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What policies for the hydrogen sector ? Lessons from city buses

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Hydrogen is a possible alternative to the internal combustion engine, alongside battery-powered vehicles, in the context of reducing greenhouse gas emissions associated with transport activities. The costs associated with hydrogen vehicles are currently high, even when considering the greenhouse gas emissions and other pollutants avoided by their use. Efforts to reduce these costs, which will determine the social and environmental desirability of hydrogen vehicles, face two challenges : the high cost of refueling, linked to the crucial problem of coordination between development of the vehicle fleet and refueling infrastructure; and high purchase prices, which may decrease when sufficient quantities generate experience effects. This policy brief argues that each of these two handicaps calls for a specific policy design : at a local level for coordination between actors, and at a European level to generate sufficient volumes. The example of hydrogen-powered urban buses offers a telling illustration of these issues.

- The growing importance of the hydrogen sector has been encouraged by various initiatives in France. These initiatives are based on the idea of a regional ecosystem : around a city, a network of local communities, or even a department or a region.
- The example of hydrogen buses shows that the abatement costs induced by this technology are still too high. The problem lies both in the price of the vehicles and the supply of fuel.
- Reducing the costs associated with the supply of fuel requires the resolution of coordination problems linked to network effects, which calls for a response at the local level.
- Achieving vehicle purchase prices low enough to be competitive requires a European approach, which alone makes it possible to reach significant volumes.

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The hydrogen sector in France

Since mid-2010, French initiatives to develop the hydrogen sector in transport have multiplied. Most of these have been instigated by local authorities, such as the Easymob project in the Manche region, or more recently, the development projects announced by the city of Dijon. [1] At the same time, on June 1st, 2018, Nicolas Hulot presented a hydrogen deployment plan for the energy transition. [2] This plan gave national impetus to a series of initiatives supported by the sector's manufacturers. [3]

The hydrogen sector seeks to meet two of the state's general objectives : to fight climate change at the global level by reducing emissions from the transport sector, responsible for 37% of CO2 emissions in 2017 in France, and to combat urban pollution, a source of premature death and respiratory diseases associated with NOx and fine-particle emissions (OECD, 2016). [4]

The ability of hydrogen vehicles to meet these two objectives rests on the characteristics of this technology. A hydrogen vehicle has three components : a high-pressure tank, a fuel cell that converts stored hydrogen into electricity, and an electric motor. Its use therefore emits only water vapor, unlike internal combustion engines, which emit greenhouse gases (GHGs) and pollutants. The environmental impact of a hydrogen vehicle therefore depends largely on the GHG and pollutant emissions associated with hydrogen production. Hydrogen can be completely decarbonized if it is produced by electrolysis. Indeed, electrolysis is a production technique that relies essentially on electrical energy : if the electricity used comes from renewable energy sources, [5] emissions associated with hydrogen transportation are very low.

Battery electric vehicles are another alternative to internal combustion engines, which also address both environmental issues (GHG and pollution). Hydrogen vehicles currently have higher costs and need an infrastructure for the production and delivery of decarbonized hydrogen. Under these conditions, the ability of hydrogen vehicles to provide an alternative to the internal combustion engine remains uncertain and controversial, even though this type of vehicle offers comparative advantages in terms of range, refueling time, and robustness to extreme weather conditions.

Largely based on the case of urban buses, this policy brief emphasizes that the regional-ecosystems approach encouraged in France can only take off if accompanied by an industrial policy at the European level.

The urban bus sector

The French Environment and Energy Management Agency, ADEME (Bénita et Fayolle, 2018), notes that buses provide 86% of urban connections in France. Standard 12-meter buses make up 68% of the fleet. In 2016, there were 26,545 buses, 4,573 of which were owned by French public transport operator RATP. An urban bus travels an average of 40,000 km per year. [6] At the European level, there are estimated to be around 100,000 buses operating in the 75 largest cities. [7]

The decarbonization of urban bus links is based on two electric bus technologies : hydrogen and battery power.

Table 1 gives an estimation in €/km of the Total Cost of Ownership (TCO) for three technologies for a standard bus from several sources (Ballard, 2019 ; Roland Berger GmbH, 2015 ; Aber, 2016 ; Eudy et Post, 2019). For a hydrogen bus this cost is 5.53 €/km, for a battery bus it is 4.97 €/km, but only 3.96 €/km for a diesel bus. In each case, this is the sum of the costs associated with capital investment, maintenance, personnel costs and fuel. The individual components for a bus traveling 40,000 km per year are calculated as follows :

- The purchase price is annualized on the basis of a 12-year useful life and a discount rate of 4.5%, corresponding to the rate recommended for public investments in France (Quinet, 2013). [8]

1. The EasHyMob project envisaged 15 stations and 250 vehicles by the end of 2018 ; the deployment focused on light commercial vehicles http://erh2-bretagne.over-blog.com/2014/03/08-03-2014-premiers-pas-vers-un-reseau-europeen-de-bus-hydrogene.html
The metropolis of Dijon announced in April 2020 its intention to run hydrogen-powered buses and waste collection vehicles https://www.lesechos.fr/industrie-services/tourisme-transport/dijon-veut-faire-rouler-ses-bus-et-ses-camions-a-lhydrogene-1194392
The French Association for Hydrogen and Fuel Cells (AFHYPAC) maintains a map of the different projects https://www.vighy-afhypac.org/
2. https://www.ecologique-solidaire.gouv.fr/sites/default/files/Plan_deploiement_hydrogene.pdf
3. At the World Economic Forum in Davos in 2017, the Hydrogen Council launched "a global initiative of leading energy, transport and industry companies with a united vision and long-term ambition for hydrogen to foster the energy transition".
4. Source : https://www.insee.fr/fr/statistiques/2015759#tableau-figure1
This share was 31% in 2000, and has increased over the past 20 years as total emissions have fallen more sharply than those from transport. For a more complete analysis, see http://www.chair-energy-prosperity.org/wp-content/uploads/2019/11/publication2019_past-trends-in-transport-co2-emissions-france_bigo.pdf
5. In 2019, according to RTE, the French electricity mix consisted of 71% nuclear energy, 21% renewable energies (including hydropower) and 8% fossil fuels.
https://www.rte-france.com/sites/default/files/bilan-electrique-2019_0.pdf
6. See also https://afdc.energy.gov/data/widgets/10309
7. https://www.globalmasstransit.net/report/Europe-Bus-Report-market-outlook-Part-1-2017.pdf
8. From the purchase price (investment) P the annualized cost ac in €/year is obtained from the following formula : $ac = P \times \frac{1-\delta}{1-\delta T}$ with $\delta = \frac{1}{1+r}$ the discount factor, r the interest rate, and T the lifetime of the investment. With $r = 4.5\%$, $T = 12$, and $P = 650,000$ we

Table 1 – Total cost of ownership (TCO) comparison of hydrogen, battery and diesel buses

	Hydrogen	Battery	Diesel
1. Fixed capital	**1.71**	**1.23**	**0.55**
Purchase price (€)	650,000	470,000	210,000
2. Maintenance	**0.4**	**0.8**	**0.3**
3. Personnel costs	**2;63**	**2.63**	**2.63**
4. Fuel	**0.8**	**0.31**	**0.48**
Unit price (kg H2, kWh, l)	10.0	0.24	0.3
Consumption per km	0.08	1.3	0.3
Total 1+2+3+4	**5.53**	**4.97**	**3.96**

Interpretation : The ownership cost of hydrogen buses, 5.53 €/km, is the sum of a fixed capital component, 1.7 €/km (which corresponds to the average purchase price of €650,000, annualized), a maintenance cost of 0.4 €/km, personnel costs of 2.63 €/km, and a fuel cost of 0.8 €/km (which is the product of the unit price of hydrogen, 10 €/kg, and the consumption of a hydrogen bus, 0.08kg/km).
Sources : This table is based on data collected in the reference study (Meunier, Moulin, Ponssard, 2019), drawing on specialized reports and interviews with professionals.

— Maintenance costs correspond to technology-specific variable costs for operations related to the age of the vehicle.
— Personnel costs are not very technology-dependent and are therefore not included in the comparison even if they are added to obtain the TCO.
— Fuel expenditure is calculated on the basis of a unit price of energy and energy consumption per km.

To assess the impact of substituting a high-emission technology (diesel buses) with a low-emission technology (electric buses) on the reduction of CO2 emissions, economic analysis commonly refers to the "abatement cost". This measures the difference in cost between one reference technology (typically fossil fuel) and another, in terms of the GHG emissions avoided by the use of the alternative technology, measured in tonnes of CO2 equivalents (Baker, Clarke et Shittu, 2008) : [9]

$$AC = \frac{\text{Cost}_{\text{clean}} - \text{Cost}_{\text{fossil}}}{\text{CO2}_{\text{fossil}} - \text{CO2}_{\text{clean}}}$$

This notion represents the additional cost generated by the avoidance of one unit of GHG emissions. Expressed in €/tCO2, it can then be compared with reference values of the social cost of CO2. The Quinet (2019) report proposes several of these values for the French strategy to reduce CO2 emissions : 87 €/tCO2 in 2020, 250 €/tCO2 in 2030, and 750 €/tCO2 in 2050. [10]

However, whether diesel buses should be replaced by hydrogen or battery-powered electric buses depends on costs, avoided CO2 emissions and the reduction of local pollution. Local pollution (mainly NOx and fine particles) has an impact on health and its social cost can be quantified. The Quinet (2013) report gives orders of magnitude for diesel buses according to the area concerned (urban, suburban) and the corresponding population density. This "local" social cost is added to the cost of fuel for diesel buses. The cost of 0.48 €/km must therefore be increased by 0.27 €/km for dense urban areas and by 1.36 €/km for very dense areas. This means that in dense urban areas, the social costs generated by the circulation of a diesel bus in terms of pollution (and therefore public health and well-being) exceed the direct costs related to the circulation of the bus.

As hydrogen or battery-powered electric buses do not emit pollutants, their circulation does not generate any local social costs. It is therefore possible to recalculate the abatement cost of hydrogen or battery-powered buses by including the effect of these additional costs for the use of diesel buses, according to the following modified formula :

$$AC_{\text{with social cost}} = \frac{\text{Cost}_{\text{clean}} - (\text{Cost}_{\text{fossil}} + \text{Cost}_{\text{social local}})}{(\text{CO2}_{\text{fossil}} - \text{CO2}_{\text{clean}})}$$

Table 2 presents the different values of the abatement cost of hydrogen and battery-powered buses, with and without taking into account the local social cost, and for different values of the latter. In addition to the cost data (presented in Table 1), it is also necessary to make assumptions about the CO2 emissions associated with the different technologies. In the case of hydrogen buses, these assumptions concern fuel production. We retain two hypotheses concerning the hydrogen production process : by methane reforming (Column 1) or by electrolysis (Column 2). The first process emits CO2, while the second emits CO2 depending on the GHG emissions associated with the electricity used. We assume that the electricity used is decarbonized and therefore does not emit CO2, while the reforming process indirectly generates 320gCO2/km. For battery-powered buses, the assumptions concern electricity production. Here, we also adopt two hypotheses : either decarbonized electricity (Column 4), or electricity from the European energy mix (Column 3); [11] in the latter case, indirect emissions are 720gCO2/km. The GHG emissions associated with the circulation of a diesel bus are about 1,200gCO2/km.

Table 2 calls for several comments. First, without consi-

obtain 68,213 €/year which we can divide by 40,000km/year to obtain 1.7 €/km.

9. In practice, difficulties may arise with the calculation of abatement costs in the presence of experience effects (Creti et al., 2018).

10. In the Quinet (2019) report the social cost trajectory of CO2 (or "carbon tutelary value") is calculated to meet the carbon-neutral objective in 2050 with a carbon budget constraint. There are other (trajectories of) reference values such as those calculated by Nordhaus (2017) with a global economic model coupled with a climate model.

11. The French electricity mix is quite decarbonized, but as electricity grids in Europe are interconnected, the actual electricity mix corresponding to the development of electric vehicles, and therefore the associated CO2 emissions, is uncertain. However, the two values considered in the table can serve as useful benchmarks.

Table 2 – Abatement cost for a hydrogen bus and an electric bus vs. a diesel bus

	Hydrogen		Battery	
	Reforming (1)	Electrolysis (2)	European mix (3)	Decarbonized mix (4)
Social cost considered				
None	1,789	1,312	2,113	845
Dense urban	1,484	1,089	1,554	622
Very dense urban	248	182	-712	-285

Interpretation : In 2020, the abatement cost of a hydrogen bus for which fuel is produced by reforming, without considering the local social cost, is 1,789 €/tCO2. It is -285 €/tCO2 for a battery bus for which electricity is produced by a decarbonized mix, taking into account a local social cost corresponding to a very dense urban environment.
Sources : This table is based on data collected in the reference study (Meunier, Moulin, Ponssard, 2019) drawing on specialized reports and interviews with professionals.

dering the local social cost, the abatement costs at more than 845 €/tCO2 are too high, even for a CO2 tutelary value in 2050 according to Quinet (2019). This means that the GHG emissions avoided by choosing to run an electric bus rather than a diesel bus do not compensate for the differences in total cost of ownership between the two technologies.

Second, the question of how the energy needed for electric buses is produced is particularly important, as it makes battery buses more attractive than hydrogen buses when electricity production is highly decarbonized, but less attractive when it is not.

Third, taking into account the local social cost has very important effects on the abatement costs of the two electrical technologies. In very dense urban settings, the abatement costs of hydrogen and battery buses are thus lower than 250 €/tCO2, i.e. the "tutelary value" of carbon suggested by Quinet (2019) by 2030, with the abatement costs of battery buses even becoming negative. [12]

This initial analysis shows why cities are major players in the energy transition because of pollution problems, aggravated by congestion. Most of them have taken drastic measures to reduce the share of diesel from 2025 onward. As such, they can act directly on urban transport, whether public or operated by public transport companies. Nevertheless, the acquisition costs of buses in 2020 are very high (€650k for a hydrogen bus, €470k for a battery bus, and €210k for a diesel bus).

Finally, the data in Tables 1 and 2 show that battery buses have a significantly lower purchase price and a lower abatement cost than hydrogen buses (for a decarbonized electricity mix). Beyond the trade-offs between monetary costs, GHG emissions and pollutant emissions, certain technical characteristics of battery buses nevertheless make hydrogen buses more attractive :

— An autonomy of 450km instead of 200km. [13]
— This autonomy is less dependent on external conditions of temperature and route topography than that of battery-powered buses.
— Excessive battery weight for articulated buses.

The constraints generated by these technical characteristics identify a market share for which battery electric buses would not be appropriate, and industry figures agree that hydrogen buses could take it over. This share will be about 7% to 9% in 2025 (Roland Berger GmbH, 2015). The evolution of the costs associated with the hydrogen bus industry is therefore a particularly crucial element in understanding its development potential.

Network and experience effects in the hydrogen-powered transport sector

If there is a fall in the purchase price of vehicles and the price of fuels, the abatement costs associated with the technology concerned also fall, making it attractive in comparison with the social value of carbon. For this reason, the structure and functioning of the markets for the construction of hydrogen vehicles (purchase price) and for the production of hydrogen (fuel price) are particularly important as they determine the future abatement cost of this technology and thus its environmental and social desirability. However, the development of a new transport sector, and especially the hydrogen transport sector, faces two major difficulties.

The first is due to an indirect network effect, according to which the more users there are of a primary good (vehicles), the more complementary goods (refueling stations) will be created, increasing the demand for the primary good. [14] This implies coordination problems between industrial actors and may explain a "lock-in" situation : without refueling stations there is no vehicle use, but without vehicles there is no interest in refueling stations. Thus, the fleet of hydrogen vehicles and the number of refueling stations must jointly reach a sufficient scale, otherwise the costs associated with operating hydrogen buses will remain high.

The second is the result of the experience effect, according to which the production costs of a good decrease over time with the quantities produced due to various me-

12. Negative abatement costs indicate that substitution is profitable in the absence of a carbon price. The fact that the same local social cost is applied to different emission reductions (the denominator of the abatement cost) explains why its impact differs between technologies and is greater the smaller the emission reductions. Thus, the battery bus with the European mix, which is the technology with the highest emissions, becomes preferable to the hydrogen bus with reforming for very dense urban areas ; whereas the opposite is true for dense urban areas.

13. The average length of Paris bus routes is less than 180km, hence RATP's lack of interest in this technology.

14. A network effect occurs when the attractiveness of a good depends on the number of users. A distinction is made between direct and indirect network effects that operate via a complementary good. See Shy (2011) for a summary of network effects.

chanisms (standardization, economies of scale, accumulation of knowledge, specialization, etc.); [15] the often high initial costs of decarbonized vehicles make this concept particularly relevant.

These concepts can be understood as a reflection of market failures that may justify government intervention. For example, at the local level, public authorities are often the only consumers of public transport vehicles : their fuel consumption alone is very high in terms of volume. This partly solves the problem of coordination with hydrogen producers, for whom a single consumer can provide a significant demand. In the case of a public transport network, the fact that the route map is also fixed, less dense than the road network as a whole, and predictable for the public authorities - i.e. for the fuel consumer - also makes it possible to reduce the costs associated with recharging vehicles. The time horizon and the financial capacity of public authorities also make it possible to overcome these network effects.

However, the case of hydrogen-powered urban buses presents specificities that are particularly well suited to resolving network effects at the local level. Local public transport bus fleets are said to be captive (i.e. the vehicles are operated by a single operator), which makes it easier to predict hydrogen needs and the stations required. This would not be the case for private vehicles, where the network effect is much less easy to control.

As far as the purchase price of vehicles is concerned, the size of public transport fleets at local level is probably not sufficient to bring the experience effect into play to reduce vehicle costs. By the end of 2019, only a few conurbations in France had put the first hydrogen-powered buses into service : Pau (8), Versailles (2) and in Bruay-La-Buissière and Auchel in Pas-de-Calais (6). However, the cost reduction needed to make hydrogen buses attractive would require the deployment of several hundred buses per year. Such a volume can only be envisaged on a European scale.

European policy can act as a lever for local policies

Several support programs for the hydrogen sector, and more particularly for hydrogen buses, have been set up by the European Union since the early 2000s. Two phases can be distinguished. [16]

The first was a "take-off" phase for the sector's development programs. Six programs were set up between 2000 and 2017. A dozen European cities have benefited from these programs. Typically, the aim was to test the technical and operational feasibility of hydrogen buses, with a very limited number of units in circulation. It was also to test the interface between the buses and their infrastructure. The issue of cost was not an obstacle at this stage.

The second phase is the ramping-up of support programs. In 2017, the European Commission launched the Clean Bus Deployment Initiative. It was in this favorable context that two new programs were launched to promote the deployment of hydrogen buses : JIVE 1 and JIVE 2 (Joint Initiative for Hydrogen Vehicles across Europe). JIVE 1 has a total budget of €106 million and JIVE 2 of €225 million, representing a total budget increase of more than 50% compared to all previous programs. [17] Under certain conditions, the JIVE 1 and JIVE 2 programs grant a subsidy of €200k per bus purchased by a city or a community of local authorities.

The number of hydrogen buses financed by these two programs reaches several hundred per year. Other indications suggest that the European market for hydrogen buses is growing; for instance, on June 3rd, 2019, a consortium of bus and hydrogen producers, the H2Bus Consortium, announced its commitment to deploy 1,000 hydrogen buses, as well as the associated infrastructure, in European cities. The first phase of this project involves 600 hydrogen buses by 2023 (Denmark, Latvia, Britain) and EU funding of €40 million. [18] In France, 1,000 hydrogen buses could be deployed by 2023. [19]

In parallel with this increase in the volumes of hydrogen buses purchased and projected on the European market, their purchase price could fall in the near future : a hydrogen bus costs €650k in 2020, but a few suppliers seem willing to commit to a price lower than €450k in 2025 for orders of at least 100 buses per year. With regard to the unit price of hydrogen, the second crucial parameter in the calculation of the TCO for hydrogen buses, the Hulot plan proposes a number of measures to reduce this price, and sets a projected price of 7 €/kg by 2030.

We retain these two projections as working assumptions for 2025 to examine their effect on the total cost of ow-

15. The experience effect is introduced, for example, in endogenous growth theory to account for various aspects of technical progress; a simple formula often used in practice makes explicit the unit cost $C(Q)$ of the production of a good based on the cumulative quantity Q in the equation $C(Q) = C(1) \cdot Q^{-\beta}$ where β is the learning coefficient; if $\beta = 0.5$ the cost drops by about 30% every time cumulative production doubles ($2^{-0.5} = 0.7$); for estimates of reduction factors, see for example International Energy Agency, 2000 and McDonald et Schrattenholzer (2001) with 25% for photovoltaic, 11% for wind power.

16. This division into successive phases is detailed (in French) in Meunier and Ponssard, October 16th, 2018, "Le plan hydrogène La France va-t-elle réussir sa montée en puissance?" https://theconversation.com/mobilite-hydrogene-la-france-va-t-elle-reussir-sa-montee-en-puissance-104125

17. For a detailed analysis of the effectiveness of these two programs, see Meunier, Moulin et Ponssard (2019).

18. https://www.fch.europa.eu/news/fch-ju-launches-new-call-project-proposals

19. https://www.afhypac.org/actualites/articles/le-plan-1000-bus-hydrogene-vient-de-franchir-un-nouveau-cap-en-france-1887/

nership and abatement cost of hydrogen buses. These projections are summarized in Table 3, which assumes that hydrogen is produced by electrolysis, and that electricity is completely decarbonized.

Table 3 – Comparison of the total cost of ownership of a hydrogen bus in 2020 and 2025

	2020	2025
1. Fixed capital	***1.71***	***1.18***
Purchase price (€)	650,000	450,000
2. Maintenance	***0.4***	***0.4***
3. Personnel costs	***2.63***	***2.63***
4. Fuel	***0.8***	***0.56***
Unit price (kg H2, kWh, l)	10.0	7.0
Consumption per km	0.08	0.08
Total 1 + 2 + 3 + 4	**5.53**	**4.77**
Abatement cost		
for a social cost in...		
...Dense urban areas	1,089	615
...Very dense urban areas	182	-621

Interpretation : In 2020, the abatement cost of a hydrogen bus for which fuel is produced by electrolysis (and under the assumption of a decarbonized mix), taking into account a local social cost corresponding to a dense urban environment, is 1,089 €/tCO2.
Sources : This table is based on data collected in the reference study (Meunier, Moulin, Ponssard, 2019) drawing on specialized reports and interviews with professionals.

Under the assumptions used in Table 3, the total cost of ownership would decrease by 5.53 €/km to 4.77 €/km from 2020 to 2025, which is still significantly higher than that of diesel buses (3.96 €/km, at unchanged diesel prices). The abatement cost, taking into account the local social cost of dense urban areas, goes from 1,089 €/tCO2 in 2020 to 615 €/tCO2 in 2025. This value is still a long way from the carbon price estimated at 168 €/tCO2 by the Quinet (2019) report. In order for this to correspond to the abatement cost of a hydrogen bus, and keeping all other parameters unchanged, it would be necessary for the purchase price of vehicles to decrease further : carbon parity in dense urban areas would be reached in 2030 with a purchase price for a hydrogen bus of €360k. If such a scenario is credible, starting the substitution process of diesel buses by hydrogen buses becomes justified as early as 2020,[20] hence the paramount importance of support programs at the European level.

Conclusion

The example of hydrogen-powered buses is highly instructive. It clearly shows the interest of policy coherence between the local level to control network effects and a macro level that is large enough to generate the volumes that alone are capable of reducing costs thanks to the experience effect.

This example can be used as a reference to evaluate current hydrogen deployment strategies in other cases. Our analytical framework suggests the systematic combination of two levels. On the one hand, a local level at which network effects are analyzed to potentially reduce the costs of coordination between infrastructure and hydrogen use, integrating transport (e.g. commercial vehicles, taxis, ambulances, trucks, dump trucks, trains) and other hydrogen uses into gas networks for heat production and industrial uses (e.g. steel plants, cement plants, chemical complexes). On the other hand, a macro level at which experience effects are analyzed, both in terms of the industrial costs on the components of added value but also the costs generated by the initiation of local projects (legal set-up, application process for obtaining public aid, etc.).

The economic, social, and environmental justification for the deployment of the hydrogen sector will depend on the proper coordination of public policies between the local and macro levels.

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The arguments developed here are taken from the following two articles.

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