ENGIE Research Chair Energy and Prosperity Ecole Polytechnique

END-OF-INTERNSHIP REPORT

Regional clusters for the energy transition a cost-benefit analysis

public version

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The content of this report is the sole responsibility of the author and does not necessarily reflect the positions neither of the managers nor of the entities involved in the ZEV project.

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Executive Summary

Hydrogen mobility could be a promising technology to decarbonize transport and decrease the atmospheric pollution.

The Zero Emission Valley (ZEV), in the French region Auvergne-Rhône-Alpes, is one of the most ambitious and politically supported projects developing captive fleet of hydrogen vehicles in France. It is an interesting project to explore the potential of projects based on fuel cell electric vehicles captive fleets.

This report uses the cost-benefit analysis framework to assess the economic efficiency of the ZEV, both from the private and public perspectives, compared to a diesel mobility status quo scenario. The public perspective encompasses social benefits of the ZEV such as the diminution of greenhouse gas (GHG) emissions or local atmospheric pollution. The report also uses the economic concept of dynamic abatement cost to assess the potential of a technology subject to learning-by-doing effects (decreasing costs with past cumulative production).

The cost-benefits analysis suggests that the economic efficiency and performance of the ZEV, both from the public and the private perspective, is not assured before 2035-2038, unless learning-by-doing effects and the longer-term is considered. This cost benefit analysis is based on a conservative (pessimistic) scenario. The main message is that the ZEV needs a higher demand for hydrogen to decrease costs.

This report then discusses the reach of the study, considering other technologies that could decarbonize transports, such as electric mobility, and formulates possible continuation of this work.

Some policy recommendations for hydrogen mobility such as developing synergies between hydrogen uses and regional cooperation to scale-up projects conclude this report.

Introduction

Transports are responsible for 23% of the greenhouse gas (GHG) emission emitted worldwide in 2010[1], 25% in the European Union in 2018[2], and 39% in France in 2015.[3] Besides, atmospheric pollution is estimated to kill 48,000 person each year in France (9% of the French mortality).[4]

Hydrogen mobility relies on promising technologies to decarbonize transport and decrease the atmospheric pollution. A fuel cell uses the reaction of dihydrogen with dioxygen to produce electricity. This reaction is considered "clean" because its only byproduct is water. Hydrogen vehicles use the electricity produced with a fuel cell to power an electric motor.[5] This can help to decarbonize transport because there is no emission of pollutants while these vehicles are circulating. However, the production of hydrogen can be polluting. "Grey" hydrogen refers to hydrogen produced from fossil fuels through carbon intensive processes (steam methane reforming or coal gasification). It amounts to 96% of the global hydrogen production[6] and the production cost is around 1,5 EUR/kg.[7] "Blue" hydrogen refers to hydrogen whose CO_2 emitted during production is sequestered via carbon capture and storage (CCS), its production cost is around 2 EUR/kg.[7] "Green" hydrogen refers to near-zero emission hydrogen produced from renewables, its production cost is around 2.5-5.5 EUR/kg.[7] Green hydrogen is considered as a sustainable source of energy that could help to decarbonize transports and to reduce atmospheric pollution.

The technologies, the producers and the political context (both national and European) are mature enough to start developing projects. In 2019, there were already 30,000 forklifts powered by a fuel cell in the US, plus 6,830 fuel cell electric vehicle (FCEV) operating in California only.[8] Passenger vehicles, light-duty-vehicles and buses are already on the market. The next vehicles that will be available are trucks and garbage trucks, followed by boats and trains.[9] In only five months, between November 2019 and March 2020, the global planned production capacity of green hydrogen doubled from 3,2 GW to 8,2 GW of electrolysers to be installed by 2030 (of which 57% in Europe).[10] The European Commission plans to install at least 6 GW of renewable hydrogen electrolysers in the EU between 2020 and 2024 to produce of up to 1 million tons of renewable hydrogen annually.[7] A few countries have mentioned hydrogen as a part of their recovery plan in the aftermath of the Covid crisis. Among them, Germany has announced a 9 billion hydrogen plan.[11]

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[1] IPCC, https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf
[2] Eurostat, https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1180.pdf
[3] ADEME, https://www.ademe.fr/expertises/mobilite-transports/chiffres-cles-observations/chiffres-cles
[4] Santé Publique France, https://www.santepubliquefrance.fr/content/download/118832/1758171
[5] Mines-Paristech, https://direns.mines-paristech.fr/Sites/Thopt/en/co/piles-combustible.html
[6] https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf
[7] European Commission, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
[8] Deloitte, https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf
[9] According to the interviews with Simon Aulagnier (Hympulsion) in Annex G and Gilles Haon (ENGIE Solutions) in Annex H.
[10] https://www.woodmac.com/reports/energy-markets-green-hydrogen-pipeline-more-than-doubles-in-five-months-393132#:~:text=The%20green%20hydrogen%20project%20pipeline,proposed%20pipeline%20for%20new%20projects.&text=Larger%20integrated%20energy%2C%20industrial%20and,carbon%20policy%20at%20their%20back.
[11] https://www.euronews.com/2020/07/22/full-steam-ahead-hydrogen-train-boosted-by-eu-climate-goals

Hydrogen refueling infrastructures and FCEV are complementary goods: the economic value of each good depends on the sufficient provision of the other. This raises a chicken and egg issue: vehicles owners are waiting for a sufficient number of hydrogen refueling stations (HRS) to buy a FCEV and HRS operators are waiting for a sufficient number of FCEVs to install a HRS. A way to overcome this difficulty is to launch local clusters of HRS and FCEVs where the FCEVs form a captive fleet around the HRS.

A few projects of captive FCEV fleet already exist in France at early stage: EAS-HyMob in the Normandy region[12], or Zero Emission Valley (ZEV) in the Auvergne-Rhône-Alpes region. The ZEV is one of the most ambitious and politically supported projects.

The launching of captive fleets of FCEV to decarbonize transport and reduce local atmospheric pollution raises a lot of issues: the profitability for the operators and the vehicles' owners, the socio-economic benefits for society, the costs of developing a technology that is not fully mature yet. This report investigates these issues and assess the conditions of the success of hydrogen mobility.

Firstly, this work presents the Zero Emission Valley (ZEV), a "natural experiment" to study the development of a hydrogen mobility cluster. Then, this report uses the cost-benefit analysis framework to assess the economic efficiency of the ZEV, both from the private and public perspectives, compared to a diesel mobility status quo scenario. The public perspective encompasses social benefits of the ZEV such as the diminution of GHG emissions or local atmospheric pollution. This work also discusses the limitations of such an analysis, for instance how does the analysis hold if battery-electric mobility is considered? It mentions the possible developments of the analysis and a few policy recommendations for hydrogen mobility such as the synergistic development of hydrogen solutions and the cooperation between regions to scale-up projects.

[12] EAS-HyMob, https://eashymob.normandie.fr/

I Background information for cost-benefit analysis

I.1 Zero emission valley

I.1.1 History of the project, economic and political context of the project

Hydrogen is a key industry in Auvergne-Rhône-Alpes. Indeed, 80% of the French actors in the sector are in the region.[13] ZEV is a project initiated by the region and two industrials : ENGIE and Michelin. It is politically supported by Laurent Wauquiez, President of the region[14].

Among the objectives of the project, the Zero Emission Valley (ZEV) project aims to demonstrate that economic development and the creation of wealth and jobs are compatible with the preservation of the environment.[15] The ZEV plans 20 hydrogen recharging stations powered by 15 electrolysers by 2023 and the financing of a fleet of 1000 to 1200 vehicles.[16,17] ZEV is a key project for the region's zero-carbon transition and to reduce local pollution. Because of its scope, it will cover 25% of the vehicle target announced in the national hydrogen plan.[18]

The project is a public-private partnership.[19] Hympulsion is the SAS leading the construction of hydrogen stations. It is owned at 49% by the public sector: the Auvergne-Rhône-Alpes region (33%) and the Banque des Territoires (16%), which belongs to the Caisse des Dépôts et Consignations. The remaining 51% are divided between three private entities: Michelin (22,8%), ENGIE (22,8%), and Crédit Agricole (4,6%).[20,21,22]

I.1.2 The stakeholders and their issues

The region Auvergne-Rhône-Alpes is the second French region in terms of population and GDP with 7,9 million inhabitants and 241 billion euros (around 10% of French national figures). As mentioned above, the region has a strategic and economic interest of developing hydrogen mobility before other regions to promote the local enterprises. In addition, the region faces the challenge of atmospheric pollution and the ZEV could help reducing local pollution. The transport sector is the main emitter of nitrogen oxides (responsible for 60% of total emissions) of which more than 90% of emissions are attributable to diesel vehicles. In large conurbations such as Lyon, Grenoble, Clermont-Ferrand and Saint-Etienne, the regulatory values of local pollutants set by the WHO are

[13] Auvergne-Rhône-Alpes, https://www.auvergnerhonealpes.fr/278-pour-une-filiere-hydrogene-d-excellence.htm
[14] Auvergne-Rhône-Alpes, https://www.auvergnerhonealpes.fr/uploads/Presse/91/203_486_CP-12-20-Zero-Emission-Valley-reconnu-au-niveau-europeen.pdf
[15] Auvergne-Rhône-Alpes, https://www.auvergnerhonealpes.fr/278-pour-une-filiere-hydrogene-d-excellence.htm
[16] Zero Emission Valley, https://www.zev-chambery.fr/data/cp-zev-21-12-18.pdf
[17] 1200 vehicles with Ademe subsidies according to our interview with Hympulsion in Annex D and G.
[18] ENGIE, https://www.engie-cofely.fr/actualites/une-station-hydrogene-dans-la-zero-emission-valley-a-chambery/
[19] Auvergne-Rhône-Alpes, https://www.auvergnerhonealpes.fr/278-pour-une-filiere-hydrogene-d-excellence.htm
[20] https://www.h2-mobile.fr/actus/region-auvergne-rhone-alpes-investit-hympulsion/
[21] https://www.h2-mobile.fr/actus/region-auvergne-rhone-alpes-investit-hympulsion/
[22] https://hydrogentoday.info/news/4972

often exceeded. The air pollution is mainly due to road traffic in the hyper-centre and on expressways.[23]

ENGIE is a leading global company in the energy sector. ENGIE is one of the initiator of the ZEV project, one of the shareholder of Hympulsion, and two ENGIE's subsidiaries (GNVERT and Tractebel) have formed a consortium in charge of assistance to the project owner (Hympulsion) to design and operate HRS in the ZEV. For ENGIE, this project is a way to gain experience in this new sector, to benefit from learning-by-doing and to stay ahead of the competition (for instance Air Liquide has similar projects). Finally, the project fits in perfectly with the group's decarbonation and renewable energy development objectives.

Michelin is a leading global company in the tires' manufacturing. Michelin has begun to expand to the market of services to fleet operators. Michelin in now trying to diversify its business with services.[24] Michelin is one of the initiator of the ZEV and shareholder of Hympulsion. Since the ZEV is based in captive fleet, Michelin may benefit from synergies between its services' activities and the ZEV.

The Banques des territoires is part of the Caisse des Dépôts et Consignations, a French public investor under the control of the French government. The mandate of the Banque des territoires is to invest a portion of the CDC's equity to finance development projects. The Banque des territoires' criteria are : the local aspects of projects (they must be led by a local authority like the region Auvergne-Rhône-Alpes), the usefulness of projects with respect to the general interest, to support territorial development and fight against territorial fractures, to help the energy and digital transition of territories.[25]

Crédit Agricole is a French bank. It is the partner of 55% of the territory's SMEs and therefore a key partner. Thus, Hympulsion's capital was opened to Crédit Agricole.[26]

The ADEME is a French public entity in charge of initiating, leading, coordinating, facilitating or carrying out environmental protection and energy management operations. The ADEME's interest in the ZEV is to intervene upstream in the creation of the sector to encourage the setting up of stations and vehicles.[27] The ADEME has granted subsidies to the ZEV project for HRS and FCEV.

The Innovation and Networks Executive Agency manages EU programmes in the field of transport, energy and telecommunications. It has granted a subsidy for HRS and FCEVs in the ZEV.

I.1.3 Current development and perspectives of the ZEV

Only two stations have been built for the moment. The 18 remaining stations should be inaugurated by 2023. Fifteen companies and structures have volunteered to commit to hydrogen mobility by

[23]https://www.cancer-environnement.fr/553-Pollution-de-lair-en-Region-Auvergne-Rhone-Alpes.ce.aspx#:~:text=Effets%20sanitaires%20chroniques,-Pr%C3%A8s%20de%205&text=La%20pollution%20atmosph%C3%A9rique%20entraine%20des,air%20et%20risque%20de%20cancer).

[24] Challenges, https://www.challenges.fr/entreprise/michelin-met-la-gomme-sur-le-service_94505

[25] See the interview with Isabelle Saffrey (Banque des territoires) in Annex F.

[26] See the interview with Thierry Raevel and Simon Aulagnier (Hympulsion) in Annex D.

[27] See the interview with ADEME in Annex I.

purchasing a total of nearly 40 vehicles.[28] The hydrogen seller is Hympulsion via the stations. Hydrogen is purchased through flat-fee contracts or paid at full tank for passing vehicles (holidaymakers). It is not a price per kilogram because hydrogen is difficult to measure. The price is around 12 to 15 EUR/kg in France, excluding VAT. This is the price integrated by Hympulsion's business model.[29]

For the moment, there are just four models of hydrogen vehicles in the ZEV. There are two hybrid battery-electric models with a hydrogen fuel cell extender (the light-duty-vehicles Renault Kangoo Hydrogen and Renault Master Hydrogen), and two fuel cell electric vehicles with no battery: a Berline (Toyota Mirai), and a SUV (Hyundai Nexo).

The ZEV has received €24 million in subsidies. 10.1 million will come from European funds (INEA). Of these 10 million, 4 are used as subsidies for the purchase of vehicles and the rest goes to Hympulsion to help build stations. The ZEV has received 14.4 million euros from the ADEME in. Of the 14,4 million euros, 6 are for vehicles' subsidies and the rest to help build stations.[30]

The granting of these subsidies is subject to three binding conditions that shape the development of the ZEV. Firstly, there must be 20 HRS operating in the ZEV by the end of 2023. Secondly, except for five HRS called "golden-bullets", all new HRS must gather 50 letters of commitment from potential vehicles' buyers before the beginning of the construction work. Finally, by the end of 2023, 1,5 ton of green hydrogen must be produced daily for hydrogen mobility in the ZEV.

I.2 Introduction to cost benefit analysis and methodology

A cost-benefit analysis is an analysis of a project to assess whether the benefits of the project overcome its costs. It allows to determine the economic efficiency of a particular project. A cost-benefit analysis can be undertaken from the perspective of a private entity or from the society's perspective. The second requires to monetize costs and benefits that a private entity would not consider such as pollution. These are called externalities in economics. Finally for the cost-benefit analysis of the ZEV, the concept of dynamic abatement cost will be used. This concept is introduced and explained at the end of this section.

I.2.1 Cost benefit analysis and externalities

Cost-benefit analysis is a standard economic tool to assess investment decisions in the sector of transports.[31] There exists a comprehensive academic literature in welfare economics on how to conduct a cost-benefit analysis.[32, 33, 34] The European Commission has also set its official

[28] SDIS 73, Vicat-SATM, ENGIE Cofely, SCDC, Savoie Déchets, EDF CIH, Taxis et VTC 73, Chambre des Métiers et de l'Artisanat, Jean Lain Automobiles, Ville de La Motte-Servolex, Ville de Chambéry, Ville d'Aix-les-Bains, Département de la Savoie, SERFIM, Grand Lac, Grand Chambéry (https://www.chambery-grandlac.fr/zev20juin/)
[29] According to the interview with Thierry Raevel and Simon Aulagnier (Hympulsion) in Annex D.
[30] According to the interview with Thierry Raevel and Simon Aulganier (Hympulsion) in Annex D.
[31] OECD, https://read.oecd-ilibrary.org/transport/quantifying-the-socio-economic-benefits-of-transport_9789282108093-en#page14
[32] Hanley, N. and Splash, C.L. (1993) Cost of Benefit Analysis and the Environment. Edward Elgar Publishing Ltd., Cheltenham
[33] Layard, R., Glaister, S. (1994) Cost-benefit analysis. 2nd edition. Cambridge University Press, Cambridge.
[34] Sen, A. K. (2000) The discipline of cost-benefit analysis. *Journal of Legal Studies*, n°29, pp. 931-952.

guidelines.[35] Put-simply, a cost-benefit analysis computes all the costs and benefits occurred by a project compared to a reference scenario. In this report the reference scenario will be a business as usual situation with diesel mobility instead of hydrogen mobility. The European guidelines differentiates the (private) financial perspective of an economic agent and the (public) economic perspective for society. As explained in the European guidelines, the public perspective should consider externalities as costs of benefits.

In the economic theory, externalities occur when an economic agent takes a decision that affect other agents (positively or negatively) and when no payment or compensation is paid for the impact of the decision on other agents. The concept is attributed to Arthur Cecil Pigou (1932).[36]

The externalities related to transports are listed in a Handbook of the European Commission : accidents, air pollution, climate change, noise, congestion, well-to-tank emissions, habitat damage and soil and water pollution.[37]

The cost-benefit analysis conducted in this report only considers the externalities that imply a significant difference of cost for society between diesel and hydrogen mobility. These externalities are the emission of local pollutants, the emission of GHG, and noise pollution. To include these externalities in the cost-benefit analysis with other financial costs and benefits, it is necessary to monetize them. The methodology used in this report for externalities' monetization is depicted below.

This work follows other cost-benefit analysis work such as the one carried out on the deployment of an FCEV fleet in the Normandy region in France (the EAS-HyMob project).[38]

I.2.2 Externalities' monetization

I.2.2.1 How to monetize GHG Emissions

GHG emissions represent a cost for society because climate change will damage society in numerous ways. A full note on GHG emissions' monetization is joined in Annex of this report. This part underlines the key aspects of this note to understand GHG monetization.

The monetization of GHG emissions is highly dependent on the choice of a social discount rate. A social discount rate (SDR) reflects how society values the future. The choice of a SDR is a key parameter, and perhaps the most important parameter, when conducting intemporal and intergenerational choices. Environmental protection policies that are costly in the present and yield benefits for future generations are typical intertemporal choices. The SDR allows to compare future benefits with present costs by discounting the future. In a survey of 200 academics who were defined as experts in the choice of social discount rate by virtue of their scientific publications, 92% reported that they would be comfortable with a social discount rate between 1% and 3%.[39]

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[35] European Commission https://eufunds.gov.mt/en/Operational%20Programmes/Useful%20Links%20and%20Downloads/Documents/2014-2020/cba_guide.pdf
[36] Pigou, A. C. (1932) The Economics Of Welfare, Macmillan And Co., Limited St. Martin's Street
[37] https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1
[38] Brunet, J., Ponssard, J.-P. (2016) Policies and deployment for Fuel Cell Electric Vehicles an assessment of the Normandy project, International Journal of Hydrogen Energy
[39] Drupp, M.A., Freeman, M.C., Groom, B. and Nesje, F. (2018) Discounting Disentangled, *American Economic Journal: Economic Policy* Vol. 10, n°4, pp. 109-34 (http://piketty.pse.ens.fr/files/Druppetal2015.pdf)

Under the assumption of a stationary demand function, a single stock of resource whose balance is known at all times, and (strictly) convex extraction costs, Hotelling (1931) showed that along the equilibrium path, the extraction rent (price or marginal revenues less marginal extraction cost) must rise at the rate of discount in order for resource owners to be indifferent about when to extract.[40]

With a "carbon budget" (a given quantity of tCO2 to be emitted by the time emissions stabilize, similar to a finite resource stock), it is efficient for the social cost of carbon (SCC) to follow a Hotelling rule: the SCC must increase at the speed of the social discount rate.

However, most carbon price are derived from integrated assessment modelling (IAM) and do not follow the Hotelling Rule. This suggests that IAM's carbon prices are not intertemporally optimized, maybe because of the political unacceptability of a high initial carbon price.[41] For example, the official French SCC of the government since 2019[42] does not reflect exactly the social cost of carbon but rather a political carbon price trajectory. Indeed, the aim of this price is to maintain continuity with the previous trajectory in 2018 (€$_{2018}$54), rather than to increase suddenly the 2019 SCC (as the SCC calculated for 2030 and 2040 would suggest).

The following ideas were inspired by a discussion between Dominique Bureau (General Delegate of the French Economic Council for Sustainable Development), Jean-Pierre Ponssard (Scientific Director of the Chair Energy and Prosperity, Institut Louis Bachelier), Guy Meunier (Associated researcher at the Chair Energy and Prosperity), and François Teyssier d'Orfeuil (intern at ENGIE Research/ Chair Energy and Prosperity).

The relatively small tax-adjusted cost of debt (3,1% in France in 2018)[43], the smaller economic growth perspective and higher growth uncertainty, and the long-term near-zero borrowing rates of the French government advocate for a SDR smaller than 4,5% in France. The discussion suggested to choose 2% instead.

The discussion suggested that the SCC should not depend on political considerations such as a continuous price over years. If an IAM models implies a high SCC in 2030 or 2040, this SCC could be considered as the right one. This suggests to use a Hotelling rule to derive the SCC before and after the date of the chosen reference SCC (either 2030 or 2040). With the relatively low SDR that the discussion above suggests (2%), this would lead to a curve flatter than the official French SCC trajectory. Hereby is an example with a 2% SDR, a Hotelling Rule, and a 2030 SCC of €$_{2018}$250 (the French official SCC trajectory value).

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[40] Hotelling, H. (1931) The Economics of Exhaustible Resources, *Journal of Political Economy*, Vol. 39, n°2, pp. 137-175

[41] Gollier C. (2020) The cost-efficiency carbon pricing puzzle, Working Paper, Toulouse School of Economics, University of Toulouse-Capitole (https://www.tse-fr.eu/sites/default/files/TSE/documents/doc/wp/2018/wp_tse_952.pdf)

[42] France Stratégie, La valeur de l'action pour le climat, Une valeur tutélaire du carbone pour évaluer les investissements et les politiques publiques, February 2019, p.124 (https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2019-rapport-la-valeur-de-laction-pour-le-climat_0.pdf)

[43] Carluccio, J., Mazet-Sonilhac, C. and Mésonnier, J.-S. (2018) Investment and the WACC: new micro evidence for France, Working Paper, Banque de France, WP #710

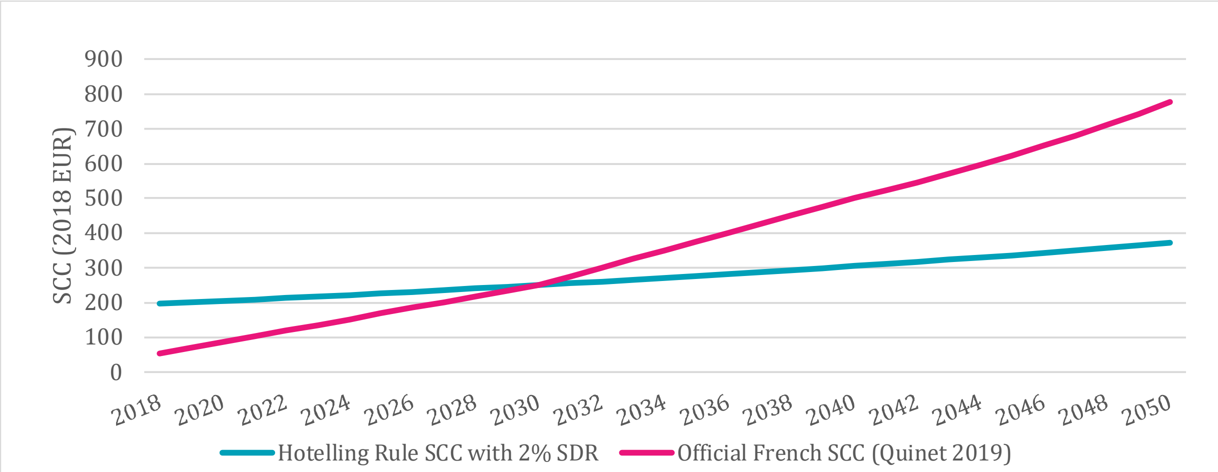

Figure 1 : Comparison of SCC trajectories

For the rest of this report, the SCC considered is the one following the Hotelling Rule with a 2% SDR. For the sensitivity analysis of the cost-benefit analysis, a 4,5% SDR will also be considered in the section II.3 of this report.

I.2.2.2 How to monetize local pollution

The local atmospheric pollution has a cost for society. It impacts the human health and the environment.

This report uses the methodology of the Quinet report (2013) to monetize local pollution.[44] This methodology of the Quinet report (2013) is inspired by the European Handbook of externalities (2008).[45]

The negative impacts of local pollution considered by the Quinet report (2013) to monetize local pollution are : the increase in mortality and morbidity occurred by the pollutants, the crop losses and deterioration of materials (in particular in the building).

The reference values proposed in the Handbook are calculated from the following input data: the HEATCO[46] and CBA-CAFE[47] projects for the costs of pollution, and the traffic data differentiated by area (dense urban, diffuse urban, lowland, etc.), by type of vehicle and by type of engine in the TREMOVE model.[48]

The Quinet report (2013) takes up the values of the 2008 Handbook but adapts them. The Quinet report (2013) formulates two critics against the Handbook (2008) values. Firstly, they do not take into account the increase in the value of human life observed since 2003, notably in the OECD report

[44] Commissariat général à la stratégie et à la prospective, Valorisation de la pollution atmosphérique dans le calcul socioéconomique, (https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/valorisation-de-la-pollution-atmosphc3a9rique-dans-le-calcul-socio-c3a9conomique1.pdf)
[45] Handbook on estimation of external costs in the transport sector Internalisation Measures and Policies for All external Cost of Transport (IMPACT) Version 1.1 Delft, CE, 2008
[46] European Commission, https://trimis.ec.europa.eu/project/developing-harmonised-european-approaches-transport-costing-and-project-assessment
[47] European Commission, https://ec.europa.eu/environment/archives/cafe/pdf/cba_methodology_vol2.pdf
[48] European Commission, https://ec.europa.eu/environment/archives/air/models/tremove.htm

of 2012 (about +50%).[49] Secondly, the values of the Handbook are calculated from German traffic, land use and population data. However, there are significant differences in population density between urban and non-urban areas in France and Germany. Moreover, the composition of the German car fleet is not comparable to the French fleet.

For these reasons, the Quinet report calculates its own reference values for the costs of marginal pollution in France. These costs are based on the French car parc in 2010 and on a value of statistical life of 3 million euro.[50] The value of statistical life allows to monetize the costs of losing human lives with increased mortality and morbidity induced by local pollution. It is estimated with economic techniques such as surveys and indirect revealed preference on the labor market (wage-risk relationship for instance).

Finally, the marginal cost of pollution depends on the local context: the more concentrated the pollutants are, the more damages they occur. The Quinet report differentiates the concentration of local pollutants by urban density.

Table 1 : Urban areas considered according to population density (hab/km²)

	Long distance urban	Diffuse urban	Urban	Dense urban	Very dense urban
Density range	< 37	37-450	450-1 500	1 500-4 500	>4 500
Average density	25	250	750	2 250	6 750

The ZEV vehicles will drive in suburban areas. This corresponds to the "urban" designation in the table above in terms of population density. The marginal costs of local pollution are computed for urban areas in the rest of the report.

This leads to the following values :

Table 2 : Marginal costs in urban areas in France in 2010 in the Quinet report (2013), based on the 2010 stock of pollution

NOX, urban (c€2002/g)	0,77
PM 2,5, urban (c€2002/g)	43,05
SO2, urban (c€2002/g)	0,72
NMVOC, urban (c€2002/g)	0,12

The Quinet report (2013) explains that these reference values depend on two parameters: the value of statistical life and the national level of emission. The report suggests that the reference value above should increase with the GDP per capita and the national emissions because the GDP per capita variation is the simplest indicator to estimate the change in the value of statistical life over years according to the report. This calculation is conducted in the section II.1.1 of this study.

[49] OECD, https://one.oecd.org/document/ENV/EPOC/WPNEP(2010)9/FINAL/en/pdf

[50] France Stratégie https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/archives/Elements-pour-une-r%C3%A9vision-de-la-valeur-de-la-vie-humaine.pdf

I.2.3 Estimation of the costs of tackling pollution in the presence of learning-by-doing with dynamic abatement costs.

A theorical case-study presenting a cost-benefit-analysis of the deployment of fuel cell electric buses is joined in annex of this report. This theorical case study is based on the work of G. Meunier, L. Moulin and J.-P. Ponssard (2019).[51] It illustrates the explanations on dynamic abatement costs mentioned in this section.

A static abatement cost is a simple and classic tool used to assess the economic efficiency of a project reducing greenhouse gas emissions. The static abatement cost is the ratio of the cost of the project to the abatements of emissions of greenhouse gas made by the project. The result is the cost of the abatement in EUR/tCO_2. A static abatement cost should be compared with the social cost of carbon (SCC) to assess the economic efficiency of a project. If the abatement cost of a project is below the SCC, the project is economically efficient for society, if it is above the project is economically inefficient and should not be conducted from society's perspective.

However, static abatement costs don't make sense to asses a deployment projects with learning-by-doing effects (decreasing costs) such as the ZEV. Static abatement costs would suggest to wait until the right time to launch the project. But with learning-by-doing effects (decreasing costs with acquired experience), the right time will never come if the project is not launched to start reducing the costs. A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard (2017)[52] showed that, in the presence of learning-by-doing, the optimal launching time of a trajectory is to start whenever the "dynamic" abatement cost is equal to the social cost of carbon. They also explain how to compute a "dynamic abatement cost".

In their paper, they use the concept of dynamic abatement cost which can be interpreted as the abatement cost of the whole progressive deployment of the FCEV fleet over years. The dynamic abatement cost of the project is the sum of two components: the cost of the deployment over years and the relative over-cost of a FECV vehicles at the end of the deployment.

As A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard (2017)[53] show, in the presence of "learning-by-doing" effect (decreasing cost of production with cumulative past output) and convexity of cost at a given time (decreasing return to scale), and with the assumption that carbon price increases at the social discount rate, the dynamic abatement cost of the deployment of a fleet can be expressed as follows:

$$DAC = \frac{rI}{N}e^{rD} + \frac{r\Omega(X) - c_0 N}{N}$$

Where r is the social discount rate, I is the discounted cash flow for the deployment schedule, N is the targeted hydrogen car park (Ncar) times the difference in emissions per unit of car at the end of deployment, D is the duration of the transition, $\Omega(X)$ is the cost of a green fleet after deployment and c_0 the cost of the corresponding diesel fleet.

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[51] Meunier, G., Moulin, L. and Ponssard, J.-P. (2019) Why local initiatives for the energy transition should coordinate. The case of cities for fuel cell buses in Europe.

[52] Creti, A., Kotelnikova, A., Meunier, G. and Ponssard, J-P. (2017) Defining the Abatement Cost in Presence of Learning-by-Doing: Application to the Fuel Cell Electric Vehicle.

[53] Creti, A., Kotelnikova, A., Meunier, G. and Ponssard, J-P. (2017) Defining the Abatement Cost in Presence of Learning-by-Doing: Application to the Fuel Cell Electric Vehicle.

In section II.2.4 of this report, for the cost-benefit analysis of the ZEV, the assumption of cost parity between diesel and hydrogen mobility in 2050 is made. Therefore, the second term of this sum is zero.

Hence, the dynamic abatement cost at the end of deployment is :

$$DAC = \frac{rI}{N} e^{rD}$$

It is more interesting for policy makers to know when to launch the deployment. Thus, the discounted dynamic abatement from the perspective of the beginning of the deployment is simply :

$$DAC = \frac{rI}{N}$$

With a more telling notation it would be:

$$DAC = \frac{r * DCF}{Abatements}$$

Where $I = DCF$ (the discounted cash flow of the deployment of FCEV and HRS), and $N = Abatements$ (the annual abatements made by the clean feet compared to a diesel fleet).

$r * DCF$ can be interpreted as an annualized investment. Indeed, if we consider an initial investment II and the corresponding annualized investment AI over n years :

$$II = \frac{AI}{1+r} + \frac{AI}{(1+r)^2} + \cdots + \frac{AI}{(1+r)^n} = AI \frac{1 - (\frac{1}{1+r})^n}{r}$$

Then, over an infinite horizon of time, when $n \to \infty$,

$$II = \frac{AI}{r}$$

Or,

$$AI = r * II$$

The dynamic abatement cost is therefore the ratio of the annualized present cost of the deployment over the annual abatements of CO_2 expected after the transition period.

The dynamic abatement cost perspective considers the decrease of CO2 emission on an infinite timeline, an illustration on the ZEV is provided in the next section on the cost-benefit analysis of the ZEV.

II Cost-benefit analysis of the ZEV in a conservative scenario

This first analysis of the ZEV is based on a conservative scenario of ZEV. Conservative means that the scenario is quite pessimistic with relatively few vehicles (1200 in 2024) and mostly Kangoo light-duty-vehicles (60% in 2024). These hybrid vehicles use both electricity via a battery and hydrogen via a fuel cell range extender, but experience has shown that they rely mostly on electricity and use little hydrogen (only 25% of the driving distance in the assumptions made here).

This scenario is built on a ramp-up of the number of vehicles between 2020 and 2030. The financial analysis is undertaken between 2020 and 2037 because a large part of hydrogen refueling stations and electrolysers needs to be replaced in 2038, after having reached their end-of-life (the majority of the stations and electrolysers are built in 2023 and they have a life duration of 15 years). The public analysis is undertaken both between 2020 and 2037, and on a longer-term perspective, using the dynamic abatement cost analysis presented in section I.2.3.

The costs-benefits analysis presented in this section consists in a comparison between a conservative scenario of the ZEV and a status-quo scenario based on diesel mobility.

II.1 Presentation of the scenario

The conservative scenario of the ZEV relies on assumptions about the costs of externalities such as the local pollution or the CO2 emissions, the ramp-up of the number of hydrogen vehicles, the deployment schedule of electrolysers and hydrogen refueling stations (HRS), and the cost of ownership of hydrogen vehicles versus diesel vehicles.

To compute the costs and benefits of the ZEV, a reference scenario is needed. The costs of the ZEV are over-costs compared to the reference scenario and the benefits are benefits in comparison with the reference scenario. The reference scenario is a status quo scenario : it assumes that without the ZEV, the vehicles owners would have bought diesel vehicles instead of hydrogen vehicles.

A key assumption of the analysis conducted below is the choice of a discount rate to value the future. For the financial analysis from the private perspective, the discount rate equals the weighted average cost of capital (WACC) and is set to 7%. For the public perspective, the choice of a social discount rate (SDR) is subject to debate among economists as explained in section I.2.2. This study considers a SDR of 2% as suggested in I.2.2, but a sensitivity analysis with a SDR of 4,5% (official SDR of the French administration) is undertaken and presented in section II.3.

II.1.1 Assumptions on externalities

In section I.2.2, this report describes how externalities such as local pollution or CO2 emissions are monetized.

Section I.2.2 explains how the marginal cost of four local pollutants (NOX, PM, SO2, NMVOC) are computed in 2010.

Table 3 : Marginal costs in urban areas in France in 2010 in the Quinet report (2013), based on the 2010 stock of pollution

NOX, urban (c€2002/g)	0,77
PM 2,5, urban (c€2002/g)	43,05
SO2, urban (c€2002/g)	0,72
NMVOC, urban (c€2002/g)	0,12

As explained in section I.2.2, the marginal cost of local pollution bared by society depends on the value of statistical life and the concentration of emission of local pollutants in the country considered.

The value of statistical life is supposed to vary in proportion to the GDP per capita. Hence, the marginal cost of the local pollutants evolves proportionally to the GDP per capita and the national level of emission. The French GDP per capita increased by 8,41% between 2010 and 2019[54] and the level of emissions diminished by 6% per year between 2010 and 2015[55] and 5% between 2015 and 2020.[56] Therefore, in 2020, the marginal costs of the four local pollutants should be as follows:

Table 4 : Marginal costs in urban areas in France in 2020, based on the 2010 stock of pollution

NOX, urban (c€2002/g)	0,44
PM 2,5, urban (c€2002/g)	24,45
SO2, urban (c€2002/g)	0,41
COVNM, urban (c€2002/g)	0,07

The marginal costs have decreased because the total national level of emission of local pollutants decreased faster than the GDP per capita increased. However, the level of emission is dependent of the localization and the local evolution may be different from the national evolution. For instance, in Grenoble, in Auvergne-Rhône-Alpes, the local pollution seems to be stationary in spite of political action.[57]

These marginal costs must be multiplied by the emissions' factors of vehicles to derive the cost of local pollution for vehicles in 2020. The emissions' factors are different for each vehicles. The Quinet report (2013) gives mean values for light-duty-vehicles (LDV) and passenger vehicles (PV) for diesel vehicles of European standard EURO 6 (a standard limitation of emission). EURO 6 is the current emission standard in the EU. EURO 7 standard values are not known yet. The cost-benefit analysis considers that the diesel vehicles (bought in the business as usual/ status quo scenario without the ZEV) would have respected the EURO 6 standard.

Table 5 : Emission factors of pollutants for vehicles of EURO 6 standard (g/veh.km)

	LDV	PV
NOX	0,0538	0,041
PM <2,5	0,0018	0,0018
SO2	0,0016	0,0011
NMVOC	0,103	0,027

The marginal costs of local pollution per vehicle type can be derived from the previous tables. Emissions factors should be multiplied with marginal costs of pollutants. The sum of these four multiplications (for each of the four pollutants) yields the marginal cost of local pollution per vehicle.

This calculation gives the following marginal costs for local pollution:

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[54] The fall in the GDP per capita due to the 2020 Covid crisis is not considered. It seems both unethical and illogical to decrease the value of statistical life by 10% because of a crisis that comes partly from the actions taken to save lives.
[55] France Stratégie, https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/valorisation-de-la-pollution-atmosphc3a9rique-dans-le-calcul-socio-c3a9conomique1.pdf (page 23)
[56] MTES, https://www.ecologique-solidaire.gouv.fr/sites/default/files/II%20-%20Sc%C3%A9nario%20de%20r%C3%A9f%C3%A9rence.pdf (tableau 11)
[57] https://france3-regions.francetvinfo.fr/auvergne-rhone-alpes/isere/grenoble/grenoble-pollution-air-ne-baisse-pas-metropole-malgre-nouveau-plan-circulation-1735225.html

Table 6 : Marginal costs of local pollution per vehicles type of EURO 6 standard in urban areas in France in 2020, based on the 2010 stock of emission

	LDV	Passenger car
Marginal cost (c€2020/veh.km)	0,097	0,083

The light-duty-vehicles pollute on average more than the passenger cars, which results in a higher marginal cost of local pollution.

To monetize local pollution in this section, the marginal costs in 2020 are multiplied by 1,01 (the yearly increase of GDP/capita between 2020 and 2030) and by 0,95 (the yearly decrease of the total national level of emissions between 2020 and 2030) each year. This results in the following yearly marginal costs.

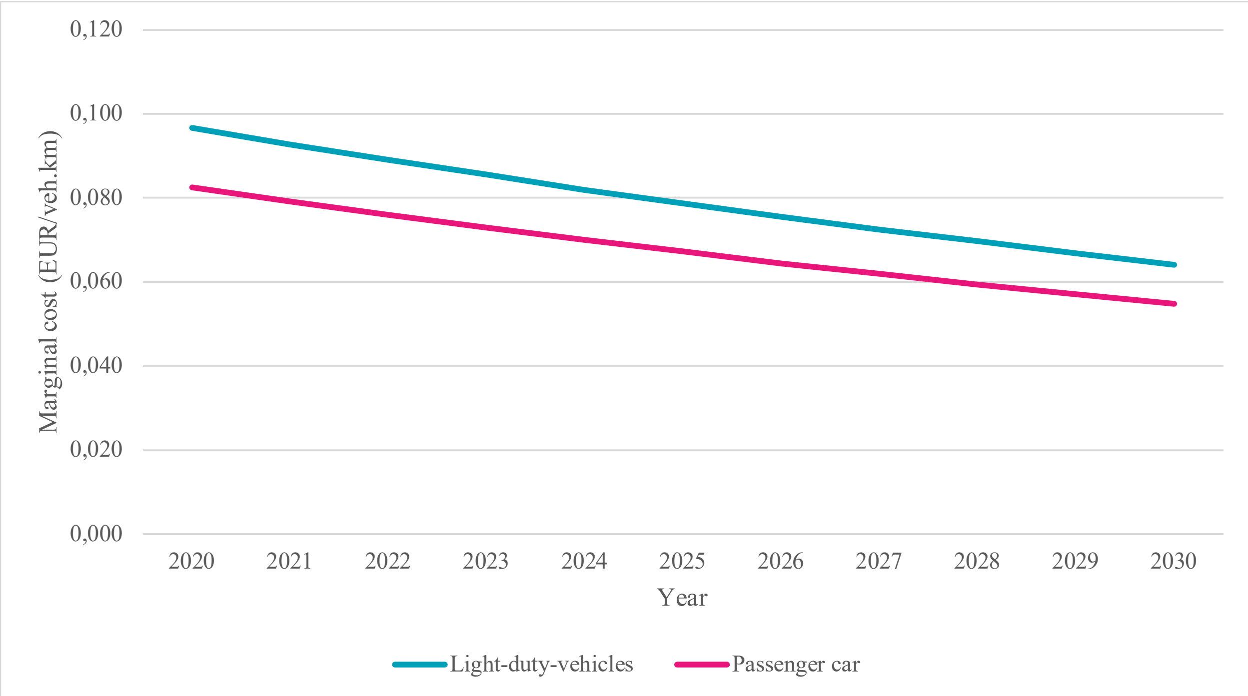

Figure 2 : Marginal cost of local pollution in urban area in France over the 2020-2030 period for vehicles of EURO 6 standard

These figures may seem a little low. It is important to underline here that they are highly dependent on the local context (the concentration of local pollutants). In a highly polluted area such as a urban center of a city, the marginal cost of local pollution would be ten times higher.

Moreover, section I.2.2 explains how a social cost of carbon can be computed with a Hotelling Rule, assuming a reference cost and a social discount rate through. As mentioned above, the cost-benefit analysis is undertaken with a social discount rate (SDR) of 2%, but a SDR of 4,5% is also used in a sensitivity analysis. The social cost of carbon (SCC) estimated for 2030 with an Integrated Assessment Model in the 2019 Quinet report (see I.2.2) is 250 EUR/tCO2. This results in the two following trajectory for the SCC, depending on the social discount rate:

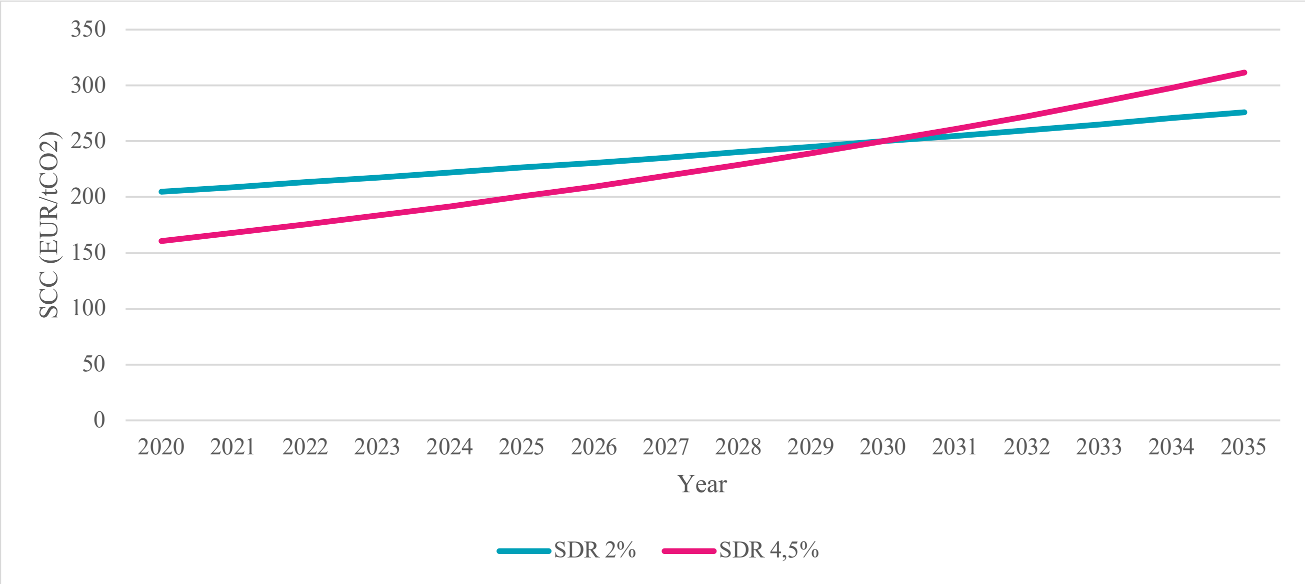

Figure 3 : Social cost of carbon (SCC) depending on the social discount rate (SDR) (EUR/tCO2)

II.1.2 Assumptions on the vehicles

Only four types of hydrogen vehicles are used in this scenario: the Renault Kangoo ZE Hydrogen, the Renault Master ZE Hydrogen, the Toyota Mirai, and the Hyundai Nexo. The Kangoo and the Master are hybrid light-duty-vehicles: they are electric vehicles with a fuel cell range extender. The Mirai and the Nexo are passenger cars, respectively a Berline and a SUV model.

The reference or status-quo scenario assumes that without the ZEV, the vehicles owners would have bought diesel vehicles instead of hydrogen vehicles. The diesel vehicles of the reference scenario are the Renault Kangoo Express, the Renault Master III, the Mercedes class E (counterpart of the Toyota Mirai), and the Audit Q5 (counterpart of the Hyundai Nexo).

The conservative scenario assumes an exponential increase of the number of vehicles in the ZEV from 30 vehicles in 2020 to 1200 vehicles in 2024, followed by a linear increase from 1200 in 2024 to 4500 in 2030. From 2030 onwards, the hydrogen vehicles' park is supposed to be stationary.

The following assumptions are made about the vehicles :

Table 7 : Assumptions on vehicles

	Kangoo		Master		SUV		Berline	
	H2	Diesel	H2	Diesel	H2	Diesel	H2	Diesel
Purchase price 2020 (EUR)	48 300	22 960	60 000	37 200	66 583	50 000	65 750	46 125
Purchase price 2025 (%2020)	80%	105%	80%	105%	80%	105%	80%	105%
Purchase price 2030 (%2020)	70%	116%	70%	116%	65%	116%	65%	116%
Duration of ownership (years)	5	5	5	5	5	5	5	5
Resale, if purchased in 2020	10%	37%	10%	37%	10%	29%	10%	29%
Resale, if purchased in 2025	15%	33%	15%	33%	15%	27%	15%	27%
Resale, if purchased in 2030	30%	30%	30%	30%	25%	25%	25%	25%
Bonus/Malus (EUR)	-3000	0	-3000	0	-3000	7462	-3000	230
ZEV grants (until 2023) (EUR)	-7600	0	-7600	0	-7600	0	-7600	0
Diesel WLTP (L/100km)	0	6,2	0	8	0	6,9	0	6,2

H2 WLTP (kg/100km)	0,90	0,00	1,16	0,00	0,95	0,00	1,00	0,00
Elec WLTP (kWh/100km)	15,5	0	27,5	0	0	0	0	0
Maintenance (EUR/1000km)	50,4	40	50,4	40	50,4	40	50,4	40
Insurance (EUR/an)	480	700	480	700	480	700	480	700
CO2 WLTP (gCO2/km)	0	165	0	236	0	180	0	164
Noise pollution (EUR/1000km)	0	2,02	0	2,02	0	2,02	0	2,02
Usage (km/year)	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000

Every varying quantity is assumed to change linearly over years. The 2025-2030 trajectories continue after 2030.

The price of the hydrogen vehicles decreases over years with learning-by-doing and scale effects. The price of the diesel vehicles increase because of scale effects and rising environmental standards. With regulation such as zero emission zones, diesel vehicles are less desirable and are produced in smaller quantities, which raises costs. The production costs also increase because of the adaptation to rising environmental standards.

The hydrogen consumption of the vehicles depends on whether they also use an electric battery or not, and on the respective distance during which they use their electric battery or their fuel cell range extender.

Table 8 : Assumptions on vehicles' consumption

	Usage H2 (km/y)	Consumption H2 (kg/100km)	Usage Elec (km/y)	Consumption elec (Wh/km)
Kangoo	5000	0,90	15000	155
Master	10000	1,16	10000	275
Nexo	20000	0,95	0	0
Mirai	20000	1,00	0	0

Finally, to compute the cost of ownership in the ZEV, this study makes assumptions on the costs of fuels.

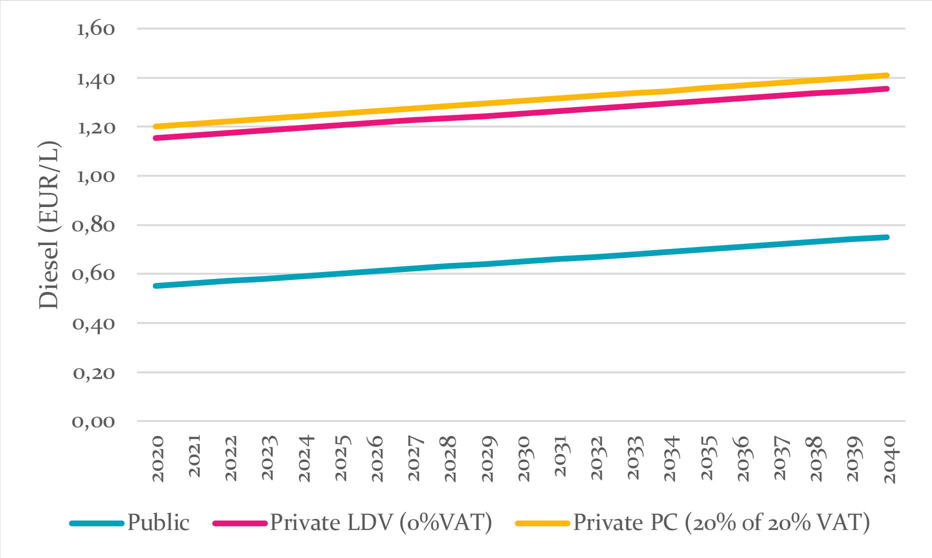

Figure 4 : Assumptions on the costs of diesel between 2020 and 2040

The public diesel price is without any tax. The private diesel price is without VAT for light-duty-vehicles (LDV) and with 20% of the VAT (of 20%) for passenger cars (PC).[58]

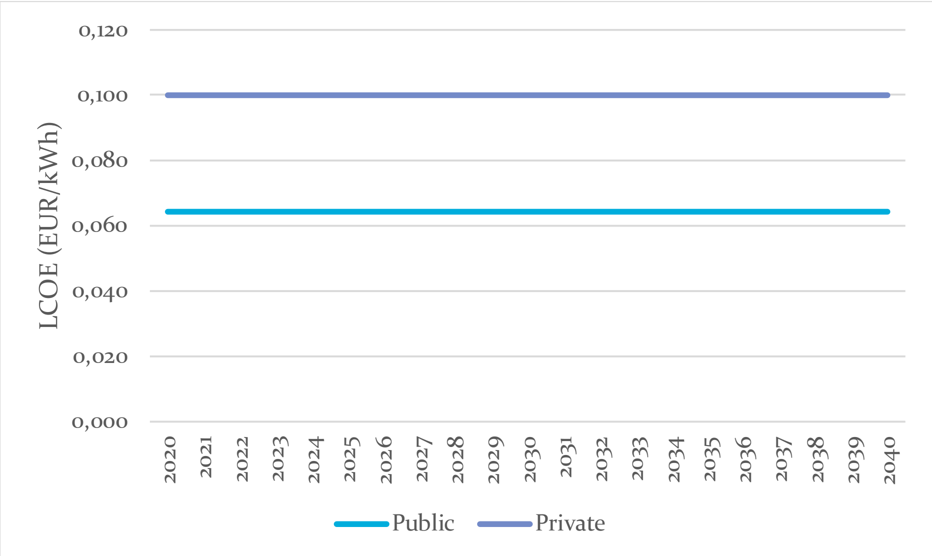

Figure 5 : Assumptions on the costs of electricty at stations between 2020 and 2040

II.1.3 Assumptions on the deployment schedules of vehicles and stations

Table 9 : Ramp-up of the number of vehicles

Year	Number	%Kangoo	Nb Kangoo	%Master	Nb Master	%Nexo	Nb Nexo	%Mirai	Nb Mirai

[58] https://www.legifiscal.fr/actualites-fiscales/2315-tva-essence-deductible-60-2020.html#:~:text=La%20TVA%20sur%20le%20gazole,100%25%20pour%20les%20v%C3%A9hicules%20utilitaires.

Exponential	2020	30	85%	26	0%	0	15%	5	10%	3
	2021	75	79%	59	0%	0	13%	9	9%	7
	2022	190	73%	138	10%	19	10%	19	8%	14
	2023	477	66%	316	20%	95	8%	36	6%	30
	2024	1200	60%	720	30%	360	5%	60	5%	60
Linear	2025	1833	58%	1069	32%	581	5%	92	5%	92
	2026	2467	57%	1398	33%	822	5%	123	5%	123
	2027	3100	55%	1705	35%	1085	5%	155	5%	155
	2028	3733	53%	1991	37%	1369	5%	187	5%	187
	2029	4367	52%	2256	38%	1674	5%	218	5%	218
	2030	5000	50%	2500	40%	2000	5%	250	5%	250

The vehicles are leased for five years and they are sold afterwards at their residual value.

The deployment schedule of hydrogen refueling stations is considered exogenous. It is designed such as to meet the binding conditions of the granting of subsidies (see I.1.3).

At the beginning of 2024, according to the original plan, there should be 20 hydrogen refueling stations : one with a nominal distribution of 40kg/day, 6 of 60kg/day, 8 of 200 kg/day with centralized production of hydrogen (1 electrolyzer of 800 kg/day and 2 of 400 kg/day). There should also be 5 stations of 200 kg/day with on-site hydrogen production.[59]

Table 10 : Hydrogen refueling stations (HRS) deployment schedule

	Electrolysers		HRS with no electrolyser			HRS+Electrolyser 200 kg
Year	Nb 800 kg	Nb 400 kg	Nb 40kg	Nb 60kg	Nb 200 kg	Number
2020			1			
2021			1			
2022			1	3		
2023		1	1	6		
2024	1	2	1	6	8	5
2025	1	2	1	6	8	5
2026	1	2	1	6	8	5
2027	1	2	1	6	8	5
2028	1	2	1	6	8	5
2029	1	2	1	6	8	5
2030	1	2	1	6	8	5

Finally, one of the binding conditions was to produce 1500 kg of hydrogen per day in the ZEV by the end of 2023. In this conservative (pessimistic) scenario of the ZEV, this binding condition cannot be met. This analysis considers that the subsidies are still granted despite that.

II.1.4 Demand for hydrogen

These assumptions lead to the following demand for hydrogen.

[59] The orignal plan is currently being updated.

Table 11 : Summary of hydrogen consumption, stations' utilization and hydrogen cost

Year	H2 Consumption (kg/d)	Utilization rate*	LCOH (EUR/kgH2)	
			Public	Private
2020	7	18%	47	55
2021	16	39%	23	27
2022	39	18%	42	49
2023	98	25%	45	52
2024	245	8%	69	80
2025	373	12%	48	55
2026	498	17%	38	43
2027	620	21%	32	36
2028	738	25%	28	32
2029	856	29%	25	28
2030	969	32%	23	26

The theorical maximum utilization rate of a hydrogen refueling station is 75% (because of maintenance and to avoid overload). Here, the utilization rates are well below this limit because of the oversized production capacity. This capacity is nonetheless required by the binding conditions of the subsidies (see I.1.3). These low utilization rates of refueling stations lead to a high levelized cost of hydrogen (LCOH), which is the mean cost of distribution at the pump in hydrogen refueling stations. An example of the calculation of the private LCOH is presented in Annex C. There is a difference between private and public LCOH because from the public perspective the discount rate is 2%, and from the private perspective the discount rate is 7%. The annualized cost of investment (annualized CAPEX) is therefore more expensive from the private perspective. The basic intuition here is that the private sector could have invested that money in another project with a 7% yield : there is a higher opportunity cost of investing for the private sector than for the public sector (because the public sector is not profit driven and takes other aspects in consideration in its discount rate[60]).

[60] See the discussion on the determination of a social discount rate (SDR) in the Annex A, on the social cost of carbon.

II.2 Presentation of the results

II.2.1 Financial analysis from the private perspective

The financial analysis is undertaken between 2020 and 2037 because the majority of the hydrogen refueling stations and of the electrolyzers needs to be replaced from 2038 onwards (they have a life duration of 15 years and most of them are built in 2023 in the HRS schedule). The next table computes the costs and benefits of the ZEV from the perspective of a private owner of HRS and electrolysers selling hydrogen to vehicles at 12 EUR/kg.

Table 12 : Private analysis on HRS

Year	LCOH (EUR/kg)	Consumption of vehicles (t/year)	H2 selling price (EUR/kg)	Loss if price of 12 (k€/year)	Subsidies HRS (k€/year)	**Total (k€/year)**
2020	54,6	3	12,0	111	0	111
2021	27,1	6	12,0	86	-309	-223
2022	49,4	14	12,0	533	0	533
2023	51,9	36	12,0	1 429	-1 158	271
2024	80,1	90	12,0	6 117	-1 930	4 187
2025	55,4	136	12,0	5 916	-11 003	-5 087
2026	43,5	182	12,0	5 718	0	5 718
2027	36,4	226	12,0	5 524	0	5 524
2028	31,8	270	12,0	5 334	0	5 334
2029	28,5	312	12,0	5 150	0	5 150
2030	26,0	354	12,0	4 970	0	4 970
2031	26,0	354	12,0	4 970	0	4 970
2032	26,0	354	12,0	4 970	0	4 970
2033	26,0	354	12,0	4 970	0	4 970
2034	26,0	354	12,0	4 970	0	4 970
2035	26,0	354	12,0	4 937	0	4 937
2036	26,0	354	12,0	4 937	0	4 937
2037	25,6	354	12,0	4 814	0	4 814

This calculation demonstrates that the HRS subsidies fail to compensate the over-cost of selling hydrogen below its production and distribution cost between 2020 and 2037. In this conservative scenario, it appears that the ZEV project is not profitable for an HRS owner selling H2 at the price of 12 EUR/kg.

The overall private cost of the ZEV, including the costs of purchase and ownership of vehicles, can be computed with the previous assumptions. This over-all cost consists in the discounted sum of costs and benefits from the perspective of a private company owning all the electrolysers, the hydrogen refueling stations and the vehicles of the ZEV (and selling the overproduction outside the ZEV at 2,5 EUR/kg). This calculation allows to determine the part of the overall private cost bared by the vehicles' owner, and the part bared by the HRS's operator.

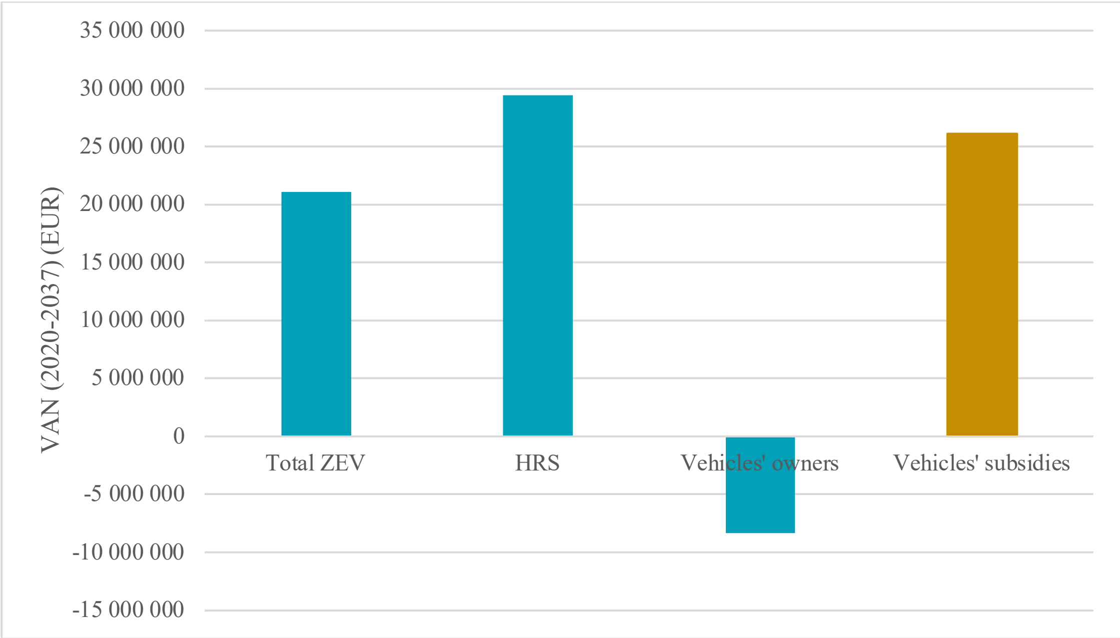

Figure 6 : VAN (7%) shared between HRS and vehicles

If the hydrogen is sold at 12 EUR/kg to vehicles' users, the burden of the over-cost of the ZEV is bared by the HRS' operator between 2020 and 2037 and the vehicles' owners make profits. It can be interesting to compare the benefits that vehicles owners take from the ZEV with the subsidies that sponsor the purchase of hydrogen vehicles. The VAN (at 7%) of the subsidies granted to vehicles buyers between 2020 and 2027 is 26 million euros and the VAN (at 7% of their benefits) is 8 million euros. Hence, without these subsidies, the ZEV would be a loss making operation for vehicles' owners.

From the private perspective, both for an HRS operator and for the ZEV globally (HRS and vehicles), the ZEV is a loss-making project between 2020 and 2037 in this scenario. Is it still the case from the public perspective when externalities are considered?

II.2.2 Yearly flows of costs and benefits from the public perspective

The next table shows the yearly flows of costs and benefits of the ZEV from the public perspective (externalities are considered and monetized).

Table 13 : Flows of costs and benefits for the ZEV

	Purchase price (k€/year)	Resale value 5 years (k€/year)	Fuel consumption (k€/year)	Maintenance (k€/year)	Insurance (k€/year)	CO2 emissions (k€/year)	Local pollution (k€/year)	Noise pollution (k€/year)	Total (k€/year)
2020	780	29	105	7	-7	-23	-1	-1	889
2021	912	-9	95	16	-17	-53	-1	-3	940
2022	2 170	-105	503	39	-42	-141	-3	-8	2 414
2023	4 755	-490	1 355	99	-105	-374	-8	-19	5 213
2024	10 155	-1 765	5 502	250	-264	-996	-19	-48	12 813
2025	7 593	-2 055	5 441	381	-403	-1 562	-28	-74	9 291
2026	6 360	-1 730	5 395	513	-543	-2 158	-37	-100	7 702
2027	5 553	-1 522	5 342	645	-682	-2 783	-44	-125	6 383
2028	5 102	-1 415	5 295	777	-821	-3 440	-51	-151	5 295
2029	5 147	-1 450	5 211	908	-961	-4 129	-58	-176	4 492
2030	2 098	-648	5 135	1 040	-1 100	-4 853	-63	-202	1 408
2031	1 403	-423	4 946	1 040	-1 100	-4 950	-61	-202	653
2032	1 411	-430	4 759	1 040	-1 100	-5 049	-58	-202	372
2033	1 697	-516	4 576	1 040	-1 100	-5 150	-56	-202	289
2034	2 655	-789	4 395	1 040	-1 100	-5 253	-54	-202	693
2035	2 098	-648	4 195	1 040	-1 100	-5 358	-52	-202	-25
2036	1 403	-423	4 020	1 040	-1 100	-5 465	-49	-202	-776
2037	1 411	-430	3 772	1 040	-1 100	-5 574	-47	-202	-1 130
2038	1 697	-516	3 483	1 040	-1 100	-5 685	-46	-202	-1 330
2039	2 655	-789	2 648	1 040	-1 100	-5 799	-44	-202	-1 590
2040	2 098	-648	2 512	1 040	-1 100	-5 915	-42	-202	-2 257

Compared to the reference scenario, the costs of the ZEV are the greater purchasing price of hydrogen vehicles, the fuel over-cost (hydrogen consumption is more expensive than diesel consumption) and the maintenance over-cost of hydrogen vehicle. The benefits of the ZEV are the greater resale value of vehicles (due to a higher purchasing price), the cheaper insurance of hydrogen vehicles, and above all the reduction of negative externalities (less CO2 and local pollutants emissions, less noise pollution).

From the public perspective, the sum of costs and benefits of the ZEV compared to the reference scenario results in an over-cost between 2020 and 2034 and starts to yield benefits from 2035 onwards.

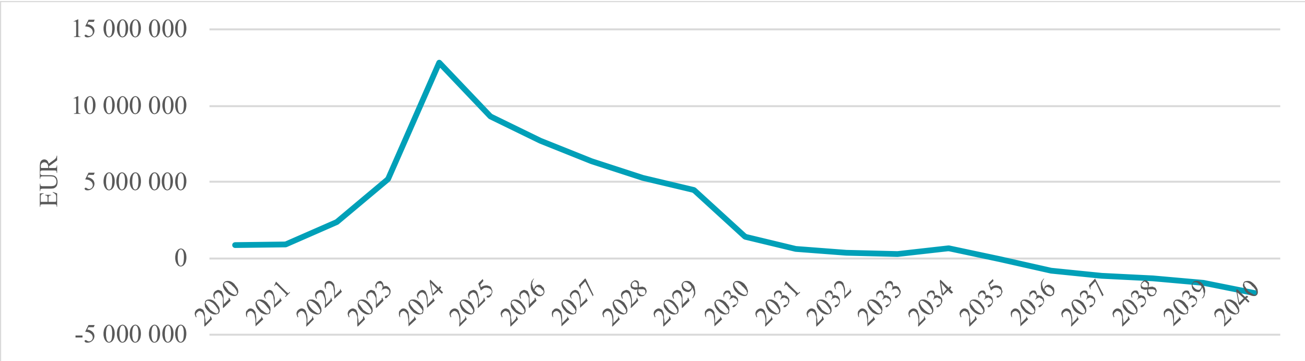

Figure 7 : Yearly flows of costs and benefits from the public perspective (2020-2040)

The VAN (at 2%) between 2020 and 2037 is an over-cost of 48 million euros.

This means that a public decider who is not interested in the long term, and is only looking at the project's merits until 2037 risks to make losses in this conservative scenario.

II.2.3 Static analysis of externalities

The yearly static abatement costs are the ratio of the yearly public over-cost of the ZEV (without monetizing the CO2) on the abatement in CO2 emissions allowed by the ZEV the same year. This gives the cost of reducing CO2 emissions with the ZEV for a specific year.

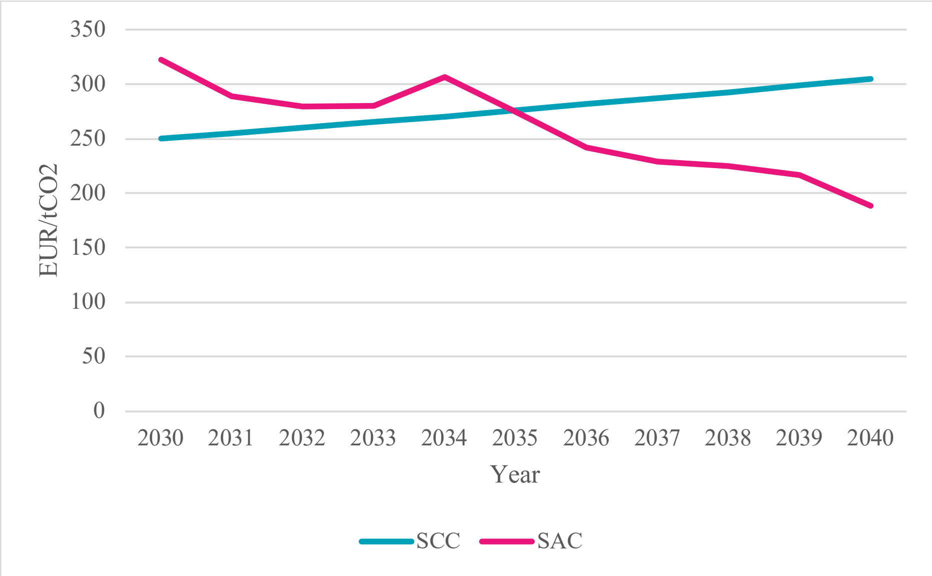

Figure 8 : Social cost of carbon compared to the yearly

These abatement costs are more expensive than the social cost of carbon (the cost of damages impose by CO2 emissions on society) until 2035. This would suggest waiting until 2035 to start the ZEV. It should be noted that, as expected, this conclusion is coherent with the yearly flows of costs and benefits from the public perspective that yields benefits from 2035 onwards (see I.2.2). This is because the yearly flows monetize GHG emissions with the same SCC.

Besides, the VAN of the benefits obtained from the decrease of local pollution is 558 k€. In Quinet (2013), the value of statistical life year in France in 2010 is estimated to be 115 k€.[61] This value is supposed to increase with the GDP per capita. In 2019, it would be 125 k€.[62] Hence, the total benefits of decreasing local pollution with this pessimistic scenario of the ZEV amounts to four times the value of statistical life year. This is equivalent to increasing by one year in good health the life of four inhabitants of the Auvergne-Rhône-Alpes region. The low results associated with the conservative scenario come from the relatively small number of vehicles and the small marginal cost of local pollution. The marginal cost is small because vehicles are believed to drive in an area with 450 to 1,500 pop/km^2 (referred as a urban area in I.2.2). As explained in II.1.1, if the assumption is made that the ZEV vehicles drive in a very dense urban area (such as the city center for example) the marginal costs would be ten times higher. Hence, a ZEV project in a city center with a fairly small number of vehicles (1200) could spare around forty years of life expectancy to inhabitants of the city center. As an illustration, there is a captive fleet of FCEV taxis that drive in Paris and brings similar benefits (see the Hype project[63]). Also the ZEV project is looking to develop FCEV taxis in cities in Auvergne-Rhône-Alpes region.[64]

[61] Quinet report (2013), https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/valorisation-de-la-pollution-atmosphc3a9rique-dans-le-calcul-socio-c3a9conomique1.pdf

[62] The fall in the GDP per capita due to the 2020 Covid crisis is not considered. It seems both unethical and illogical to decrease the value of statistical life by 10% because of a crisis that comes partly from the actions taken to save lives.

[63] https://hype.taxi/

[64] See interview with Simon Aulagnier (Hympulsion) in Annex G, and with Gilles Haon (ENGIE Solutions) in Annex H.

At this point, in this conservative (pessimistic) scenario, both the private financial analysis, the public cost-benefit analysis with the yearly flows of costs and benefits, and the static abatement costs analysis, suggest that the ZEV should not be launched in 2020, but rather in 2035 (from the public perspective). This is the consequence of the fact that hydrogen vehicles and stations will be a lot cheaper in 2035, that the utilization rate of stations will allow to produce hydrogen at a lower cost, and that the cost of emitting GHG increases between 2020 and 2035 in the assumptions (from 205 EUR/tCO2 in 2020 to 276 EUR/tCO2 in 2035).

However, this reasoning is flawed. Indeed, if HRS operators, and vehicles buyers wait for the prices to fall off, they will not decrease since there will not be any learning-by-doing and scale effects to diminish them. Furthermore, with the chicken and egg issue between stations and vehicles, it is not possible to launch a station with a good enough utilization rate to produce cheap hydrogen: it takes a few years to attract the users in the new stations.

Overall, this suggests adapting the analysis to consider the future benefits of the financial efforts made today. It is precisely the principle of dynamic abatement cost analysis that considers the future benefits of a transition conducted today.

II.2.4 Dynamic abatement cost

The theory and methodology to compute dynamic abatement cost are explained in section I.2.3. This framework allows to derive an abatement cost while considering the abatements made after the transition to a clean vehicles' park.

To compute a dynamic abatement cost, a stationary state is needed. This means that the difference of costs between diesel and hydrogen mobility must be steady at a certain point. The assumption made here is that the over-cost of hydrogen mobility from the public perspective, excluding the benefits from CO2 abatements, shrinks linearly from 2040 to reach zero in 2050. From 2050 onwards, it is assumed that all the costs have reached stationary state.

Table 14 : Assumptions for dynamic abatement cost calculation

	Public overcost without CO2 monetization (k€)	CO2 abatements (tCO2)	SAC CO2 (EUR/tCO2)
2040	3 658	19 410	188
2041	3 292	19 410	170
2042	2 927	19 410	151
2043	2 561	19 410	132
2044	2 195	19 410	113
2045	1 829	19 410	94
2046	1 463	19 410	75
2047	1 097	19 410	57
2048	732	19 410	38
2049	366	19 410	19
2050	0	19 410	0

The previous assumption implies that the static abatement cost (SAC) becomes null from 2050 onwards.

With these assumptions, the ZEV consists in an investment made between 2020 and 2050 that will yield constant benefits in the future (the 19,410 tons of CO2 abated each year). As explained in section I.2.3, the dynamic abatement cost (DAC) can be derived from these assumptions with the formula:

$$DAC = \frac{rI}{N}$$

Where r is the social discount rate (2%), I the discounted cash flow of the public over-cost of the ZEV without monetizing CO2 abatements between 2020 and 2050, and N the yearly abatements after 2050.

Table 15 : Dynamic abatement cost of the conservative scenario

Social discount rate	2%
CO2 abatements (tCO2)	19 410
Discounted cash flow without CO2 (2020-2050) (M€)	115
DAC (2%) (EUR/tCO2)	119

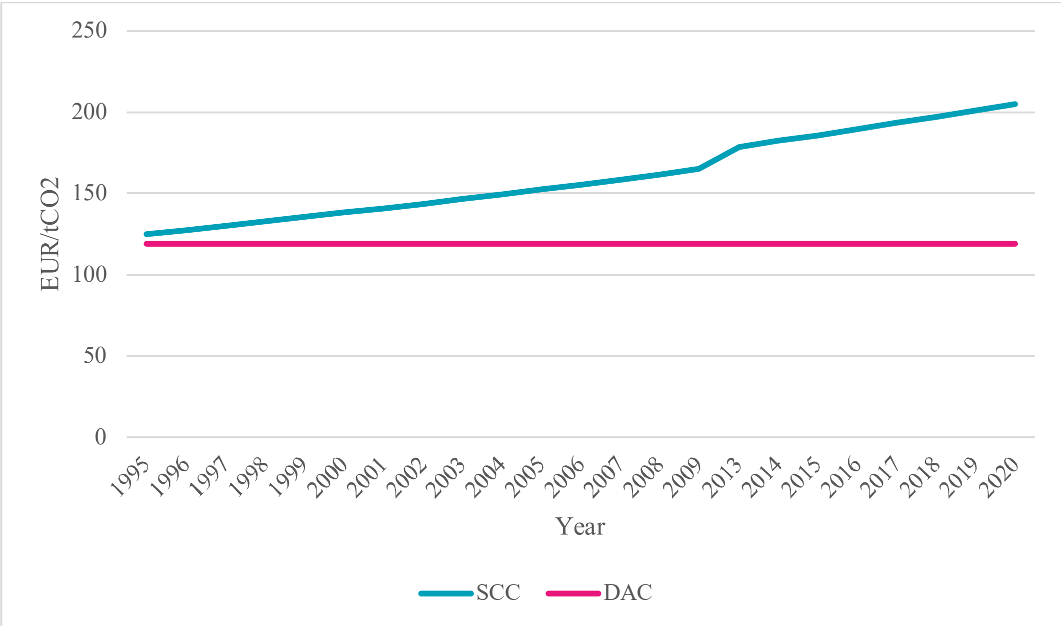

Figure 9 : dynamic abatement cost (DAC) compared to social cost of carbon (SCC)

The DAC of the conservative scenario of the ZEV is therefore 119 EUR/tCO2. This abatement cost is supposed to be compared with the social cost of carbon (SCC) in 2020, which is 205 EUR/tCO2 with the previous assumptions. This implies that if the hydrogen park's abatements last, the ZEV project could be launched as soon as 2020 (and even before).

It could be argued that it is optimistic to consider that the ZEV project allows abatements of CO2 emissions for an unlimited number of years from 2050 onwards. Mobility could be so different in the future that the comparison between diesel and hydrogen technologies may not make sense anymore. However, the theoretical framework of dynamic abatement costs is justified by the fact that this study compares these two technologies only. There may be other options to decarbonize mobility, but each option should be explored and examined for its own merits.

A different approach without an infinite timeline is possible. The total static abatement cost of the ZEV can be derived between 2020 and 2060 with the same assumptions. It is the ratio of the discounted cash flow of the transition on the total abatements between 2020 and 2060. This calculation could be justified if a disruptive technology emerged in 2060 and made hydrogen mobility obsolete. The static abatement cost associated with this approach is 268 EUR/tCO2. It would suggest to wait 2033 to launch the ZEV.

Overall, with the previous assumptions, a dynamic analysis that considers the benefits of the ZEV on the longer-term shows that the ZEV project makes economic sense from the perspective of society. Since this was not the case with the cost-benefit analysis between 2020 and 2037, the advantages of the ZEV for society depends on the timeline considered and the confidence that the project could last in the long term.

II.3 Sensitivity analysis

As discussed in section I.2.2, the choice of a social discount rate is subject to debate among economists. It is a key parameter for the public analysis since it has many contradictory effects on the calculation. The choice of a 2% social discount rate (SDR) was motivated by economic considerations explained earlier. What would be the impact on the public analysis if the SDR was increased up to 4,5% (the current official SDR of the French administration)?

On the one hand, increasing the SDR will make investments (CAPEX of stations) costlier which will result in a higher LCOH. This will result in a higher yearly cost for the ZEV, which will increase the yearly static abatement costs. On the other hand, the social cost of carbon (SCC) trajectory becomes steeper. The assumption that the price of carbon in 2030 is 250 EUR/tCO2 remains.

With a 4,5% SDR instead of 2%, the SCC will be lower before 2030 and greater after 2030 (the curve is steeper). With the 2% SDR in the previous analysis, 2035 is the key year where the yearly static abatement cost becomes cheaper than the SCC, which results in profits from 2035 onwards for the ZEV from the public perspective. With the two contradictory effects discussed above, what is the key year with an SCC of 4,5%?

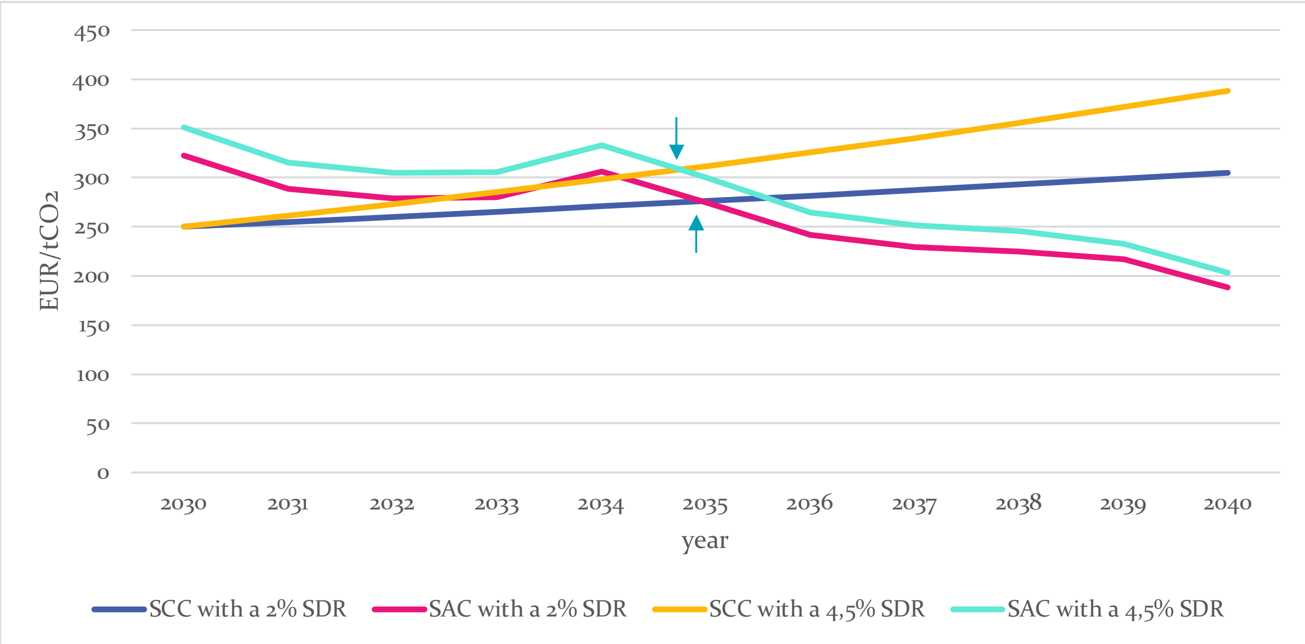

Figure 10 : Effects of the choice of a social discount rate (SDR) on the social cost of carbon (SCC) and the yearly static abatement costs (SAC) in the ZEV (2020-2040)

The previous table and graph show that the two effects offset each other and that 2035 is still the key year where the ZEV starts to bring profits from the public perspective.

What effects will the increase of the SDR have on the rest of the public analysis ? It is hard to predict: the yearly over-costs increase, but they are more discounted, which lowers their present value.

Table 16 : Comparison of the two social discount rates

Social discount rate	2%	4,5%
CO2 abatements (tCO2/year)	19 410	19 410
Discounted cash flow without CO2 (M€)	115	97
Dynamic abatement cost (EUR/tCO2)	119	226
Social cost of carbon in 2020 (EUR/tCO2)	205	161

It appears that these contradictory effects result in a smaller discounted cash flow (excluding CO2 monetization) between 2020 and 2050 (the increase of the discounting prevails).

The effect on the dynamic abatement is again hard to predict: the overall cost of the transition has decreased (it is the discounted cash flow without CO2) but its yearly equivalent on an infinite timeline increases with the SDR because the discounting increases. In other words, the opportunity cost of investing in a project increases (a 4,5% yield instead of a 2% yield is expected by society). These effects result in a higher dynamic abatement cost (226 instead of 119).

With a 4,5% SDR, the DAC is 226 EUR/tCO2. It means that the ZEV project should be deployed from 2028 onwards.

Overall the increase of the SDR from 2% to 4,5% has a limited effect on the static analysis (2038 is still the year where the ZEV starts to bring profits to society) but it has an impact on the dynamic analysis: it suggests to launch the ZEV in 2028, whereas with a 2% SDR the ZEV could be launched before 2020.

II.4 Conclusion on the scenario

To sum-up this analysis of the conservative scenario presented above, the conclusion on the cost-benefit analysis of the ZEV depends on the timeline considered.

On the one hand, between 2020 and 2037, the ZEV is a loss-making operation both from the public and the private perspective. Only vehicles' owners gain from the ZEV between 2020 and 2037 with the help of vehicles subsidies. This could suggest that the total amount of subsidies is not optimally distributed between stations and vehicles: hydrogen refueling stations could get a bigger share of the subsidies under the previous assumptions. The 2020-2037 period was relevant to analyze because the primary investments last until 2037: the majority of stations and electrolysers are built in 2023 and they have a life-duration of 15 years.

On the other hand, in the longer-term, even with this conservative (pessimistic) scenario, the ZEV could be a profit-making operation for society (under the assumption of cost parity between diesel and hydrogen in 2050). The dynamic abatement cost analysis (implying an infinite timeline) concludes that the ZEV is of interest for society (if the social discount rate is 2%). In particular, the dynamic abatement cost suggests that it could have been economically sound to launch the project before 2020. However, this result depends highly on the choice of the social discount rate. A 4,5% discount rate would advocate for a launching in 2028. Since there is a lot of debate and uncertainties on the choice of social discount rate, we can conclude that the dynamic abatement cost calculation suggests to launch the ZEV somewhere between before 2028 (see the Annex on the social cost of carbon for a debate and more information on the social discount rate).

This conservative scenario was rather pessimistic in terms of the number of vehicles, the kilometers driven, and the demand for green hydrogen. This results in high LCOH costs that undermines the profitability of the ZEV. The policy recommendation suggested by this analysis is to increase the number of vehicles (to have better utilization rates in hydrogen refueling stations) or to build the stations at a lower rhythm. Since the binding conditions require a fixed number of stations as soon as 2023, and because vehicles' owners need a big enough network of stations to drive in the region, this study recommends in particular to increase the number of vehicles.

In an "optimistic" scenario of the ZEV with more vehicles and a higher demand for green hydrogen, the conclusion could have been more favorable.

III Discussion on the cost-benefit analysis

This section builds on the cost-benefit analysis of the ZEV undertaken above to tackle important issues raised by the CBA. The discussion that follows addresses the interest of the cost-benefit analysis conducted in this study in the broader context of technologies' evaluation for the development of green mobility. It is also a way of highlighting the limitations of the previous analysis and of identifying areas for improvement and further analysis.

III.1 How to take into account competition with electric mobility?

The previous cost-benefit analysis compares the deployment of hydrogen vehicles and hydrogen refueling stations with a status quo scenario (diesel mobility) to conclude on the economic interest of developing hydrogen mobility. Although this theorical framework is sound and insightful, one could argue that it forgets that hydrogen mobility competes with other technologies to decarbonize transports (in particular electric and biofuels mobilities). The purpose of the cost-benefit analysis is to estimate the economic efficiency of a solution (see I.2.1). This intellectual approach suggests conducting a cost-benefit analysis of different solutions (hydrogen, electric, biofuels, etc.) and to compare the results. Nevertheless, the scope of this study does not encompass a cost-benefit analysis of other technologies such as electric or biofuels mobilities.

Despite that, it is relevant and crucial to consider that hydrogen mobility competes with other mobilities and to underlines the consequence for the hydrogen cost-benefit analysis. Since a hydrogen car is an electric car where the battery is replaced by a tank and a fuel cell, and because electric mobility is rapidly taking off, this part focuses on the competition between hydrogen and electric mobilities.

Many reports from consulting companies such as Deloitte[65], PwC[66], Roland Berger[67], or from a consortium of European stakeholders (the Fuel Cells and Hydrogen Joint Undertaking or FCH JU)[68] converge on their comparison of Fuel Cell Electric Vehicle (FCEV) and Battery Electric Vehicles (BEV). They all observe that the total costs of ownership of FCEV are higher than that of BEV in 2020. All the afore mentioned reports forecast cost-parity between FCEV and BEV in 2030 or later.

Why would it make sense to develop hydrogen mobility if it is costlier than electric mobility (at least until 2030) ? This report argues that, on certain mobility segments, the comparative advantages of hydrogen mobility overcome the difference in the total cost of ownership. The energy density of hydrogen tanks exceeds the one of electric batteries, which allow FCEV to have a longer range and to charge faster than BEV. Therefore, FCEV may be the more suitable option on certain segments that require a high energy density and a long range (trucks, coaches, garbage trucks) or a short charging time (vehicles driving around the clock, taxis, etc.).

Since the scenario of the ZEV developed in this study assumes a relatively small number of FCEV (around 1‰ of the market)[69], the cost-benefit analysis conducted in this report remains insightful even if BEV mobility is more cost-competitive and if the segments where FCEV have a comparative advantage are narrow.

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[65] Deloitte China, Fueling the Future of Mobility Hydrogen and fuel cell solutions for transportation, Vol. 1 (https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf)

[66] PwC, From CO2 neutral fuels to emission free driving (https://www.pwc.de/de/automobilindustrie/alternative-fuels-powertrains-v2.pdf)

[67] Roland Berger, Fuel Cells and Hydrogen Applications for Regions and Cities Vol. 2 (https://www.fch.europa.eu/sites/default/files/documents/Power_trains_for_Europe.pdf)

[68] Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Fuel Cells and Hydrogen Applications for Regions and Cities Vol. 2 (https://www.fch.europa.eu/sites/default/files/documents/Power_trains_for_Europe.pdf)

[69] They are 40 million circulating vehicles in France (https://www.insee.fr/fr/statistiques/2045167#tableau-figure1_radio1). If 10% are in the region Auvergne-Rhône-Alpes (which represents roughly 10% of the French population and of French GDP), there would be 4 millions of circulating vehicles in the region. 5000 FCEV would represent 0,1% or 1‰ of the market.

The consensus that emerged from discussions with professionals both inside and outside ENGIE is that hydrogen and electric mobilities are at the same time competitors and complementary technologies. Hydrogen mobility can intervene when a high energy density is needed. For long haul flights and navigation, where even more dense energy carrier particles are needed, hydrogen can still play a role in the synthesis of hydrocarbons.[70]

To continue beyond this report, it could be interesting to conduct a comparative cost-benefit analysis of the different green technologies and to identify the most promising technologies for each segment of mobility. This would be an interesting extension of this work.

III.2 What is the relevance of externalities quantification and monetization for public investors?

The whole point of carrying out a cost-benefit analysis from society's point of view is to consider the externalities. As a reminder of section I.2.2, negative externalities are shadow costs or hidden costs imposed by an economic actor on other economic actors without being internalized, i.e. considered, in its decisions. If they are not internalized, externalities can result in non-optimal decisions that can impoverish society. The public perspective quantifies and monetizes externalities to allow a public decider to make the best decisions for society as a whole.

However, it emerged from the various interviews conducted for this report that the quantification and monetization of externalities was not the top-priority of field actors, even public stakeholders.

- Capenergies quantify CO2 often, compute an abatement cost sometimes, but rarely monetize or quantify other externalities (such as local pollution for instance). Externalities are mostly used to communicate on projects, rather than to make investment decisions, or they are used as a qualitative indicator.
- The Caisse de dépôts et Consignations' first criteria to invest is sustainability : at the end of the day, the public investor should not make a loss. Externalities can be a qualitative criteria that is considered for choosing a project but they are not monetized.
- For the région Auvergne-Rhône-Alpes, it seems that the externalities were not the core of the ZEV project. It may have been taken from granted that the ZEV was environmentally interesting and the focus of political deciders seemed more on the economic benefits for the region (H2 actors well implemented in Auvergne-Rhône-Alpes) than on environmental considerations. The main issue seems to be the launch of a sector capable of promoting local industries.

Nevertheless,

The ADEME will quantify and evaluate ex-post the diminution of local pollution allowed by the ZEV. Their indicator is not to compare abatement costs with CO2 price but to estimate the abatement per EUR invested by the ADEME (abatement cost from ADEME perspective) and to consider this performance indicator when helping projects.

Overall, it seems that public decision-makers do not monetize externalities to subsidize H2 green mobility projects. It is rather the massification of H2 uses that motivates their investments. This

[70] Mertens, J., Belmans, R. and Webber, M. (2020)) Why the Carbon-Neutral Energy Transition Will Imply the Use of Lots of Carbon, *C*, Vol. 6, n° 39

may be different from one project to another. For instance for Hype taxis, reducing local air pollution may have been a key motivation for the project as discussed in II.2.3.

Finally, it is important to highlight that this should not undermine the interest of a cost-benefit analysis from the public perspective. The little appetite of public-decisionmakers for externalities quantification and monetization might just result from a lack of familiarity with this exercise. The consequence for future analysis is that they should be constructed hand in hand with stakeholders, and that explanations on the benefits of such analysis should be provided with the results.

III.1 Development options

The cost-benefit analysis concluded that the ZEV needed more users or uses to become profitable, in other words it needs a higher demand for hydrogen. The following segments seem promising for the ZEV:

- Forklifts, because they could be cost competitive with other fuels as soon as 2020.[71]
- Taxis with their long annual driving distance and the fact that they may need fast charging (comparative advantage over battery-electric vehicles).
- Heavy mobility such as waste trucks, trucks, coaches, buses. These technologies are not ready yet but they appear promising and hydrogen could have a comparative advantage over electric batteries for these segments in terms of energy density.

All these segments are currently being explored by Hympulsion for the ZEV with the aim of developing new uses and increasing the demand for hydrogen. Further cost-benefit analysis of the ZEV should try to gather elements on these segments and to incorporate them into scenarios for hydrogen mobility.

Furthermore, the dynamic abatement cost analysis depends on learning-by-doing assumptions. As in A. Creti, A. Kotelnikova, G. Meunier and J-P. Ponssard (2017)[72] or G. Meunier, L. Moulin and J.-P. Ponssard (2019)[73], the learning-by-doing effect (decrease of FCEV costs with cumulative past output) should be analyzed at a global scale (i.e. European or worldwide). A limitation of this study is that only the FCEV production in the ZEV is considered. For further analysis, a cost-benefit analysis with a dynamic abatement cost calculation could be undertaken for each segment of mobility (LDV, trucks, coaches, etc.) on a European or global scale to better understand the effects of scaling-up globally on the economic interest of H2 mobility.

IV How to scale-up hydrogen projects? A few policy recommendations

Coordination and cooperation between stakeholders is a key parameter for success in developing hydrogen mobility. The ZEV projects, and other projects investigated in this report, depend and rely on coordination and cooperation between users, local authorities, enterprises, public or private financers, and national or European support.

[71] https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf

[72] Creti, A., Kotelnikova, A., Meunier, G. and Ponssard, J.-P. (2017) Defining the Abatement Cost in Presence of Learning-by-Doing: Application to the Fuel Cell Electric Vehicle

[73] Meunier, G., Moulin, L. and Ponssard, J.-P. (2019) *Why local initiatives for the energy transition should coordinate. The case of cities for fuel cell buses in Europe*.

There is complementarity, cooperation and subsidiarity between the different scales of political action : local projects are monitored and supported by regional clusters (Capenergies in Provence-Alpes-Côte-D'Azur[74], or Tenerrdis in Auvergne-Rhône-Alpes[75]), regional projects in France are part of the National Hydrogen Plan,[76] and national plans are part of a European strategy and of the European Commission's notorious green deal.[77]

This study has demonstrated the importance of scaling-up hydrogen projects to make them competitive. Coordination seems to be crucial for scaling-up projects. This matter of coordination raises issues such as what organizational management and what policies can help developing hydrogen mobility?

This part analyses three main issues related to the strategic development of hydrogen mobility projects: organization of the project's development (top-down and bottom-up strategies), synergies between uses of hydrogen, and coordination between regions.

IV.1 Top-down strategy or bottom-up approach ?

This part mentions the work of Sabatier (1986) on top-down and bottom-up approaches to implementation research.[78]

A top-down strategy starts from a policy decision and sets goals to implement change. The ZEV development can be analyzed as a top-down strategy. The project arose from a consortium of top entities (ENGIE, Michelin, the region Auvergne-Rhône-Alpes), with a clear political support from Laurent Wauquiez, President of the regional council of Auvergne-Rhône-Alpes. This consortium has set goals (20 HRS, 1200 vehicles, 1,5 ton of hydrogen per day produced through electrolysis by 2023) and it is seeking to meet them by looking for users and uses.

Sabatier (1986) raises some concerns about top-down strategies. They tend to focus on the perspective of decision-makers and neglect other stakeholders, they are difficult to use when there are a multitude of actors involved in decision-making, and they are likely to ignore that the targeted group could act differently than expected by the policy.

The difficulties met by the ZEV project to find uses and users for green hydrogen suggest that a top-down strategy for hydrogen mobility may face these challenges.

According to Sabatier (1986), a bottom-up approach starts from identifying the network of actors involved in local areas. It spots their goals, strategies, activities, and contacts. The contacts should then help developing a network to identify the local, regional, and national actors involved in the planning, financing, and execution of the relevant governmental and non-governmental programs.

The usual scheme and the stages of H2 projects' development mentioned by Capenergies illustrate the bottom-up approach. Local authorities mention issues to Capenergies. Then, Capenergies tries to bring the problems to the actors of the H2 club, a network that gathers enterprises, research institutions and other stakeholders of H2 development in the region Provence-Alpes-Côte-d'Azur.

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[74] Capenergies, https://www.capenergies.fr/
[75] Tenerrdis, https://www.tenerrdis.fr/fr/
[76] https://www.gouvernement.fr/argumentaire/plan-hydrogene-faire-de-notre-pays-un-leader-mondial-de-cette-technologie
[77] European Commission, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
[78] Sabatier, P.A. (1986) Top-Down and Bottom-Up Approaches to Implementation Research: a Critical Analysis and Suggested Synthesis, *Journal of Public Policy*, Vol 6, pp 21-48

This sharing of information often leads to dedicated working groups, and then to the creation of consortiums. The region can then mobilize a lot of resources: it sometimes provides direct support (financing) or in kind assistance. The ultimate development stage for a project is when the region mobilizes a financing committee with large public and private institutional investors (Caisse des Dépôts et Consignations, banks).

Bottom-up approaches also raise concerns in Sabatier (1986). The local actors are likely to overemphasize their ability to influence deciders and there is no process or theory to explain the actors participation in a program.

A first policy recommendations that could be derived from this small analysis is that hydrogen development projects should include users and uses from the beginning. This would enable to move from the pessimistic scenario of this report's cost-benefit analysis to a scenario of resounding success.

However, the limit of a bottom-up strategy is that spontaneous local demand may not be enough to scale-up hydrogen mobility. The ZEV project and its top-down strategy should be credited for setting ambitious targets, with the implications of major enterprises and public entities.

Finally the best strategy seems to take the best of both world : setting ambitious targets supported by deciders, and organizing the animation and implication of local networks, local authorities, and local enterprises to help developing uses and to find users for hydrogen.

IV.2 Scaling-up through synergies of uses

This report puts an emphasis on the need to scale-up projects both in the ZEV and in PACA. This need of scaling-up projects to reach a certain level of competitiveness was also the key finding of a paper on EasHyMob in the Normandy region by Brunet and Ponssard.[79]

The immediate question raised by this idea is how to scale-up hydrogen projects? One of the means investigated in this study is by relying on the synergies between hydrogen uses.

For example, H2V project in Normandy aims at producing a massive quantity of green hydrogen with electrolysers. The project targets a production of 28,000 tons of H2 per year as soon as 2023, which represents more than 76 tons of H2 per day. This would amount to 3% of the French hydrogen production. This scale of production could allow a relatively cheap price for green H2. The production would be managed in order to control the peak load with elimination of consumption (RTE is in the project). The green hydrogen would then be injected into the gas grid.[80] This projects illustrates how the synergies between two uses (peak load elimination of consumption, and hydrogen consumption for gas infrastructures) can help scaling-up projects and cutting costs.

The ZEV project is also looking for industrial uses of hydrogen to increase the demand. In Provence-Alpes-Côte-d'Azur, the HYGREEN project combines production by electrolysis, geological storage and mobility.

This report suggests that such synergies should be sought in hydrogen mobility projects to scale-up projects. An IFRI report on hydrogen perspectives mentions that the most probable uses for green hydrogen are chemicals' production, steels' manufacture, trucks, ships (through ammonia), planes

[79] Brunet, J., Ponssard, J.-P. (2016) Policies and deployment for Fuel Cell Electric Vehicles an assessment of the Normandy project, *International Journal of Hydrogen Energy* (http://dx.doi.org/10.1016/j.ijhydene.2016.11.202)
[80] http://h2vnormandy-concertation.net/comprendre-projet/

(through synthetic fuels).[81] An article from Jan Mertens, Ronnie Belmans and Michael Webber explains how hydrogen is likely to play a key role as an energy carrier for storage, transport and heavy mobility (ships and planes) by being used in the production of synthetic hydrocarbons.[82] All these uses could make sense to seek synergies in future hydrogen mobility projects.

Finally, to best choose among options of green hydrogen uses and potential synergies, credible and predictable carbon price seem necessary to help enterprises in their R&D choices.

IV.3 Scaling-up through the coordination between regions.

On top to synergies between uses, another mean of scaling-up hydrogen mobility projects is by improving the coordination between regions to multiply the number and scale of projects.

In a policy brief of the Chair Energy and Prosperity (Institut Louis Bachelier), it is argued that to decrease costs and increase the scale of hydrogen mobility, local projects should be backed-up, encourage and coordinated at the European level.[83] In addition to European financial support, the European scale can decrease costs through learning and spill-over effects and help to reach a critical size for hydrogen mobility. These positive network effects can be maximized through coordination, cooperation and the sharing of information and best practices.

This coordination at the European level can take place through European Union's programs such as Interreg. Interreg is part of the EU Cohesion Policy (2014-2020 period). It is funded by the European Regional Development Fund (ERDF). Interreg has a budget of EUR 10.1 billion invested in cooperation programs. The cooperation programs must be a cross-border, transnational, or interregional programs.[84]

Region hydrogen 2.0, SMART HY AWARE and H2SHIPS are three relevant Interreg programs related to the cooperation between European regions for the development of hydrogen mobility.

Region hydrogen 2.0 is a cooperation between Flanders (Belgium) and the Southern Netherlands to develop hydrogen infrastructures. It includes two HRS with green hydrogen on-site production, Europe's biggest fleet of 75 forklift trucks, and the development and demonstration of the first big (forty tons) hydrogen truck in Europe.[85] The total budget is EUR 3 185 125.00 and EUR 1 592 562.50 are funded by the EU through ERDF budget.

SMART-HY-AWARE aims at promoting hydrogen mobility by addressing infrastructural, technological and market barriers related to hydrogen. It consists in the preparation of a methodology, seven Regional analysis reports, and a Good Practices Sourcebook and Transferability Model report. The total budget is EUR 447 797.00 among which EUR 380 627.45 are financed by the EU through ERDF budget.[86]

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[81] Philibert, C. (2020) Perspectives on a Hydrogen Strategy for the European Union Etudes de l'Ifri (https://www.ifri.org/sites/default/files/atoms/files/philibert_hydrogen_strategy_2020.pdf)

[82] Mertens, J., Belmans, R. and Webber, M. (2020) Why the Carbon-Neutral Energy Transition Will Imply the Use of Lots of Carbon, *C*, Vol. 6, n° 39

[83] Chair Energy and Prosperity, La filière hydrogène dans les transports a besoin de l'Europe, Policy Brief, March 2020 (http://www.chair-energy-prosperity.org/wp-content/uploads/2020/04/publication2020-filiere-hydrogene-europe.pdf)

[84] https://interreg.eu/about-interreg/

[85] https://keep.eu/projects/18141/

[86] https://keep.eu/projects/21548/

H2SHIPS is an Interreg North-West Europe project that aims at demonstrating the technical and economic feasibility of hydrogen bunkering and propulsion for shipping. The goal is to identify the conditions for successful market entry for the technology. Two projects will be implemented: an hydrogen powered port vessel in Amsterdam, and a H2 refuelling system suitable for open sea operation in Belgium. A further output will be an action plan for the implementation of a pilot on the river Seine in Paris in 2022. The Project has a total budget of EUR 6.33 million and receives EUR 3.47 million from Interreg North-West Europe between 2019 and 2022.[87]

This report suggests multiplying such coordination's effort at the European level, with or without European institutions. More coordination is needed between local, regional and national initiatives to make sure that information, best practices and experience is shared between projects. This will help to decrease costs through learning effects and spill-over effects.

Conclusion

Hydrogen mobility could be a promising technology to decarbonize transport and decrease the atmospheric pollution. As an illustration, the ZEV is an interesting project to explore the potential of project based on FCEV captive fleets.

Even if the technologies, the producers and the political context (both national and European) are mature enough to start developing projects, their economic efficiency and performance, both from the public and the private perspective cannot be taken for granted. Indeed, it depends on the ability of projects to generate sufficient demand for hydrogen to scale up and reduce costs.

The cost-benefit analysis is a sound economic tool which could be more widely used in the assessment of projects. For public investors, such analysis should include, quantify and monetize externalities to contribute to general interest. Dynamic abatement cost could also be included in public cost-benefit analysis to consider learning-by-doing effects and assess investments in new technologies accordingly. This work also discusses the limitations of such an analysis, for instance

[87]https://www.nweurope.eu/projects/project-search/h2ships-system-based-solutions-for-h2-fuelled-water-transport-in-north-west-europe/

how does the analysis hold if battery-electric mobility is considered ? It mentions the possible developments of the analysis and a few policy recommendations for hydrogen mobility such as the synergistic development of hydrogen solutions and the cooperation between regions to scale-up projects.

The cost-benefit analysis undertaken in this report holds true even when battery-electric mobility is considered, as long as the two technologies compete on different segments. The development of the segments where FCEV have a comparative advantage (forklifts, taxis, heavy mobility) will be a key parameter to reach success. To scale-up hydrogen projects and further decrease costs, this report suggests developing synergies between hydrogen uses and cooperation between hydrogen initiatives.

The continuation of this work could be to make additional cost-benefit analyses combining different mobility segments (passenger cars, light-duty-vehicles, heavy mobility, etc.) and different technologies (FCEV, battery-electric, diesel, biofuels, etc.) to spot the best options for each segment and usage to decarbonize transports and reduce local pollution. Another idea could be to conduct cost-benefit analysis on a European or global scale to better consider the learning-by-doing spill-overs effects for hydrogen mobility.

Finally, projects for the development of hydrogen mobility seem interesting at this stage, but research work will make it possible to better define the potential and interest of this technology. In particular, it will certainly be very interesting to complete this study with an *in itinerary* or *ex-post* analysis in 2023-2025.

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Annex A : Memo on the social cost of carbon

This note investigates the determinants of the social cost of carbon and the consequences for ENGIE. It covers the choice of a social cost of carbon and the importance of the social discount rate to value carbon prices. It presents the "official" carbon prices recommended in France and it discusses their value. It then concludes on the relevance of keeping track of carbon prices for ENGIE.

1. What is a social discount rate (SDR) ?

A social discount rate (SDR) reflects how society values the future. The choice of a SDR is a key parameter, and perhaps the most important parameter, when conducting intemporal and intergenerational choices. Environmental protection policies that are costly in the present and yield benefits for future generations are typical intertemporal choices. The SDR allows to compare future benefits with present costs by discounting the future.

The Ramsey Rule

The Ramsey Rule is a focal theoretical result among economists for choosing a SDR.

This rule is based on the optimality condition for the savings decisions of a representative agent (Ramsey 1928).[88] On the optimal path the marginal productivity of capital, r, equals the Social Rate of Time Preference (SRTP), defined as the right hand side of Equation 1:

$$r = SDR = SRTP = \delta + \eta g \qquad (1)$$

The SRTP is composed of the rate of pure time preference or utility discount rate (δ), and the interaction of the expected real growth rate of per-capita consumption (g) and the elasticity of marginal utility of consumption (η).

The choice of a social discount rate (SDR)

In real life markets are not perfect and usually r > SRTP.[89]

According to Drup et al. (2018)[90], the debate about the choice of the SDR is based on two different interpretations of the Ramsey Rule (1). The first interpretation of the Ramsey Rule associates the SDR solely with the SRTP: SDR = δ + ηg. ("SRTP perspective"). Alternatively, the social opportunity cost of capital perspective considers SDR = r ("r perspective").

Most European institutions and some European countries use the "SRTP approach" with relatively low SDR. Some countries, notably New Zealand, Canada and Australia, chooses the "r approach" with a relatively high discount rate. Finally, some countries, including Norway, with other Scandinavian

[88] F. P. Ramsey, A Mathematical Theory of Saving, The Economic Journal, Vol. 38, No. 152, December 1928, pp. 543-559 (http://piketty.pse.ens.fr/files/Ramsey1928.pdf)
[89] Marco Boscolo, Jeffrey R. Vincent, and Theodore Panayotou, DISCOUNTING COSTS AND BENEFITS IN CARBON SEQUESTRATION PROJECTS, Environment Discussion Paper No. 41 February 1998, Figure 1, adapted from Jenkins and Harberger (1996)
[90] Moritz A. Drupp, Mark C. Freeman , Ben Groom and Frikk Nesje, Discounting Disentangled, American Economic Journal: Economic Policy Vol. 10, No. 4, November 2018, pp. 109-34 (http://piketty.pse.ens.fr/files/Druppetal2015.pdf)

countries tending that way, apply discount rates based more explicitly on government borrowing rates. This generally leads to lower discount rates (even lower than the "SRTP approach").[91]

In a survey of 200 academics who were defined as experts in the choice of social discount rate by virtue of their scientific publications, 92% reported that they would be comfortable with a social discount rate between 1% and 3%.[92] This means that they consider 1 to 3% as an acceptable range for the social discount rate.

The SDR is a key parameter in the calculation of the social cost of carbon. The following part explains how to compute a social cost of carbon.

2. How to compute carbon shadow prices (or Social Cost of Carbon) ?

A shadow price is a price that society faces and that is not reflected by the market. Economists also call it the social cost of carbon or SCC (the cost that society pays when it pollutes).

The Hotelling Rule

Under the assumption of a stationary demand function, a single stock of resource whose balance is known at all times, and (strictly) convex extraction costs, Hotelling (1931) showed that along the equilibrium path, the extraction rent (price or marginal revenues less marginal extraction cost) must rise at the rate of discount in order for resource owners to be indifferent about when to extract.[93]

With a "carbon budget" (a given quantity of tCO_2 to be emitted by the time emissions stabilize, similar to a finite resource stock), it is efficient for the social cost of carbon (SCC) to follow a Hotelling rule: the SCC must increase at the speed of the social discount rate.

However, most carbon price are derived from integrated assessment modelling (IAM) and do not follow the Hotelling Rule. This suggests that IAM's carbon prices are not intertemporally optimized, maybe because of the political unacceptability of a high initial carbon price.[94]

The integrated assessment modelling (IAM)

Integrated Assessment Models (IAMs) are used to compute the SCC by coupling an economic model with a climate model. The SCC is then the discounted flow of damages induced by additional ton of CO_2 in the atmosphere.

[91] Michael Spackman, Social discounting: the SOC/STP divide, Centre for Climate Change Economics and Policy Working Paper No. 207, Grantham Research Institute on Climate Change and the Environment Working Paper No. 182, February 2017 (http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2017/02/Working-paper-182-Spackman-Feb2017.pdf)

[92] Moritz A. Drupp, Mark C. Freeman , Ben Groom and Frikk Nesje, Discounting Disentangled, American Economic Journal: Economic Policy Vol. 10, No. 4, November 2018, pp. 109-34 (http://piketty.pse.ens.fr/files/Druppetal2015.pdf)

[93] Harold Hotelling, The Economics of Exhaustible Resources, Journal of Political Economy, Vol. 39, No. 2, April 1931, pp. 137-175

[94] Christian Gollier, The cost-efficiency carbon pricing puzzle, Working Paper, Toulouse School of Economics, University of Toulouse-Capitole, February 2020. (https://www.tse-fr.eu/sites/default/files/TSE/documents/doc/wp/2018/wp_tse_952.pdf)

An IAM predicts the effects of climate change on the economy and allows for calculation of monetized damages. One of the most widely used IAMs is the Dynamic Integrated model of Climate and the Economy (DICE) model, developed by William Nordhaus.[95]

The SCC usually increases over time. The rate of change of the SCC depends upon several factors, particularly the rate of growth of world output, the removal rate of atmospheric carbon, and the discount rate.

Hence, with a more elaborated climate model, the rule to calculate SCC is adjusted to integrate climate dynamics which is not pure stock (as in Hotelling Rule), but the focus remains on carbon budget and the choice of a social discount rate.

SCC values based on a meta-analysis

The estimated SCC ranges from −13.36 to 2386.91$/tCO2, with a mean value of 54.70$/tCO2 and it equals to 30.78$/tCO2 with a pure rate of time preference at 3% in peer-reviewed studies.[96]

3. How the French SCC trajectory was computed ?

The French Prime Minister asked Alain Quinet to convene a commission to review the French official SCC, taking into account the developments that have taken place over the last ten years.

The commission recommends a value of $€_{2018}$250 in 2030, $€_{2018}$500 in 2040 and $€_{2018}$775 in 2050. These values are within the range of the carbon values identified in the IPCC Special Report of 2018 (with an objective of global warming below 1,5°C).

The five IAM used by the Quinet commission (2019) for the calculation were TIMES-France, POLES-Enerdata, IMACLIM-R France, ThreeME and NEMESIS.

<u>SCC according to IPCC, Special Report on Global Warming (2018)</u>[97]

Objectif de réchauffement	2030	2050	2070	2100
Inférieur à 2 °C (*Higher-2 °C*)	15-220 $\$_{2010}/tCO_2e$	45-1050 $\$_{2010}/tCO_2e$	120-1100 $\$_{2010}/tCO_2e$	175-2340 $\$_{2010}/tCO_2e$
Inférieur à 1,5 °C (*Below-1.5 °C*)	135-6500 $\$_{2010}/tCO_2e$	245-14300 $\$_{2010}/tCO_2e$	420-19300 $\$_{2010}/tCO_2e$	690-30100 $\$_{2010}/tCO_2e$

The SCC chosen by the Quinet commission (2019) does not reflect exactly the social cost of carbon but rather a political carbon price trajectory. Indeed, the aim of this price is to maintain continuity with the previous trajectory in 2018 ($€_{2018}$54), rather than to increase suddenly the 2019 SCC (as the SCC calculated for 2030 and 2040 would suggest). The choice of the trajectory is supposed to be coherent with the French and European objectives of zero net emissions in 2050. After 2040, the report suggests to respect a Hotelling rule with the official French SDR (4.5%).

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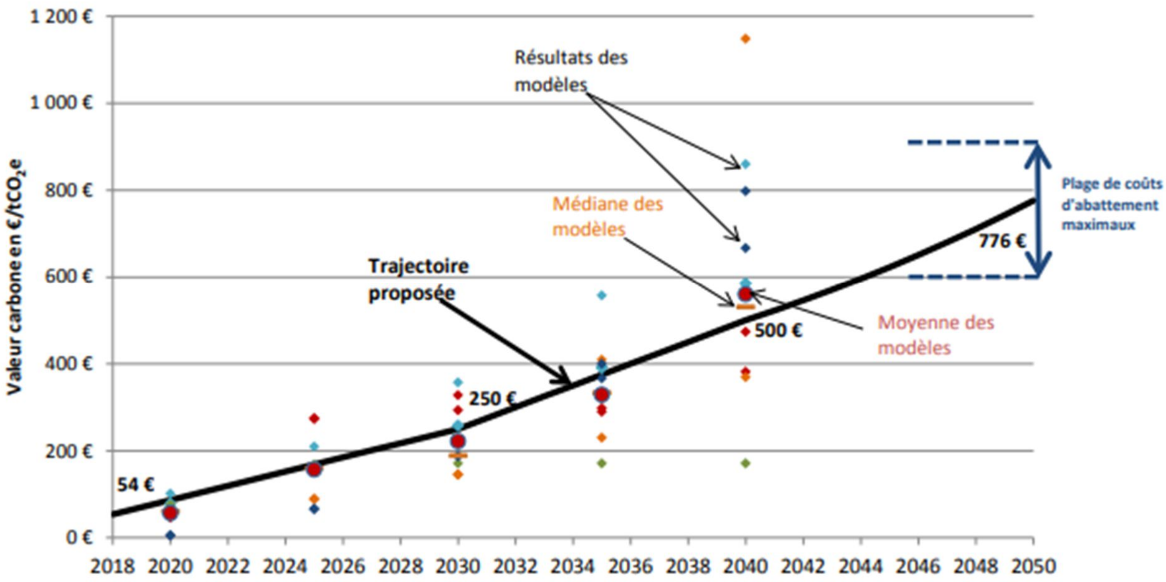
[95] http://www.econ.yale.edu/~nordhaus/homepage/homepage/documents/DICE_Manual_100413r1.pdf
[96] Wang, Pei, Deng, Xiangzheng, Zhou, Huimin, Yu, Shangkun, Estimates of the social cost of carbon: A review based on meta-analysis, Journal of cleaner production, Vol 209, 2019, pp. 1494-1507 (https://pubag.nal.usda.gov/catalog/6233428)
[97] GIEC, Special Report on Global Warming of 1.5 °C, October 2018, chapter 2, p.152 (https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf)

SCC trajectory according to the Report of the commission headed by Alain Quinet (2019)[98]



4. Discussion on the choice of a SDR and a SCC for France.

The following ideas were inspired by a discussion between Dominique Bureau (General Delegate of the French Economic Council for Sustainable Development), Jean-Pierre Ponssard (Scientific Director of the Chair Energy and Prosperity, Institut Louis Bachelier), Guy Meunier (Associated researcher at the Chair Energy and Prosperity), and François Teyssier d'Orfeuil (intern at ENGIE Research/ Chair Energy and Prosperity).

The French social discount rate (SDR)

Currently, the French SDR recommended by the Quinet Commission (2013) is 4,5%.[99] This consists of the sum of a discount rate of 2,5% based on a social rate of time preference (SRTP) calculation derived from the Ramsey Rule (see part I.A.) and a risk premium of 2%. The 2,5% interest rate is calculated with a modified Ramsey Rule to capture the systematic uncertainty on the economic growth.

$$r_f = \delta + \eta g - 0{,}5\eta^2\sigma^2 \qquad (2)$$

Where r_f is the social interest rate, δ the pure time preference or utility discount rate, g the expected real growth rate of per-capita consumption, η the elasticity of marginal utility of consumption, and σ^2 the variance of GDP per capita growth.

[98] France Stratégie, La valeur de l'action pour le climat, Une valeur tutélaire du carbone pour évaluer les investissements et les politiques publiques, February 2019, p.124 (https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2019-rapport-la-valeur-de-laction-pour-le-climat_0.pdf)

[99] France Stratégie, L'évaluation socioéconomique des investissements publics, September 2013, p.6 https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/archives/CGSP_Evaluation_socioeconomique_17092013.pdf

The Quinet Commission (2013) considers r_f to be equal to 2,5%.[100]

The Quinet Commission (2013) recommends to add to this rate a risk premium to better favor projects whose benefits are less correlated with economic growth (which act as group risk insurance) over those whose returns are highly dependent on growth.

$$r = r_f + \beta\phi \tag{3}$$

Where r is the SDR, r_f the risk free interest rate, β the project's benefits elasticity with respect to GDP per capita growth, and ϕ is the systematic risk on economic growth.

There is a debate to determine if benefits from the fight against climate change are positively or negatively correlated with economic growth. A positive correlation could be explained by the fact that a smaller economic growth results in less emissions and less benefits from fighting climate change. A negative correlation could be explained by the fact that climate change affects economics growth: the larger the benefits in fighting climate change, the larger the damages on the economy and the smaller the economic growth.[101]

The Quinet Commission (2013) considers that β equals to 1 (positive correlation) and ϕ equals to 2%. This leads to a SDR of 4,5% (2,5%+1*2%).[102]

Ideas advocating for a French SDR lower than 4,5%

The discussion between Dominique Bureau, Jean-Pierre Ponssard, Guy Meunier, and François Teyssier d'Orfeuil brought out ideas advocating for a smaller French SDR.

If the SDR is derived from the opportunity cost of capital, then a smaller r advocates for a smaller SDR. In 2018, the tax-adjusted cost of debt was 3,1% in France which is smaller than 4,5%.[103]

If the SDR is derived from the social rate of time preference, a smaller economic growth perspective and a higher growth uncertainty than in 2013 implies a smaller SDR.

Finally if SDR is derived from the government borrowing rate, like Scandinavian governments do, the long-term near-zero borrowing rates of the French government advocate for a smaller SDR.

The conclusion of this discussion was that a SDR of 2% or 2,5% would make sense.

On the choice of the French social cost of carbon (SCC) trajectory.

The discussion suggested that the SCC should not depend on political considerations such as a continuous price over years. If the IAM models consider a high SCC in 2030 or 2040, this SCC could be considered as the right one. This suggests to use a Hoteling rule to derive the SCC before and after the date of the chosen reference SCC (either 2030 or 2040). With the relatively low SDR that

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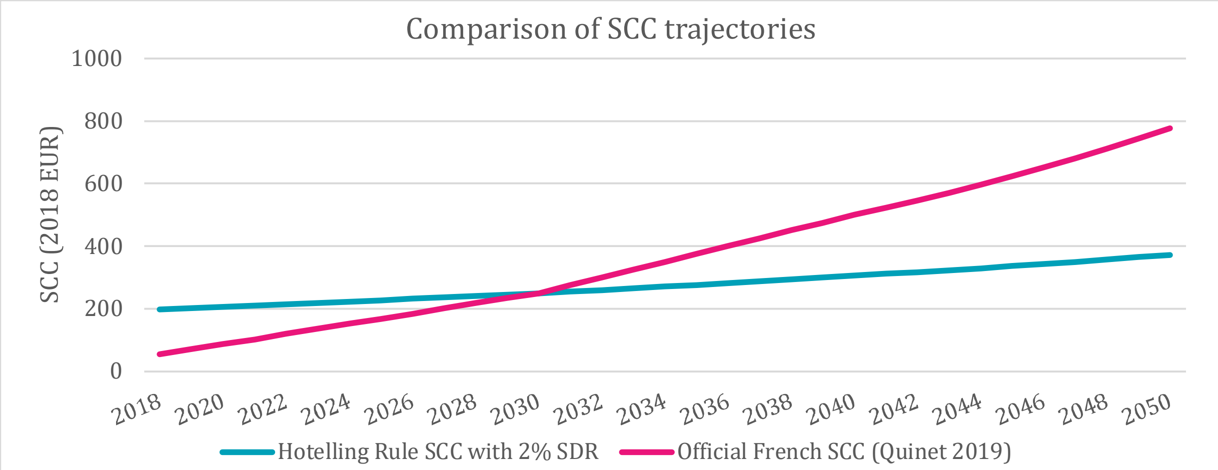
[100] France Stratégie, L'évaluation socioéconomique des investissements publics, September 2013, p.80 and p. 83 https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/archives/CGSP_Evaluation_socioeconomique_17092013.pdf

[101] France Stratégie, L'évaluation socioéconomique des investissements publics, September 2013, p.123 https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/archives/CGSP_Evaluation_socioeconomique_17092013.pdf

[102] https://www.strategie.gouv.fr/debats/taux-dactualisation-levaluation-projets-dinvestissement-public

[103] Juan Carluccio, Clément Mazet-Sonilhac and Jean-Stéphane Mésonnier, Investment and the WACC: new micro evidence for France, Working Paper, Banque de France, February 2018, WP #710

the discussion above suggests (2%), this would lead to a flatter/less steep curve. Hereby is an example with a 2% SDR, a Hotelling Rule, and a 2030 SCC of €$_{2018}$250 (the French official SCC trajectory value).



However a steeper curve can be explained by a zero-net-emission objective that differs from a limited stock of carbon emission objective. With a zero-net-emission objective, the Hotelling Rule is not adapted : a higher price is necessary in 2050 to ensure the zero-net-emission objective.

5. Relevance of carbon prices for an private company

From an economic perspective the SCC is the relevant value to be introduced in cost benefit analysis for public investments decisions. In absence of a market value for carbon, either through a tax or through allocations to be bought in an emission trading scheme, its relevance for private investments decisions can be seen as follows:

- It provides a possible indication of the potential value of carbon should governments agree in the future on an international carbon tax. It can therefore be used by private firms in strategic planning exercises to be in line with long term zero-emissions objectives.
- Independently of a carbon tax, governments may use the SCC to select green projects. The benefit for private firms to participate in a selected green project should then be discussed on its own merits.
- In absence of a carbon tax governments would typically induce participation to green projects through subsidies, the value of which may be compared to the value derived from the SCC. This could be used as a reference for private firms to argue for higher subsidies (eventually to be paid back in case a carbon tax were implemented).
- The abatement costs of carbon associated with private investments decisions may be compared to the SCC which may be considered as an absolute ceiling. However, the notion of abatement cost should be used with care in particular in presence of learning-by-doing which is common in green technologies.

Annex B : Theorical case study on the deployment of Fuel Cell Electric Buses (FCEB) in Europe.

This Memo is based on the work of G. Meunier, L. Moulin and J.-P. Ponssard (2019) on fuel cell buses in Europe.[104] The question under consideration is the following: does the deployment of Fuel Cell Electric Buses (FCEB) in France and Europe make economic sense?

The analysis is conducted in three steps. The first step is the comparison of total costs of ownership for two technologies (FCEB and diesel) in 2020 and 2030. The second is the comparison of static abatement costs over the same years. And the third is the calculation of a dynamic abatement cost that takes into account learning-by-doing effects.

It is shown that the deployment of FCEB buses in early 2020's makes economic sense as long as there is a credible scenario to achieve 10% market share of the total bus market in Europe in 2030.

1. Background elements

The European Union actively promotes the decarbonation of transport both to reduce greenhouse gas emissions and to preserve local air quality. The Directives on Ambient Air Quality and Cleaner Air for Europe (2008) and on the Promotion of Clean and Energy-Efficient Road Transport Vehicles (2009) have paved the way for regulatory standards to achieve this aim. More recently, the Clean Vehicles Directive (2019) set targets of clean vehicles by country to be reached before 2026 and 2031. For instance, France must reach a target of 43% of clean buses by 2026 and 61% by 2030. The Directive defines as a clean heavy-duty vehicle any truck or bus using one of the following alternative fuels: hydrogen, battery electric (including plug-in hybrids), natural gas (both CNG and LNG, including biomethane), liquid biofuels, synthetic and paraffinic fuels, or LPG.[105] European cities are key players of the transport systems, for example with the Clean Bus Declaration of the C40 Cities Initiative.[106] This work focuses on urban mobility and more specifically the deployment of a European fleet of fuel cell buses (FECB).

2. Methodology

This work revisits the methodology of G. Meunier, L. Moulin and J.-P. Ponssard (2019)[107] to estimate the total cost of ownership of FCEB and diesel buses. Then, it computes the static abatement costs of replacing diesel buses with FCEB buses in 2020. The notion of abatement cost has been conveniently used to set the optimal time for launching a clean technology. Two point of views are adopted for these analysis : the private point of view which takes the taxes into account but does not consider the externalities (noise, local pollution, GHG emissions), and the public point of view which does not take the taxes into account (they are transfers between agents of the same society) and internalizes the cost of externalities. It appears that from either point of view it would not be economical justified to make that substitution. We reproduce these calculations for 2030, based on cost estimates for that year. It appears that a substitution would now be justified from a social point

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104 G. Meunier, L. Moulin and J.-P. Ponssard *Why local initiatives for the energy transition should coordinate. The case of cities for fuel cell buses in Europe*, December 2019.

105 https://ec.europa.eu/transport/themes/urban/clean-vehicles-directive_en

106 https://www.c40.org/blog_posts/c40-clean-bus-declaration-urges-cities-and-manufacturers-to-adopt-innovative-clean-bus-technologies

107 G. Meunier, L. Moulin and J.-P. Ponssard *Why local initiatives for the energy transition should coordinate. The case of cities for fuel cell buses in Europe*, December 2019.

of view. However, the expected cost decrease could only be achieved if production had been launched previously. This contradiction calls for a different approach.

The transition to FCEB buses can be analyzed dynamically. A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard (2017)[108] develop an analytical framework for that purpose. They show that in the presence of a "learning-by-doing" effect (decreasing cost of production with cumulative past output) the static abatement cost is not an appropriate indicator. The whole trajectory that seeks to substitute a park of fossil buses by clean buses should be considered and a "dynamic" abatement cost for this trajectory be derived. Using this methodology, we show that launching such a trajectory would be justified in early 2020's. The credibility of the underlying trajectory appears as key in this reasoning. The existence of a European program to encourage major cities to engage in the deployment of FCEB can significantly contribute to this credibility.

3. Total costs of ownership

To compare the value of diesel vs. FECB buses, one should not compare their purchase price but their total cost of ownership. This cost is the purchase price of an asset plus the costs of operation. It gives its value overtime or in the long run.

Parameters

To assess the total cost of ownership of buses, this study takes the following element into account:

- Purchasing price
- Life duration
- Usage
- Bus maintenance
- Labor cost
- Fuel price (excl. tax)
- Fuel Taxes
- Efficiency
- Infrastructure costs
- Local emissions cost (noise and local pollutants)
- CO2 emissions

The total cost of ownership is specified in EUR/km. This require to use the yearly usage of buses. All costs are annualized (expressed for a given year). To annualize the purchasing price, life duration of buses and a social discount rate are additional are also assessed.

Figure 1 : parameters of interest in 2020

Bus type		**FCEB**	**Diesel**
Purchasing price	€	650 000,00	250 000,00
Life duration	Years	15,00	15,00
Usage	km/year	40 000,00	40 000,00
Bus maintenance	€/km	0,38	0,38
Labor cost	€/year	92 200,00	92 200,00

[108] A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard Defining the Abatement Cost in Presence of Learning-by-Doing: Application to the Fuel Cell Electric Vehicle. August 2017.

Fuel price (excl. tax)	€/kg (H2) or €/l (Diesel)	6,40	0,42
Fuel taxes (VAT TICPE)	€/kg (H2) or €/l (Diesel)	1,28	0,82
Local emissions cost	€/km	0,00	0,33
Efficiency	kg/100km (H2) or l/100km (Diesel)	8,17	47,80
Infrastructure costs	€/km	0,15	0,00
Discount rate	R	0,05	0,05
Emissions of CO2	kg/l	0,00	3,07

Figure 2 : parameters of interest in 2030

Bus type		**FCEB**	**Diesel**
Purchasing price	€	450 000,00	250 000,00
Life duration	Years	15,00	15,00
Usage	km/year	40 000,00	40 000,00
Bus maintenance	€/km	0,38	0,38
Labor cost	€/year	101 800,00	101 800,00
Fuel price (excl. tax)	€/kg (H2) or €/l (Diesel)	5,70	1,00
Fuel taxes (VAT TICPE)	€/kg (H2) or €/l (Diesel)	1,14	1,13
Efficiency	kg/100km (H2) or l/100km (Diesel)	7,73	45,30
Infrastructure costs	€/km	0,14	0,00
Social discount rate	R	4,5%	4,5%
WACC	R	8,5%	8,5%
Local pollution cost	€/km	0,00	0,33
Emissions of CO2	kg/l	0,00	3,07

Local externalities cost

There are various local externalities caused by vehicles using diesel. Pollutants such as particulate matter or carbon monoxide can impact the health of local inhabitants. Indeed, a high concentration in the local atmosphere can lead to premature deaths and various diseases. Another source of externalities that have effect on local social welfare and possibly health is the noise of the vehicles.

The cost of local pollutants is assumed to be 0,27 EUR/km for diesel buses and zero for FCEB buses. This figure is the cost of local pollutants in dense urban areas in 2018 according to the 2013 Quinet report.[109]

Figure 3 : Local pollutants cost rapport Quinet 2013

	2010	2018
Diffuse urban (€/km)	0,06	0,07
Urban (€/km)	0,12	0,13
Dense urban (€/km)	0,25	0,27
Very dense urban (€/km)	1,25	1,36

[109] Commissariat général à la stratégie et à la prospective. *L'évaluation socioéconomique des investissements publics,* Volume 1, September 2013.

The cost from noise pollution is assumed to be 0,06 EUR/km for diesel buses and zero for FCEB buses. This figure comes from a costs-benefits analysis of the French Ministry of the Ecological Transition.[110]

The total cost of local externalities is therefore 0,33 EUR/km. We will consider a social price of fuel which is the sum of the price of fuel excluding taxes and local externalities.

Annualized costs

To convert the purchasing price in an annualized price we use the formula:

$$PP = \frac{AP}{1+r} + \frac{AP}{(1+r)^2} + \cdots + \frac{AP}{(1+r)^n} = AP\frac{1-(\frac{1}{1+r})^n}{r}$$

With PP is the purchasing price, AP the annualized price, and $\frac{r}{1-(\frac{1}{1+r})^n}$ the capital recovery factor to annualize a net present price.

We compute the annualized costs of buses from the point a view of the private sector and the public sector. For the private sector, r is the WACC which is equal to 8,5%. For the public sector, r is the social discount rate which is equal to 4,5% according to the 2013 Quinet report.[111]

Figure 4 : annualized costs of buses (private)

Annualized cost FCEB 2020	72 141
Annualized cost Diesel 2020	27 747
Annualized cost FCEB 2030	49 944
Annualized cost Diesel 2030	27 747

Figure 5 : annualized costs of buses (public)

Annualized cost FCEB 2020	57 918
Annualized cost Diesel 2020	22 276
Annualized cost FCEB 2030	40 097
Annualized cost Diesel 2030	22 276

[110] Commissariat général au développement durable. *Analyse coûts bénéfices des véhicules électriques Les autobus et autocars*, October 2018.
[111] Commissariat général à la stratégie et à la prospective. *L'évaluation socioéconomique des investissements publics,* Volume 1, September 2013.

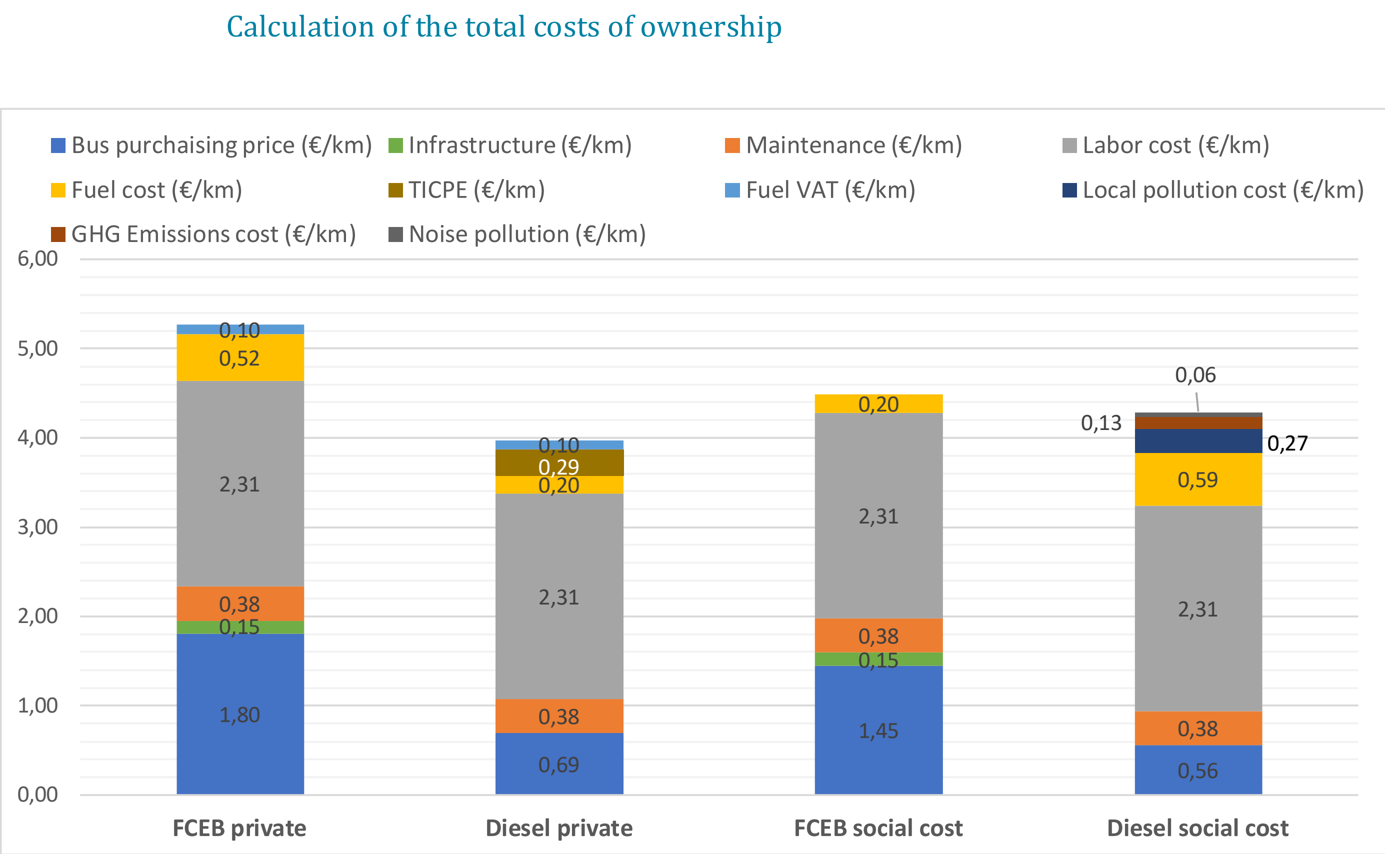
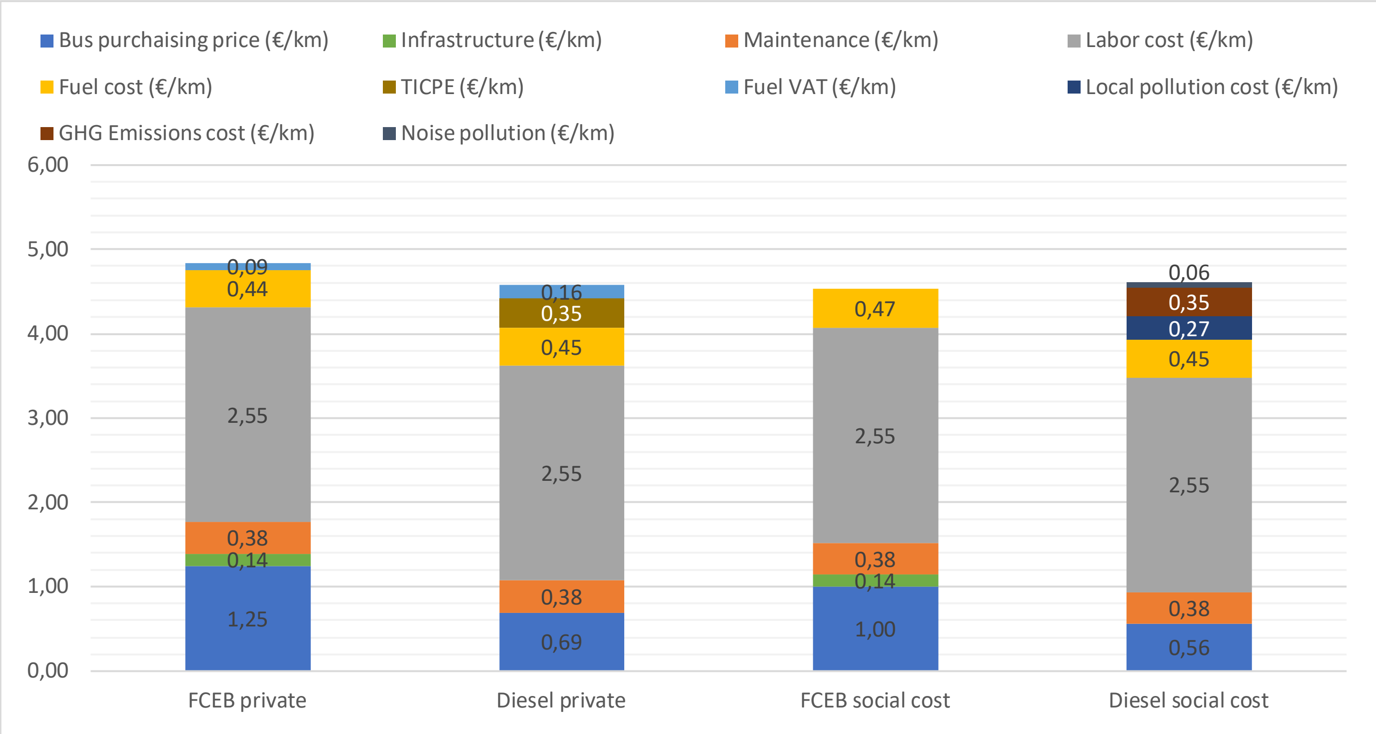


Figure 6 : TCO in 2020

Figure 7 : TCO in 2030



4. Static analysis for a project

Static abatement costs

A static abatement cost is a simple and classic tool used to assess the economic efficiency of a project reducing greenhouse gas emissions. The static abatement cost is the ratio of the cost of the project to the abatements of emissions of greenhouse gas made by the project. The result is the cost of the abatement in EUR/tCO_2.

Figure 8 : Private static abatement cost, 2020

Bus type	FCEB	Diesel
Bus purchaising price (€/km)	1,80	0,69
Maintenance (€/km)	0,38	0,38
Labor cost (€/km)	2,31	2,31
Fuel cost excl. tax (€/km)	0,52	0,20
Fuel taxes cost (€/km)	0,10	0,39
Infrastructure (€/km)	0,15	0,00
Total (€/km)	**5,27**	**3,97**
GHG Emissions (gCO2/km)	0,00	1 467,46
Abatement costs (€/tCO2)	**882,86**	

Figure 9 : Social static abatement cost, 2020

Bus type	FCEB	Diesel
Bus purchaising price (€/km)	1,45	0,56

Maintenance (€/km)	0,38	0,38
Labor cost (€/km)	2,31	2,31
Fuel cost excl. tax (€/km)	0,52	0,20
Infrastructure (€/km)	0,15	
Local pollution cost (€/km)		0,27
Noise pollution (€/km)		0,06
Total (€/km)	**4,81**	**3,77**
GHG Emissions (gCO2/km)	0,00	1 467,46
Abatement costs (€/tCO2)	**703,07**	

Figure 10 : Private static abatement cost, 2030

Bus type	FCEB	Diesel
Bus purchaising price (€/km)	1,25	0,69
Maintenance (€/km)	0,38	0,38
Labor cost (€/km)	2,55	2,55
Fuel cost excl. tax (€/km)	0,44	0,45
Fuel taxes cost (€/km)	0,09	0,51
Infrastructure (€/km)	0,14	
Total (€/km)	**4,84**	**4,58**
GHG Emissions (gCO2/km)	0,00	1 390,71
Abatement costs (€/tCO2)	**185,68**	

Figure 11 : Social static abatement cost, 2030

Bus type	FCEB	Diesel
Bus purchaising price (€/km)	1,00	0,56
Maintenance (€/km)	0,38	0,38
Labor cost (€/km)	2,55	2,55
Fuel cost excl. tax (€/km)	0,44	0,45
Infrastructure (€/km)	0,14	
Local pollution cost (€/km)		0,27
Noise pollution (€/km)		0,06
Total (€/km)	**4,51**	**4,27**
GHG Emissions (gCO2/km)	0,00	1390,71
Abatement costs (€/tCO2)	**171,95**	

Social cost of GHG emissions

A static abatement cost should be compared with the social cost of greenhouse gas emission to assess the economic efficiency of a project (the project in that case is the substitution of one diesel bus by one FCEB). The social cost of carbon is the marginal damage imposed by CO_2 emissions on society. In the theory of negative externalities, it is the answer to the question: how much costs the emission of one tone of CO_2 to society? Put simply, if the static abatement cost of a project is below the social cost of carbon, then the project improves social welfare; and if the static abatement cost is superior then the project reduces social welfare.

There is no certainty in the assessment of the social cost of carbon. Estimations vary approximately between 20 and 200 EUR/tCO_2. This work chooses to focus on the carbon price trajectory of the 2019 Quinet report.[112]

Figure 12 : Carbon price Quinet report 2019

Year	Carbon price (EUR/tCO2)
2018	54
2019	70
2020	87
2021	103
2022	119
2023	136
2024	152
2025	168
2026	185
2027	201
2028	217
2029	234
2030	250

Analysis

To get an idea of the economic efficiency of the deployment of a fleet of FCEB buses, let's compare the static abatement costs with the social price of carbon mentioned above.

In 2020, the static abatement costs, both private (883 EUR/tCO_2) and public (703 EUR/tCO_2) are way above the social cost of GHG emissions in 2020 (87 EUR/tCO_2). This suggests that the project should not be launched in 2020 : it would reduce social welfare. Others projects with competitive abatement costs should be prioritized. On the other hand, in 2030, the static abatement costs both private (186 EUR/tCO_2) and public (172 EUR/tCO_2) are below the social cost of GHG emissions (250 EUR/tCO_2). This suggests that the project should be launched in 2030 and even before. In fact ideally, it should be launched as soon as the static abatement cost equals the social cost of GHG emissions.

However, this assessment forgets that there is a learning-by-doing effect at a given time. Indeed, as A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard (2017)[113] showed, with these hypotheses, the optimal launching time of a trajectory is to start whenever the "dynamic" abatement cost is equal to the social cost of carbon.

To tackle this issue, we consider a whole trajectory instead of a one shot substitution.

5. Dynamic analysis

A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard (2017) develop an analytical framework to estimate the optimal deployment time of a green technology replacing a polluting one.

[112] France Stratégie. *La valeur de l'action pour le climat Une valeur tutélaire du carbone pour évaluer les investissements et les politiques publiques,* February 2019.
[113] A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard Defining the Abatement Cost in Presence of Learning-by-Doing: Application to the Fuel Cell Electric Vehicle. August 2017.

In this paper, they use the concept of dynamic abatement cost which can be interpreted as the abatement cost of the whole progressive deployment of the FCEB fleet over years. The dynamic abatement cost of the project is the sum of two components: the cost of the deployment over years and the relative over-cost of a FECB buses at the end of the deployment.

This work replicates their methodology to estimate the dynamic abatement cost (DAC) of a transition between 2020 and 2030. The calculation is explained in Annex A.

The DAC can be valued from the 2020 or 2030 perspective. Policy makers want to know when to launch the transition so we focus on the discounted DAC, which is the DAC valued in 2020 and which should be compared with the social price of carbon in 2020. We simply refer to it as the dynamic abatement cost or DAC in the analysis that follows.

For simplicity purpose, let's consider that the social cost of carbon increases at the discount rate (r). This means that the present (discounted) value of future emissions equals the social cost of carbon today. Let's also consider that a stationary state is reached once that there is TCO parity between diesel and FCEB buses. The dynamic cost of abatement therefore simplifies to the marginal abatement cost of the transition.

Deployment model assumptions

The following assumptions are made in the deployment model:

- This study considers that between 2020 and 2030, the market for diesel buses is big enough to produce FECB buses only in replacement of diesel buses that would have been produced otherwise. This implies that the cost of diesel buses should be subtracted from the cost of FCEB buses to measure the additional cost of the deployment.[114]
- This study considers that a stationary state is reached as soon as there is parity between FCEB and diesel buses. Therefore, the study focuses on the deployment because the dynamic cost of abatement simplifies to the marginal abatement cost of the transition.
- The price of new FCEB buses decreases over years. The learning rate assumption means that the cost of production diminishes by the learning rate every time the cumulated production doubles.
- Finally let's consider that the FCEB buses production is exponential over years.

Deployment schedule of FECB buses

It is assumed that the deployment starts in 2020.

- Let's consider that there is a cumulated production of 650 FCEB buses in 2020.
- Let's consider that 150 new FCEB buses are produced in 2020 and that the annual production grows exponentially to reach 2600 buses in 2030. In 2030 there is therefore a park of 10 022 FCEB buses (1/10th of the European bus market size). The life duration of a bus is 15 years. The production is stopped between 2031 and 2034 to keep the size of the FCEB park constant. Then, in 2035, 150 FCEB buses are produced to replace the 150 FCEB buses produced in 2020, and so on over next years. Our study stops in 2037 because TCO

[114] This assumption makes sense. The size of the European market for buses is approximately 100 000 buses and the life duration of a bus is 15 years. Hence, around 1/15th of buses are replaced each years (6667 buses replaced). The annual FCEB production of our model is far below this number (maximum 2600 buses per year).

parity between FCEB and diesel buses is reached. We consider a stationary state of TCO parity after 2037.

With these assumptions, the purchasing price of a bus in 2020 (650 000 EUR) and the purchasing price to be reached in 2030 (450 000), we can deduce the complete deployment schedule.

Figure 13 : Deployment schedule

Year	Production	Park	Cumulated	FCEB unit cost (€)
Initialization		0	650	
2020	150	150	800	650 000
2021	200	350	1 000	629 779
2022	265	615	1 265	609 078
2023	353	968	1 618	588 167
2024	470	1 437	2 087	567 276
2025	624	2 062	2 712	546 588
2026	831	2 893	3 543	526 247
2027	1 105	3 997	4 647	506 355
2028	1 470	5 467	6 117	486 988
2029	1 955	7 422	8 072	468 193
2030	2 600	10 022	10 672	450 000
2031	0	10 022	10 672	450 000
2032	0	10 022	10 672	450 000
2033	0	10 022	10 672	450 000
2034	0	10 022	10 672	450 000
2035	150	10 022	10 822	449 109
2036	200	10 022	11 021	447 946
2037	265	10 022	11 287	446 436

The implied learning rate calculated with this trajectory is 9,4%. This is a plausible learning rate. A learning rate is typically between 0 and 30%. For instance, it is estimated that PV systems have known a learning rate of approximately 30%.[115] But FCEB buses cannot be compared with PV systems because many of the components of a bus are not subject to learning-by-doing effects. The fuel cell price can decrease rapidly with learning-by-doing, but the bus chassis price will realistically not change since the technology is already well known.

Abatement cost of the transition

The dynamic abatement cost is the sum of two terms: the abatement cost of the transition and the static abatement cost after the transition. We consider that the transition lasts until 2037. From

[115] Elshurafa A. M., Albardi S. R., Bigerna, S., Bollino, C., A. 2018. Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations, *Journal of Cleaner Production*, Volume 196, 122-134.

2037 onwards there is TCO parity between diesel and FCEB buses and we assume that a stationary state is reached. Therefore the second term s null.

Thus, the dynamic abatement cost is the price of the transition divided by the CO2 abatements of this transition.

The assumption that the social cost of CO2 emissions growths at the social discount rate implies that they have the same present value for every year in the future.

The transition can therefore be interpreted as an investment made today that yields constant CO2 abatement from 2030 onward. So, the discounted cash flow of the transition can be multiplied by the social discount rate r to annualize this investment.

The dynamic abatement cost formula is : $DAC = r * DCF/Abatements$ where DAC is the dynamic abatement cost and DCF the discounted cash flow of the transition.

Figure 14 : Dynamic abatement cost

Discounted cash flow (€)	1 272 469 657
CO2 abatements 2030 (tCO2)	557 492
Dynamic abatement cost (€/tCO2)	**102,7**

The dynamic abatement cost is 102,7 EUR/tCO_2, it is between the social cost of carbon in 2020 (87 EUR/tCO_2) and the social cost of carbon in 2021 (103 EUR/tCO_2). Hence, with this production trajectory, it makes economic sense to launch the deployment at the end of the year 2020 or in year 2021.

We warn that the comparison of two given trajectories with different speed of transition requires some care (one should introduce the avoided CO2 emissions during the two trajectories).

6. Impact of the market share of FCEB buses on dynamic abatement cost

Learning-by-doing effects depend on the cumulated production of FCEB buses. Therefore, if the overall production is smaller, every single project becomes less profitable.

To get a better understanding of the impact of the market share of FCEB buses on the abatement cost, let's investigate a case where only one third of the previous trajectory in produced. In this case the market share at the end of deployment is 4% instead of 10%. Let's consider that the learning rate is the same than before (9,4 %).

The deployment schedule of the new trajectory is :

Figure 15 : New deployment schedule

Year	Production	Park	Cumulated	FCEB unit cost (€)
Initialization		0	650	
2020	50	50	700	650 000
2021	67	117	767	641 680
2022	88	205	855	631 808
2023	118	323	973	620 349
2024	157	479	1 129	607 348
2025	208	687	1 337	592 934
2026	277	964	1 614	577 304
2027	368	1 333	1 983	560 705
2028	490	1 823	2 473	543 400
2029	652	2 475	3 125	525 652
2030	867	3 342	3 992	507 694
2031	0	3 342	3 992	507 694
2032	0	3 342	3 992	507 694
2033	0	3 342	3 992	507 694
2034	0	3 342	3 992	507 694
2035	50	3 342	4 042	506 798
2036	67	3 342	4 108	505 625
2037	88	3 342	4 197	504 098
2038	118	3 342	4 314	502 124
2039	157	3 342	4 471	499 590
2040	208	3 342	4 679	496 373

With this new trajectory, the cumulated production increases less rapidly and thus, the cost per unit of FCEB buses decreases slower. The discounted cash flow of the deployment is therefore increased and thus, the dynamic abatement cost increases.

Figure 16 : Dynamic abatement cost

Discounted cash flow (€)	498 866 988
CO2 abatements 2030 (tCO2)	185 884
Dynamic abatement cost (€/tCO2)	**120,8**

The dynamic abatement cost has increased from 102,7 EUR/tCO_2 to 120,8 EUR/tCO_2. This illustrates how a limited market share for FCEB buses has a negative impact on a deployment project through learning-by-doing and scale effect. With this production trajectory, the optimal time to launch the deployment would be 2023.

7. Comparison with of a costs-benefits analysis in Normandy

J. Brunet and J.-P. Ponssard have published a costs-benefits analysis of a Fuel Cell Electric Vehicle (FCEV) deployment project in France, taking place in Normandy.[116] The key findings of their study are discussed in this section. The project relies on the substitution of diesel Kangoo vehicles by electric Kangoo ZE vehicles with a fuel cell range extender. The project lasts between 2016 and 2025 and two deployment scenarios are explored. The first scenario reflects a moderate success under which the project relies on public subsidies and the second scenario reflects a full success under which the project becomes self-profitable.

Presentation of the scenarios

Figure 17 : parameters of the scenarios

			2016	2025	
		Unit	**Reference**	**Scenario 1**	**Scenario 2**
Vehicles	Hydrogen fleet	#	50	5 000	10 000
	Of which Kangoo ZE	#	40	2 000	4 000
Production	Production technology	""	SMR	Electrolysis	Electrolysis
	H2 production process	""	Centralised	Centralised on 2 sites	On-site
Distribution	HRS[117] capacity	kg/j	20	100	400
	Number of HRS	#	5	50	25
	HRS utilization rate	%	50%	80%	100%

The impact of hydrogen production and distribution on hydrogen costs.

Several factors drive the difference in hydrogen costs between the scenarios :

- A higher power needed for centralized than for decentralized production;
- A lower utilization rate for scenario 1 than for scenario 2;
- A lower electricity price for centralized than for decentralized production (exemption of TURPE and CSPE taxes);
- There is no transport costs for hydrogen in scenario 2 (on-site production).

These differences yield a total cost for hydrogen of 21,3 EUR/kgH2 in the reference scenario, of 10,6 EUR/kgH2 in scenario 1, and of 5,4 EUR/kH2 in scenario 2.

Results of the study

The results of the study are that the total cost of ownership of the Kangoo ZE is 0,36 EUR/km in the reference scenario, 0,24 EUR/km in scenario 1 and 0,16 EUR/km in scenario 2. These TCOs are higher than the TCO of a diesel Kangoo, which is estimated to be 0,15 EUR/km. The static abatement cost of the deployment of Kango ZE is 1636 EUR/tCO_2 in the reference scenario, 500 EUR/tCO_2 in scenario 1 and 47 EUR/tCO_2 in scenario 2.

[116] J. Brunet and J.-P. Ponssard, *Policies and deployment for Fuel Cell Electric Vehicles an assessment of the Normandy project*, The International Journal of Hydrogen Energy, December 2016.
[117] Hydrogen refueling station (HRS).

While these results are not immediately comparable with the analysis on the deployment of FCEB buses in Europe they give an important insight. The deployment of a hydrogen fleet cannot be studied independently of the production and distribution of hydrogen because the cost of hydrogen vary vastly depending on the choices made for production and distribution.

8. Conclusion

Several assumptions and results of this analysis can be discussed.

Firstly, the dynamic analysis considers that that the social cost of carbon grows at the social discount rate. This simplification allows to avoid considering the abatements made during the deployment. However, this assumption is a matter for debate in the literature and is not coherent with the Quinet trajectory for carbon price mentioned in section IV. part B. Further work would be necessary to take into account the abatements made during the deployment.

Then, the stationary state reached after TCO parity is hit is questionable. If the previous trends continue, the TCO of FCEB buses would become smaller than the TCO of diesel buses. Furthermore, the technology is evolving rapidly and other buses compete with FCEB buses (especially electric buses). This raises questions about this assumption.

Finally, as opposed to the costs-benefits analysis in Normandy, this study does not make assumptions on hydrogen refuelling stations and on the production and distribution of hydrogen. This can be problematic because the Normandy analysis shows the impact of such assumptions on hydrogen costs and abatement costs.

The reasoning conducted in this analysis is not based on exact figures and depends on the two first simplifying assumptions discussed above. However, the findings of this simple analysis are relevant and give three key insights.

First, the economic efficiency of a project depends on the perspective (public or private) and on the launching time of the project. This raises a question for enterprises that wish to take into account the effect of their investment on social welfare. Which externalities should be considered ? How does an enterprise value these externalities ? At their social cost ? At an intermediate cost between their private cost (zero) and the social cost ?

Second, in the presence of learning-by-doing effects, the static analysis is not sufficient to assess the economic efficiency of a project and a dynamic analysis must be handled. Although the parameters of the model are just estimates, the dynamic abatement costs calculated bring confidence that the deployment of FCEB buses in early 2020's is economically efficient.

Third, the scale of the deployment plays a key role in the presence of learning-by-doing. Since the analysis models that FCEB buses price depend on the cumulative quantity produced, the results are sensitive to the production of FCEB buses. The calculation conducted is section VI shows how a smaller production raises the cost of FCEB buses and the dynamic abatement cost of the deployment.

9. Dynamic abatement cost calculation

As A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard (2017)[118] show, in the presence of "learning-by-doing" effect (decreasing cost of production with cumulative past output) and convexity of cost at a given time (decreasing return to scale), and with the assumption that carbon price increases at the social discount rate, the dynamic abatement cost of the deployment of a fleet can be expressed as follows:

$$DAC = \frac{rI}{N}e^{rD} + \frac{r\Omega(X) - c_0N}{N}$$

Where r is the social discount rate, I is the discounted cash flow for the deployment schedule, N is the targeted hydrogen car park (Ncar) times the difference in emissions per unit of car at the end of deployment, D is the duration of the transition, $\Omega(X)$ is the cost of a green fleet after deployment and c_0 the cost of the corresponding diesel fleet.

The assumption of TCO parity at the end of the deployment of the FCEB buses in 2030 implies that the cost of the green and diesel fleet are equal in 2030. Therefore, the second term of this sum is zero.

Hence, the dynamic abatement cost is :

$$DAC = \frac{rI}{N}e^{rD}$$

As explained at the beginning of section V. this dynamic abatement cost is from the 2030 perspective and should be compared with the social cost of carbon in 2030. It is more interesting for policy makers to know when to launch the deployment. Thus, the analysis conducted in section V. focuses on the discounted dynamic abatement cost from the 2020 perspective. This discounted DAC is simply :

$$DAC = \frac{rI}{N}$$

With the notation of section V. part D. the DAC is :

$$DAC = \frac{r * DCF}{Abatements}$$

Where $I = DCF$ (the discounted cash flow), and $N = Abatements$ (the annual abatements made by the clean feet compared to a diesel fleet).

$r * DCF$ can be interpreted as an annualized investment. Indeed, if we consider an initial investment II and the corresponding annualized investment AI over n years :

$$II = \frac{AI}{1+r} + \frac{AI}{(1+r)^2} + \cdots + \frac{AI}{(1+r)^n} = AI\frac{1 - (\frac{1}{1+r})^n}{r}$$

[118] A. Creti, A. Kotelnikova, G. Meunier & J-P. Ponssard Defining the Abatement Cost in Presence of Learning-by-Doing: Application to the Fuel Cell Electric Vehicle. August 2017.

Then, over an infinite horizon of time, when $n \to \infty$,

$$II = \frac{AI}{r}$$

Or,

$$AI = r * II$$

The dynamic abatement cost is therefore the ratio of the annualized present cost of the deployment over the annual abatements of CO_2 expected from 2030 onwards.

Annex C : Example of the calculation of the private LCOH

	Year	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Electrolysers	Annualized CAPEX (k€)	0	0	0	205	667	667	667	667	667	667	667	667	667	667	667	667	667	667	585	400
	OPEX (k€)	0	0	0	190	670	670	670	670	670	670	670	670	670	670	670	670	670	670	670	670
	Electricity cost (€/kgH2)	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,39	6,33
	Production (tonne/year)	0	0	0	36	60	91	121	151	180	208	236	236	236	236	236	236	236	236	236	236
	Utilization rate %	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
	Production cost (€/kgH2)	2	2	2	17	29	21	17	15	14	13	12	12	12	12	12	12	12	12	12	11
HRS without electrolyser	Transports to HRS	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Annualized CAPEX (k€)	82	82	390	698	1 724	1 724	1 724	1 724	1 724	1 724	1 724	1 724	1 724	1 724	1 724	1 691	1 691	1 568	1 445	1 034
	OPEX (k€)	50	50	260	470	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110	1 110
	Distribution (tonne/year)	3	6	14	36	60	91	121	151	180	208	236	236	236	236	236	236	236	236	236	236
	Utilization rate %	24%	52%	24%	33%	11%	17%	22%	28%	33%	38%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
	Distribution cost (€/kgH2)	55	27	49	52	78	54	43	36	31	28	26	26	26	26	26	26	26	25	24	22
HRS with electrolyser	Annualized CAPEX (k€)	0	0	0	0	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	1 437	862
	OPEX (k€)	0	0	0	0	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
	Electricity cost (€/kgH2)	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,45	6,39	6,33
	Production (tonne/year)	0	0	0	0	30	45	61	75	90	104	118	118	118	118	118	118	118	118	118	118
	Utilization rate %	24%	52%	24%	33%	11%	17%	22%	28%	33%	38%	43%	43%	43%	43%	43%	43%	43%	43%	43%	43%
	Distribution cost (€/kgH2)					85	58	45	37	32	29	26	26	26	26	26	26	26	26	26	21
	LCOH ZEV (€/kgH2)	**55**	**27**	**49**	**52**	**80**	**55**	**43**	**36**	**32**	**28**	**26**	**26**	**26**	**26**	**26**	**26**	**26**	**26**	**25**	**22**