the **moment** when combining several usages could happen in time.

- The residual demand could be addressed to markets with large capacity to absorb the intermittency at any moment, with high liquidity and large volume, such as the spot power market and the gas market, by means of flexible contracts on the day-ahead segment. Here, an additional infrastructure would be necessary, such as gas network or fuel cells and electricity grid.
- Hydrogen-to-X concept raises the issue of the complex transactions underpinning the business model, involving a long chain of stakeholders, legal compliances, permit authorizations, multi-market skills and trading know-how. Large transactions costs could ultimately overtake the economies of scale suggested by the multi-usage business model and restrict the frame to one usage only, at least during the transition period to fully mature chain.

Specifically, at launching stage, hydrogen-to-mobility has the best opportunity cost in front of imminent rise in oil prices, and hence seems to gather the best features for building the necessary business ecosystem when triggered by proactive macro-policy support. Yet, its implementation at meso-level faces the bottlenecks of missing supply chain and practice-turn strategies that create the territorial value and set-up rules and tactics such as to shortly end-up to scale green hydrogen marketization.

The main policy recommendations are towards helping H2 consumers and industries selecting carbon-free technologies by means of ambitious long-term targets. Regionally, policy support

could make industrials and consumers familiar with the technology and the hydrogen use, and could further involve them in R&D activities. With the decentralization of the energy production, a strong commitment of regional policy makers is essential to the development of hydrogen infrastructure. This would give confidence in the investment possibilities and could guide the equipment manufacturers, energy operators and car and shipping stakeholders in making hydrogen technology an effective solution.

In the strategy to develop H2 industry, the anticipation of the commercialization timeline is key for infrastructure planning and to guide customer preferences. France has already the assets to create a leadership in the H2 market, with experienced electrolyzer manufacturers and hydrogen and fuel cell operators, specialized material suppliers, strong research institutions in H2, well advanced R&D programs in support to the H2 industry, automotive industry, and well developed gas network enabling H2 distribution for households and industry. They all need further coordination to align their long-term strategic interests as part of the national energy transition with appropriate policies and supporting schemes.

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