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Par

Alena Kotelnikova

Analysis of a hydrogen-based transport system and the role of public policy in the transition to a decarbonized economy

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Composition du Jury :

M. J. G. Devezeaux de Lavergne, Directeur, l'I-tésé CEA, Rapporteur
Mme. A. Creti, Professeure, Université de Paris Dauphine, Directeur de thèse
M. P. E. Franc, VP, Advanced Businesses and Technologies Air Liquide, Examinateur
M. Y. Perez, Professeur Associé, Centrale Supélec, Rapporteur
M. J. P. Ponssard, Professeur, Ecole Polytechnique, Directeur de thèse

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Each of us has cause to think with deep gratitude of those
who have lighted the flame within us.
Albert Schweitzer

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Choix de politiques sectorielles pour la décarbonisation de l'économie. Application au cas de l'hydrogène pour le secteur du transport

Résume

Quel cadre économique et réglementaire à long terme (2030-50) pour soutenir la transition énergétique des carburants fossiles vers l'hydrogène dans le secteur européen des transports ? Cette recherche combine les approches théoriques et empiriques pour répondre aux trois questions suivantes :

1. Comment concevoir des politiques de soutien adaptées pour pallier les imperfections de marché lors du déploiement de technologies de mobilité hydrogène ?
2. Comment modéliser les coûts d'abattement en tenant compte des effets d'apprentissage (LBD) ?
3. Comment définir la trajectoire optimale de déploiement quand le LBD et la convexité des coûts d'investissement sont présents ?

L'article *'Transition vers un Système de Transport de Passagers à Hydrogène : Analyse Politique Comparée'* passe au crible des politique de soutien destinées à résoudre les imperfections de marché dans le déploiement de la mobilité hydrogène. L'article effectue une comparaison internationale entre les instruments en faveur du déploiement des véhicules. Les indicateurs ex post d'efficacité des politiques sont développés et calculés pour classifier les pays selon leur volontarisme dans la promotion des véhicules à piles à combustible (FCEV). La comparaison est fondée sur une série d'indicateurs complémentaires, dont le coût du véhicule rapporté aux revenus moyens, la différence de coût marginal entre différentes technologies de véhicules et la participation financière de l'Etat. Le prix d'achat d'un FCEV est plus faible au Danemark, en Norvège et au Japon, et plus élevé ailleurs. Par ailleurs, un prix d'achat élevé pourrait être compensé par des coûts de fonctionnement moindres, en moins de 10 ans, notamment en France, Suède et Californie, EUA. L'analyse montre aussi que les pays avec les incitations les plus généreuses utilisent des instruments prix, permettant de maximiser le déploiement à court terme. Aujourd'hui le Japon et le Danemark apparaissent comme les meilleurs fournisseurs d'un environnement favorable au déploiement de la mobilité hydrogène. Les autorités locales introduisent de solides instruments prix (tels que des subventions et des exemptions fiscales) pour rendre le FCEV plus attractif par rapport à son analogue à essence et coordonnent le déploiement de l'infrastructure hydrogène sur le territoire.

L'article *'Modélisation des Coûts d'Abattement en Présence d'Effets d'Apprentissage : le Cas du Véhicule à Hydrogène'* présente un modèle de transition du secteur des transports d'un état polluant à un état propre. Un modèle d'équilibre partiel est développé pour un secteur automobile de taille constante. L'optimum social est atteint en minimisant le coût de la transition du parc automobile au cours du

temps. Ce coût comprend les coûts privés de production des véhicules décarbonés (sujets aux effets d'apprentissage) ainsi que le coût social des émissions de CO2 qui suit une tendance haussière exogène. L'article caractérise la trajectoire optimale qui est un remplacement progressif des véhicules polluants par les décarbonés. Au cours de la transition, l'égalisation des coûts marginaux tient compte de l'impact des actions présentes sur les coûts futurs via l'effet d'apprentissage. L'article décrit aussi une trajectoire sous-optimale où la trajectoire de déploiement serait une donnée exogène : quelle serait alors la date optimale de début de la transition ? L'article présente une évaluation quantitative de la substitution des FCEV aux véhicules à combustion interne (ICE). L'analyse conclut que le FCEV deviendra une option économiquement viable pour décarboner une partie du parc automobile allemand à l'horizon 2050 dès que le prix du carbone atteindra 50-60€/t.

L'article *'Le rôle des Effets d'Apprentissage dans l'Adoption d'une Technologie Verte : le Cas LBD Linéaire'* étudie les caractéristiques d'une trajectoire optimale de déploiement des véhicules décarbonés dans le cas où les effets d'apprentissage et la convexité sont présents dans la fonction de coût. Le modèle d'équilibre partiel de Creti et. al (2015) est utilisé comme point de départ. Dans le cas LBD linéaire la trajectoire de déploiement optimale est obtenue analytiquement. Un apprentissage fort induit une transition antérieure vers les véhicules verts dans le cas d'une convexité faible et une transition ultérieure dans le cas d'une convexité forte. Ce résultat permet de revisiter le projet H2 Mobility en Allemagne. Un effet d'apprentissage plus fort et une accélération du déploiement aboutissent à une transition moins coûteuse et une période de cash flow négatif plus courte.

Analysis of a hydrogen-based transport system and the role of public policy in the transition to a decarbonized economy

Summary

What economic and policy framework would foster a transition in the European transport sector from fossil fuels to hydrogen in the long term (2030-50)? This research combines empirical and theoretical approaches and aims to answers the following questions:

1. How to design appropriate policy instruments to solve inefficiencies in hydrogen mobility deployment?
2. How to define abatement cost and an optimal launching date in the presence of learning-by-doing (LBD)?
3. How to define an optimal deployment trajectory in presence of LBD and convexity in investment costs?

The paper *'Transition Towards a Hydrogen-Based Passenger Car Transport: Comparative Policy Analysis'* draws a cross-country comparison between policy instruments that support the deployment of Fuel Cell Electric Vehicle (FCEV). The existing policy framework in favour of FCEV and hydrogen infrastructure deployment is analysed. A set of ex-post policy efficiency indicators is developed and calculated to rank the most active countries, supporters of FCEV. The comparison stands on a series of complementary indicators including vehicle Affordability, Annual Advantage in Running Cost and Total Cost of Ownership (TCO), State Financial Participation. FCEV possession price is shown to be lower in Denmark, Norway and Japan, and is higher elsewhere. A high possession price of FCEV could be compensated by the advantage of lower running costs within ten years notably in France, Sweden and California, USA. The analysis shows that the most generous incentives are available under price-based policy instruments design, which allows maximising short-term FCEV deployment rate. Denmark and Japan emerge as the best providers of favourable conditions for the hydrogen mobility deployment: local authorities put in place price-based incentives (such as subsidies and tax exemptions) making FCEV more financially attractive than its gasoline substitute, and coordinate ramping-up of their hydrogen infrastructure nationally.

The paper *'Defining the Abatement Cost in Presence of Learning-by-doing: Application to the Fuel Cell Electric Vehicle'* models the transition of the transport sector from a pollutant state to a clean one. A partial equilibrium model is developed for a car sector of a constant size. In this model the objective of the social planner is to minimize the cost of phasing out a stock of polluting cars from the market over time. The cost includes the private cost of green cars production, which are subject to LBD, and the social cost of carbon, which has an exogenous upward trend. The optimal path involves (i) a waiting period for the transition to start, (ii) gradual

replacement of polluting cars by the green ones, and (iii) final stabilization of the green fleet. During the transition, the equalization of marginal costs takes into account the fact that the current action has an impact on future costs through LBD. This paper also describes a suboptimal plan: if the deployment trajectory is exogenously given, what is the optimal starting date for the transition? The paper provides a quantitative assessment of the FCEV case for the substitution of the mature Internal Combustion Engine (ICE) vehicles. The analysis concludes that the CO2 price should reach 53€/t for the program to start and for FCEV to be a socially beneficial alternative for decarbonizing part of the projected German car park in the 2050 time frame.

The impact of LBD on the timing and costs of emission abatement is, however, ambiguous. On the one hand, LBD supposes delaying abatement activities because of cost reduction of future abatement due to LBD. On the other hand, LBD supposes starting the transition earlier because of cost reduction due to added value to cumulative experience. The paper *'The Role of Learning-by-Doing in the Adoption of a Green Technology: the Case of Linear LBD'* studies the optimal characteristics of a transition towards green vehicles in the transport sector when both LBD and convexity are present in the cost function. The partial equilibrium model of (Creti et al., 2015) is used as a starting point. For the case of linear LBD the deployment trajectory can be analytically obtained. This allows to conclude that a high learning induces an earlier switch towards green cars in the case of low convexity, and a later switch in the case of high convexity. This insight is used to revisit the hydrogen mobility project in Germany. A high learning lowers the corresponding deployment cost and reduces deepness and duration of the, investment 'death valley' (period of negative project's cash flow). An acceleration of exogenously defined scenario for FCEV deployment, based on the industry forecast, would be beneficial to reduce the associated transition cost.

Synthèse

La décarbonisation du système de transports est l'un des défis clés pour l'atténuation du changement climatique. En Europe, le secteur des transports est le deuxième plus grand émetteur de gaz à effets de serre (GES) après les industries de l'énergie. Il contribue à hauteur d'environ 25 % du total des émissions de GES, parmi lesquelles 75 % sont dues au transport routier :

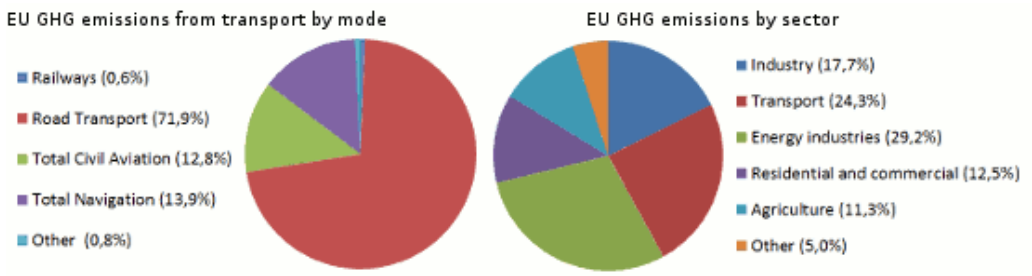

Figure 1 EU28 émissions de gaz à effet de serre par secteur et mode de transports (EC, 2012).

Tandis que d'autres secteurs (énergie, habitations, etc.) réduisent leurs émissions, celles du secteur des transports continuent à augmenter. Les émissions de gaz à effet de serre dans d'autres secteurs ont en effet diminué d'environ 15 % entre 1990 et 2007 alors que les émissions provenant des transports ont augmenté de 36 % sur la même période :

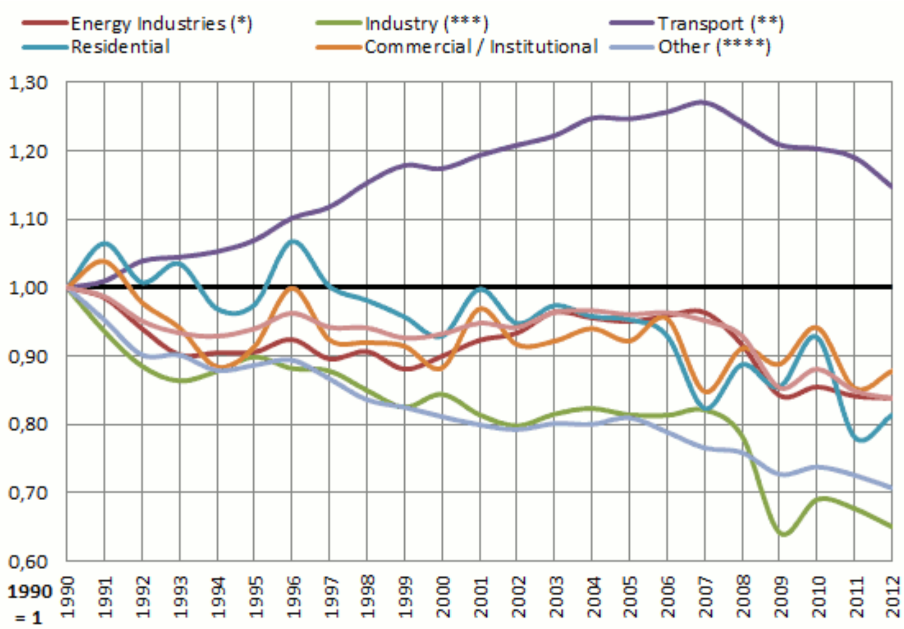

Figure 2 Les émissions de gaz à effet de serre de l'UE provenant des transports et d'autres secteurs, 1990-2012 (EC, 2012).

Cette augmentation des émissions dues aux transports a eu lieu malgré les améliorations de l'efficacité énergétique des véhicules, et ce en grande partie du fait de l'augmentation des transports de personnes et du fret. Depuis 2008, les émissions propres au secteur des transports ont commencé à décroître. Néanmoins, en 2012, celles-ci étaient toujours 20,5 % plus élevées par rapport au niveau de 1990. En Europe, les émissions dues aux transports doivent décroître de 67 % d'ici 2050 pour atteindre l'objectif de réduction de 60 % des émissions (par rapport au niveau de 1990), défini dans le Livre Blanc des Transports (EC, 2011).

Malgré les tendances actuelles, selon lesquelles il n'est pas attendu que le parc automobile européen croisse de façon significative dans les années à venir, le nombre de voitures dans le monde pourrait doubler en 2050 du fait de la croissance de la population et de la hausse des revenus (IEA, 2013). Il est à noter qu'en Asie, les experts anticipent une augmentation du nombre de véhicules légers d'un facteur allant de 6 à 8 , liée à un accroissement de la population, et notamment à la croissance de la classe moyenne (ADB, 2010).

Il est ainsi nécessaire de mettre en place des programmes de grande ampleur en Europe pour réduire les émissions de GES et ainsi réussir à atteindre les objectifs globaux d'émissions de GES pour 2050. Les bénéfices tirés de ces programmes se propageront aux pays hors de l'OCDE dans lesquels les émissions liées au transport routier sont contraintes à croitre.

L'introduction de véhicules dits « zéro-émission », qui n'émettent pas de gaz d'échappement polluant lors de leur utilisation, constitue une partie nécessaire de la solution pour la décarbonisation du secteur du transport de passagers. Des recherches récentes montrent que les voitures à pile à combustible (FCEV) et les voitures électriques à batterie (BEV) peuvent jouer un rôle décisif dans la décarbonisation du secteur des transports à la fois au niveau global (Anandarajah, McDowall, & Ekins, 2013; Franc, 2015; Oshiro & Masui, 2014) et au niveau national (Grahn & Williander, 2009).

La décarbonisation complète du secteur des transports ne peut être achevée qu'avec l'amélioration des traditionnels moteurs à combustion interne (ICE), qui sont limités par des freins techniques liés à la consommation des moteurs et au taux de carbone dans le carburant. Une fois pris en compte la raréfaction et le coût croissant des ressources énergétiques, il apparaît essentiel de développer toute une gamme de technologies sans pétrole, afin d'assurer la durabilité à long terme de la mobilité en Europe.

Les voitures électriques (BEV, FCEV et les véhicules hydrides – PHEV – en mode de fonctionnement électrique) n'émettent aucun gaz d'échappement pendant la conduite, et améliorent significativement la qualité de l'air à l'échelle locale. Ces voitures sont aussi substantiellement moins polluantes en dioxyde d'azote et en particules, ainsi qu'en niveau sonore. De plus, elles sont proches d'une pollution du puits à la roue (well-to-wheel) de l'ordre de zéro, en fonction de la source d'énergie primaire utilisée :

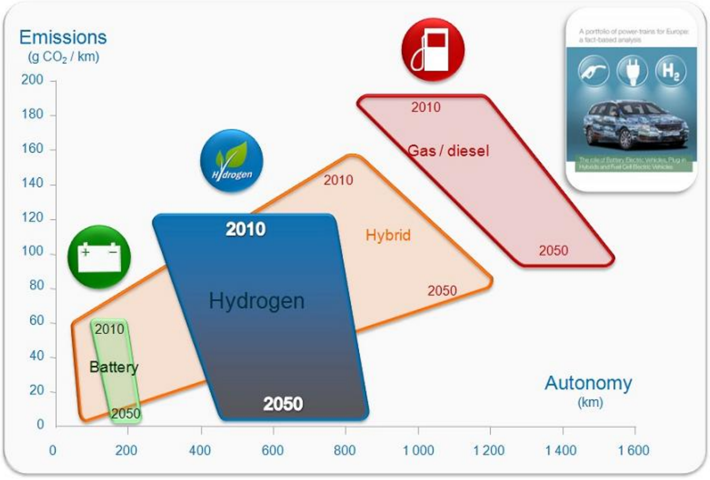

Figure 3 Potentiels de réduction d'émissions de différents motopropulseurs en fonction de l'autonomie (McKinsey & Company, 2010).

Comme le montre le graphique, malgré les améliorations réalisées au niveau de la consommation de carburant, la capacité des moteurs à combustion interne (ICE) à réduire les émissions de CO_2 est significativement moins importante que celle des BEV et FCEV, qui peuvent par ailleurs n'émettre aucun CO_2 du fait de l'utilisation d'énergies alternatives dans la production d'électricité et d'hydrogène.

L'hydrogène, s'il est produit par des voies durables, offre la possibilité d'accroître l'utilisation des énergies renouvelables en Europe, car il pourrait servir comme moyen de stockage provisoire d'énergie et ainsi faciliter l'introduction à grande échelle de ressources telles que le vent ou l'énergie solaire. Dans les pays qui ont une électricité très carbonée (comme par exemple l'Allemagne), les BEV à eux seuls ne résoudront pas le problème de la décarbonisation des transports, tandis que les FCEV pourraient à la fois réduire les émissions liées aux transports et permettre d'équilibrer une production intermittente d'électricité provenant de sources renouvelables.

Le FCEV semble être une technologie alternative prometteuse, qui peut assurer une mobilité comparable aux voitures traditionnelles d'aujourd'hui : une grande autonomie et un temps de recharge court, tout ceci en gardant possiblement un niveau d'émissions carbones très bas le long de son cycle de vie. Grâce à son autonomie (environ 500 km), le FCEV peut couvrir tous les types de déplacement :

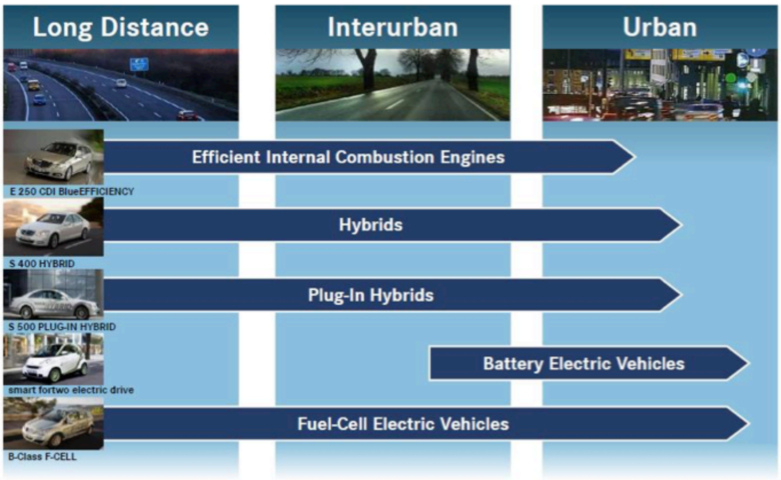

Figure 4 Le portfolio Drivetrain en fonction des types de trajets (Daimler communication, 2014)

La segmentation du marché automobile est très forte. Aussi, aujourd'hui les FCEV et BEV n'apparaissent-ils pas comme des concurrents directs, mais plutôt comme des solutions complémentaires. Le FCEV couvre une longue distance et est mieux positionné pour répondre aux usages urbains et interurbains des véhicules à gabarit de type Berline. Quant à BEV, étant donné que son autonomie est limitée, ce type de véhicule est plus adapté pour des trajets sur des durées et distances plus courtes. Toutefois, les délais dans le développement de l'infrastructure FCEV, de possibles avancées majeures dans l'autonomie et le chargement des batterie, ou encore la préférence nationale en terme d'option technologique, favorisent un développement plus intense du BEV dans le futur.

Un certain nombre d'études reconnaissent une potentielle contribution significative de la mobilité hydrogène pour décarboner le secteur des transports en Europe et apporter des bénéfices additionnels tels que : la création d'emploi local (Cambridge Econometrics, 2013), une réduction de la dépendance de l'Europe aux importations de pétrole (EC, 2003), un impact positif sur la santé publique (Balat, 2008), ainsi qu'une augmentation de l'usage des énergies renouvelables (HyWays, 2008). La mobilité hydrogène est assez mature et prête pour pénétrer le marché (Roads2HyCom, 2009).

Pour atteindre une part de marché substantielle sur le long-terme, la mobilité hydrogène devra cependant surmonter un certain nombre de défis : la décarbonisation de la production d'hydrogène, un déploiement coordonné de son infrastructure de distribution, et une forte concurrence de coûts par la technologie à pétrole actuelle.

Quel cadre économique et réglementaire à long terme (2030-50) pour soutenir la transition énergétique des carburants fossiles vers l'hydrogène dans le secteur européen des transports ? Cette recherche combine les approches théoriques et empiriques afin de répondre aux trois questions suivantes :

(i) Comment concevoir des politiques de soutien adaptées afin de pallier aux imperfections de marché lors du déploiement de technologies de mobilité hydrogène ?

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AAC	Adjusted Abatement Cost
BEV	Battery Electric Vehicle
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
ICE	Internal Combustion Engine vehicle
FCEV	Fuel Cell Electric Vehicle
H_2	Hydrogen
HRS	Hydrogen Refueling Station
LBD	Learning-by-Doing
MAC	Marginal Abatement Cost
TCO	Total Cost of Ownership
PHEV	Plug-in Electric Vehicle
R&D	Research and Development
ZEV	Zero Emission Vehicle

Introduction

The decarbonisation of the transport system is one of the key challenges in mitigating climate change. In Europe the transport sector is the second biggest emitter of greenhouse gas (GHG) emissions after energy industries and contributes about 25% of total GHG emissions, 75% of which are from road transport:

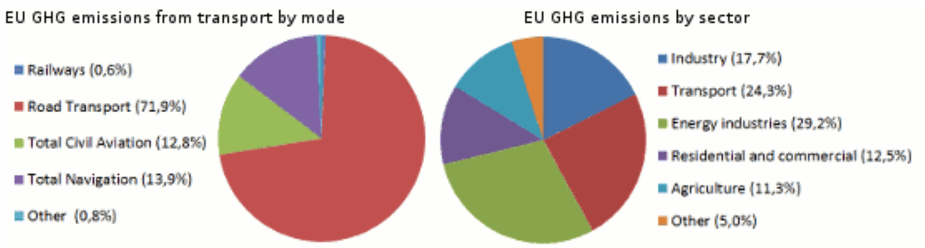

Figure 1 EU28 greenhouse gas emissions by sector and mode of transport (EC, 2012)

While other sectors reduce their emissions, emissions of the transport sector continue to increase. Greenhouse gas emissions in other sectors decreased by around 15% between 1990 and 2007, however, during the same period emissions from transport increased by 36%:

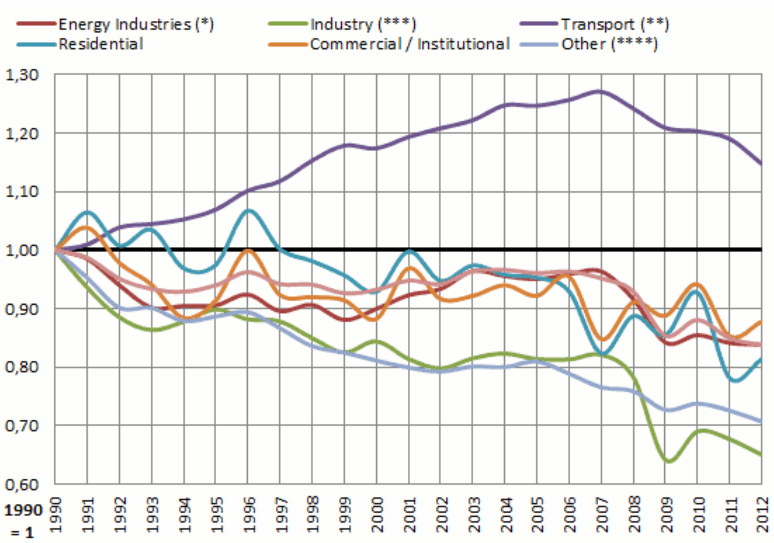

Figure 2 EU greenhouse gas emissions from transport and other sectors, 1990-2012 (EC, 2012)

This increase in transport emissions has happened despite the improvements in vehicle efficiency, mainly due to the increase in the amount of personal and freight transport. Since 2008 greenhouse gas emissions from transport sector have started to decrease. Nevertheless, transport emissions were still 20.5 % above 1990 levels in

2012. In Europe transport emissions need to fall by 67 % by 2050 in order to meet target reduction of 60% compared to 1990 levels, which is defined in the Transport White Paper[1] (EC, 2011).

Even if according to current trends the European car park is not expected to significantly grow in the future, the number of cars may double worldwide until 2050 due to population and income increases (IEA, 2013). Notably, in Asia experts anticipate six- to eight-fold increase in the number of light-duty vehicles due to population and notably middle class growth (ADB, 2010).

Therefore, there is a need for major programs in Europe to reduce the corresponding GHG emissions in order to achieve the global GHG targets for 2050. The benefits from these programs will spread out to non-OECD countries in which road emissions are bound to increase.

The decarbonisation of the transport sector can be achieved both through change in commuting habits and technological change. Today, there is a shift towards a more environmental friendly behaviour, which aims to change or even avoid commuting: telework; switch towards other transport modes such as bicycles and public transport; car sharing (a model of car rental where people rent cars for short periods of time); carpooling (sharing of car journeys so that more than one person travels in a car), etc. For example, the worldwide carpooling community of BlaBlaCar has saved 500 000 tons of oil during last year[2], which is the equivalent of lighting the city of Los Angeles for an entire year. However, a behavioural change alone will not be enough to completely decarbonise transport sector and technological a change will play crucial role in coming decades.

Introduction of zero-emission vehicles (ZEV), which emit no tailpipe pollutants from the on-board source of power, is a necessary part of the solution to decarbonise passenger transport sector. Recent research shows that both Fuel Cell Electric Vehicles (FCEV) and Battery Electric Vehicles (BEV) can play a critical role in decarbonising the transport sector both on global (Anandarajah, McDowall, & Ekins, 2013; Franc, 2015; Oshiro & Masui, 2014) and national (Grahn & Williander, 2009) levels. The full decarbonisation of the transport sector cannot be achievable only through improvements to the traditional internal combustion engine (ICE), which are bounded by technical limits for engine's efficiency and carbon content of gasoline. Once accounted for the increasing scarcity and cost of energy resources, it appears essential to develop a range of oil free technologies in order to ensure a long-term sustainability of mobility in Europe.

Electric vehicles (BEV, FCEV and plug-in electric vehicles (PHEV) in electric drive) have zero tailpipe emissions while driving and significantly improve local air quality. These vehicles also have substantially lower pollution from noise, NO_2 and particles. Moreover, they can reach close to zero well-to-wheel CO_2 emissions, depending on the primary energy source used:

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1 2011 Transport White Paper available at *http://ec.europa.eu/transport/themes/strategies/2011_white_paper_en.htm*

2 BlaBlaCar blog *https://www.blablacar.in/blog/cop21-to-post-india*

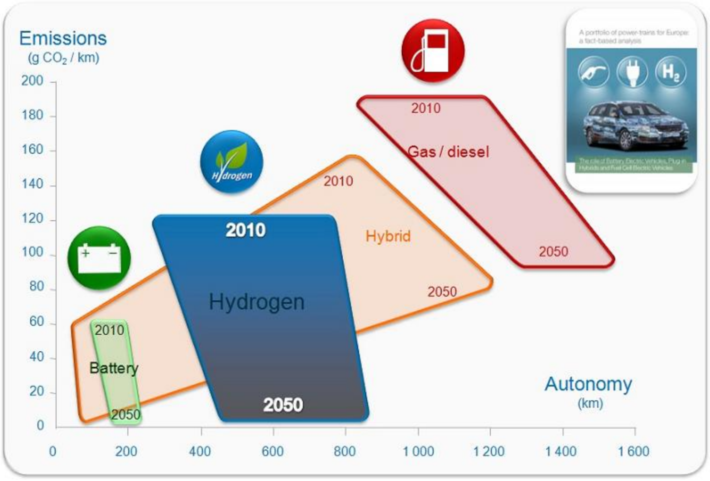

Figure 3 Emissions reduction potential of different power trains with respect to the autonomy range (McKinsey & Company, 2010)

As can be seen, despite improvements in fuel economy, the capacity of ICE to reduce CO_2 is significantly less than that of BEV and FCEV, which can be CO_2 emissions free due to use of alternative energies in central power and hydrogen production by 2050.

Hydrogen, if produced through sustainable pathways, offers the opportunity to increase the utilisation of renewable energy in Europe because it could act as a temporary energy storage option and might thus facilitate the large-scale introduction of intermittent resources such as wind and solar energy. In countries with a high carbon content of electricity (for example, Germany) BEV alone will not solve the transport decarbonisation issue, while FCEV may both reduce emissions related to passenger transport and allow equilibrating intermittent renewable electricity production.

FCEV appears as a promising alternative technology that can ensure a mobility service compared to today's conventional cars: high autonomy range and short recharging time, all at potentially very low life cycle carbon emissions. Thanks to its large autonomy range (about 500 km), FCEV covers all commuting types:

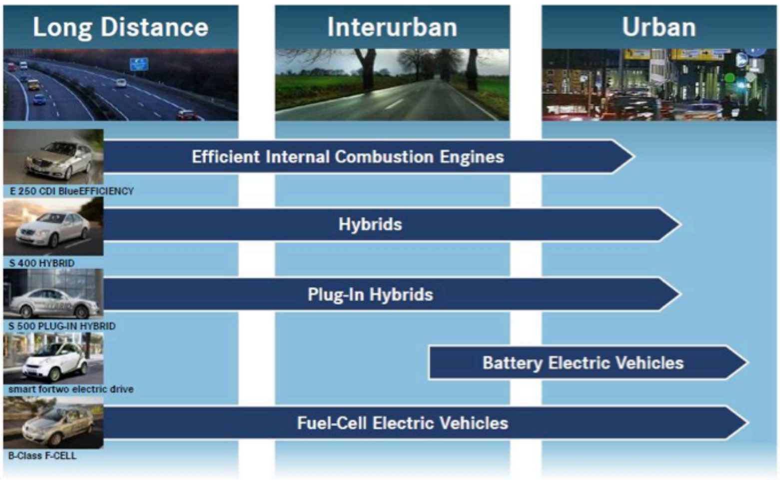

Figure 4 Drivetrain portfolio with respect to commuting types (Daimler communication, 2014)

The segmentation on the car market is very strong and today FCEV and BEV appear not as direct competitors but rather as complementary solutions. FCEV covers longer distance and is better positioned to satisfy interurban and urban use within large cars class. As the range of BEV is limited, they are more adapted for smaller cars and shorter trips. However, delays in the development of FCEV infrastructure, possible breakthroughs in battery technology, and promotion of national preferable technological option may change the nature of this competition, making it more intense in the future.

A number of studies recognise a high potential contribution of hydrogen mobility to decarbonise the transport sector in Europe and to create extra environmental benefits such as an increase in domestic employment (Cambridge Econometrics, 2013), a reduction of Europe's dependence on imported oil (EC, 2003), positive impact on public health (Balat, 2008), and an increased use of renewable energy (HyWays, 2008). Hydrogen mobility technology is mature enough and is ready for market penetration (Roads2HyCom, 2009).

To reach a substantial long-term market share hydrogen mobility should, however, overcome a number of important deployment challenges: decarbonisation of hydrogen production; coordinated deployment of hydrogen distribution infrastructure; and severe cost competition with incumbent gasoline technology.

FCEV has the potential to significantly reduce CO_2 and local emissions, assuming CO_2 reduction is performed at the production site (Creti and al., 2015; McKinsey & Company, 2010). Today hydrogen production via steam reforming of methane is the most economical and widely used method, however, pollutant. Progressive introduction of new methods, such as combining steam methane reforming with carbon capture and storage, steam reforming of biogas, electrolysis using solar and wind power will allow massive production of decarbonised hydrogen and will progressively bring its cost down (Creti and al., 2015).

FCEV deployment also requires a simultaneous ramp-up of vehicles and the deployment of the infrastructure. This is known as the chicken-and-egg dilemma:

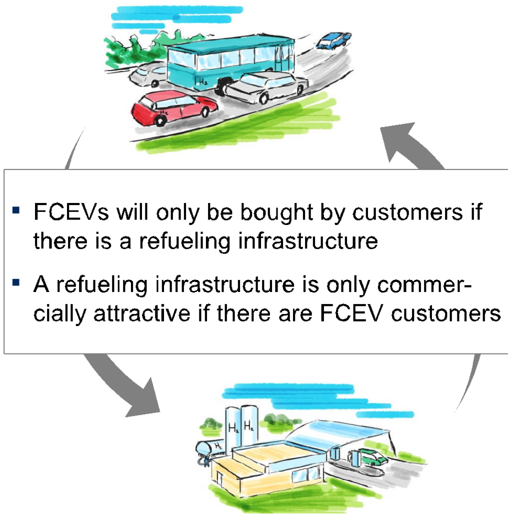

Figure 5 FCEV deployment is subject to chicken-and-egg dilemma (H2 Mobility Germany, 2014)

On one hand, car manufacturers sell FCEV and consumers buy them in large series only if there is a dense enough infrastructure in place. On the other hand, public and private investors deploy hydrogen infrastructure only if there is a demand for hydrogen from the hydrogen fleet in place.

Two strategies to overcome this chicken-and-egg dilemma have been used for FCEV. The first one is to build for a captive fleet. A captive fleet is a group of vehicles (companies, governmental agencies with large delivery fleet). This approach greatly facilitates the forecasting of fuel consumptions, and the deployment needs for the network. Significant early markets are created by specialised application niches and by the political will of municipal early adopters (Roads2HyCom, 2009). The second strategy relies on public subsidies to quickly set up a large infrastructure, with a possible first focus on clusters and later expansions to interregional roads. In this case, State expects to gain the trust of car manufacturers and customers and reduces the uncertainty related to the FCEV deployment.

Costs for a hydrogen infrastructure fall approximately between 5% (McKinsey & Company, 2010) and 10% (Creti and al., 2015) of the overall cost of FCEV (€1,000-2,000 per car) and are comparable to rolling out a charging infrastructure for BEV and PHEV (McKinsey & Company, 2010). A temporary consortium for hydrogen infrastructure could solve early-phase network market failure. For example, the German government established a private public partnership H2 Mobility, which aims to ensure a hydrogen infrastructure deployment on the national territory and aims to offer a hydrogen refuelling station at least every 90 kilometres of highway between densely populated areas.

Numerous studies showed that hydrogen mobility can become a cost-effective option for the reduction of CO_2 in the long-term (Creti and al., 2015; McKinsey & Company 2010). Creti and al. (2015) conduct a cost-benefit analysis and modelise competition between FCEV and ICE on the German market of passenger cars. The authors conclude that without policy support the difference in Total Cost of Ownership (TCO) between FCEV and ICE can be brought to zero around 2040, mainly due to FCEV cost reduction via learning effect and growing gasoline price. The study on passenger cars of McKinsey & Company (2010) provides a factual evaluation of BEV, FCEV, PHEV and ICE based on proprietary industry data and combine a forecasting and backcasting approaches. The study concludes that with tax incentives, FCEV could be cost-competitive with ICE as early as 2020.

Today, society willingness to pay for a positive environmental externality is extremely small and the existing energy and transport system is locked-in into an incumbent pollutant technology (Zachmann et al., 2012). This is the reason why policy intervention appears indispensable to support deployment of ZEV, especially during early deployment stages. For example, by setting an 'adjusted' carbon price, incentives for developing and investing in new low-carbon vehicles will be created. However, an 'adjusted' abatement cost should take into account both learning-by-doing effects for new green cars and convexity in production costs.

The goal of this research is to identify economic and policy framework that could foster the transition from fossil fuels to hydrogen in the transport sector in Europe in 2030-2050 perspectives. The research combines empirical and theoretical approaches and answers the following questions:

1. How to design appropriate policy instruments to solve inefficiencies in hydrogen mobility deployment?
2. How to define abatement cost and an optimal launching date in the presence of learning-by-doing (LBD)?
3. How to define an optimal deployment trajectory in presence of LBD and convexity in investment costs?

These questions are treated in three respective papers described above.

Transition Towards a Hydrogen-Based Passenger Car Transport: Comparative Policy Analysis

The market force alone is not sufficient to initiate the transition towards ZEV and thus public support is crucial during initial deployment stages. ZEV deployment suffers from market failure due to economies of scale. Economies of scale (particularly increasing returns to scale) refer to a situation where the average cost of producing a unit decreases as the rate of output increases (due to a fixed cost for example). Along with economies of scale, there is a "chicken-and-egg" problem, whereby multiple actors must simultaneously invest and ramp up production in order to commercialize a new technology. This problem is extremely relevant for FCEV, which require deployment of a new costly infrastructure.

Such investment project requires inter-industry cooperation, which delays necessary investment. Moreover, under certain conditions the initial sunk costs cannot be recouped through pure market equilibrium behaviours. Many authors have highlighted a necessity of public intervention during early deployment stages (Beltramello, 2012; Bleijenberg et al.; 2013; Egenhofer, 2011; Saugun, 2013; Bruegel institute, 2012). Public support in the beginning of the deployment period helps to attain an initial critical mass of refuelling stations and vehicle stock.

Once a critical mass is reached the need for public intervention will be significantly reduced thanks to learning-by-doing effect. The idea behind learning-by-doing is that the cost of producing goods declines with the cumulative production of goods. In other words, the act of producing more ZEV increases the stock of cumulative experience of the car manufacturer and thus leads to declines in future costs. However, the learning-by-doing ensures a long-term cost reduction only when the problem of economies of scale has been overcome due to public support and when a market kick-off has taken place.

In order to initiate a market kick-off, the critical mass of stations and vehicle stock could be attained through two mechanisms: first, vehicle deployment push; second, infrastructure deployment pull. Indeed, State could implement policy instruments targeting either vehicles or infrastructure deployment in order to solve chicken-and-egg dilemma (Plotkin, 2007; Bento, 2008). In the first case, State acts mainly on the demand side of the problem and addresses consumers by creating monetary and non-fiscal incentives in order to make FCEV possession more attractive. The associated demand for refuelling is supposed to push the corresponding infrastructure deployment. In the second case, State acts more on the supply side of the problem by inducing infrastructure deployment through subsidies or coordinated public-private partnerships, which in its turn will pull the demand for vehicles.

A complementarity between State support for vehicles supply and infrastructure deployment is supposed. The intuition to be verified within this analysis is that a coordinated ramp-up of vehicles and infrastructure deployment is the most complete approach to deal with chicken-and-egg dilemma.

The present study focuses on a short-term policy impact and evaluates a relative advantage within a set of different countries. Today, the deployment of ZEV has started thanks to a voluntary policy action. There is no common target, policy or strategy for the FCEV and BEV deployment. The long-term structural effects such as creation of new products in response to legislation (for, example, emergence of Nissan Leaf to comply with ZEV regulation in California) are not considered in this paper.

Recent papers provide a qualitative overview of policies promoting BEV worldwide (Leurent & Windisch, 2011; Tietge, Mock, Lutsey, & Campestrini, 2016; Trigg, Telleen, Boyd, & Cuenot, 2013). Some works (ACEA, 2014; ICCT, 2014) focus more generally on ZEV and overview existing CO_2-based vehicle taxation schemes, which could be applicable to both BEV and FCEV. This paper suggests a classification, which allows a quantitative analysis of existing policy instruments. Identified classes of Quotas, Monetary, Fiscal and Non-Fiscal incentives for vehicle deployment are further divided in price-based and quantity-based policy instruments groups. This classification enables to develop a set of indicators, which could be used in future ex-post policy analysis, when enough empirical data on FCEV deployment will be available.

This study focuses on large and luxury cars segments, for which FCEV is the lowest-carbon solution for long trips (McKinsey & Company, 2010). FCEV ensures a long-range autonomy and a short refuelling time compared to BEV and makes the use of FCEV similar to its gasoline substitute.

This paper focuses on FCEV and gives a perspective on a supportive policy framework for a new FCEV model launch on the example of Toyota Mirai. Toyota launched the sales of Mirai in Japan in December 2015. Initially, sales were limited to government and corporate customers and were not available to individual customers. As of December 2014, domestic orders had already reached over 400 Mirais, surpassing Japan's first-year sales target, and as a result, there was a waiting list of more than a year. It will be interesting to evaluate future diffusion of this technology within the framework of current analysis.

Two deployment strategies have been used for FCEV. The first one consists in deploying a captive fleet. A captive fleet is a group of vehicles possessed by one large entity (e.g. companies, governmental agencies with large delivery fleet). This approach greatly facilitates forecast of fuel consumptions, and the deployment needs for the network. The second strategy relies on public subsidies to quickly set up a large infrastructure, with a possible first focus on clusters and later expansions to interregional roads. In this case, State proves its engagement in ZEV deployment for car manufacturers and customers and reduces the uncertainty related to mass market FCEV deployment.

Indicators developed in this paper are inspired by classical industrial indicators (such as Capex, Opex, Pay Back Period, and Cumulated State Subsidy). The proposed set includes vehicle-related indicators such as *Affordability*, *Annual Advantage in Running Cost*, *TCO Convergence*, *Advantage in TCO, Static CO_2 price* and *State Financial Participation*; and infrastructure-related indicators such as *Coverage* and *Availability*. These indicators allow comparing incentives targeting consumers at the moment of vehicle purchase and maintenance; evaluating State financial implication; and making an assessment of hydrogen refuelling infrastructure deployment. Countries with the highest values of these indicators appear at the top of the final ranking and are supposed to provide the most favourable conditions for the FCEV deployment.

A few papers focus on FCEV and make a qualitative overview of public policies supporting its deployment (Bleischwitz & Bader, 2010; Ogden, Yang, Nicholas, & Fulton, 2014). The quantitative framework developed in this paper enables ranking of national policies according to the developed indicators and identifying countries with the most favourable FCEV deployment conditions. The scope of this paper covers France, Germany, Denmark, Norway, Japan, and California.

The most favourable policy framework for hydrogen mobility deployment is observed in Denmark and Japan. These countries are leaders according to both vehicle- and infrastructure-related indicators and concentrate their efforts on coordinated ramp-up of vehicles and infrastructure.

Defining the Abatement Cost in Presence of Learning-by-doing: Application to the Fuel Cell Electric Vehicle (co-written with A. Creti, G. Meunier and JP. Ponssard)

Marginal abatement costs (MACs) are practical indicators used in policy discussions. The MAC is the cost of reducing polluting emissions at the margin, by a factory, a firm, a sector or a country. In policy discussions MACs are notably used to critically assess decarbonisation efforts among sectors and arbitrage between technical options (Marcantonini and Ellerman, 2014). This apparently simple indicator may hide some traps. Whereas this convenient tool is conceptually valid for short-term practices that reduce emissions, there are major difficulties for applying it to long-term reductions that necessitate sunk investments in physical and human capital along the deployment of a new technology. The objective of this paper is to propose an extension of the standard concept of static abatement costs in a context in which dynamic features such as learning-by-doing cannot be neglected.

More precisely, we consider a partial equilibrium model, with the objective to minimize the cost of phasing out polluting goods from a market in presence of learning spillovers over time. The market size is fixed and initially served by polluting goods that must be produced at every point in time at constant marginal cost. The cost of the green goods depends on the rate of production, which rationalizes a smooth phase-out. It also depends on the cumulated past output, introducing a learning-by-doing effect to the model. The total cost for the social planner includes the private cost of production and the social cost of carbon. The latter has an exogenous upward trend.

Under these assumptions we show that the optimization problem can be decomposed into two questions: (i) at what rate the transition should be completed that is, the design of a transition trajectory as such; (ii) when to launch a given trajectory. Interestingly the second question can be answered also for suboptimal trajectories, which provides interesting insights. We define an adjusted abatement cost (AAC) associated to a trajectory, possibly suboptimal. This AAC can be interpreted as the MAC of the whole trajectory and gives the date, when the transition should start. Our model also allows comparing a given trajectory with the optimal one. If the deployment cost is not minimized or the total number of green goods produced during deployment is larger than the optimal one, the launching date should be postponed. If the total number of green goods produced during deployment is lower than the optimal one, the launching should instead take place earlier.

The case of FCEV as a substitute to the mature ICE provided the primary motivation for our methodology. There exist a number of studies on this subject. Harrison (2014) provides an extensive analysis of the environmental and macroeconomic impacts (growth, employment, trade) of alternative power trains (ICE, BEV, FCEV) at the European level in the 2050 time frame. Rosler et al. (2014) carry an in-depth investigation using the energy bottom-up model TIAM-ECN (Loulou, 2008; Loulou and Labriet, 2008) to build scenarios up to 2100 for passenger car transportation in Europe. They show that FCEV could take most of the market in 2050 if no significant breakthrough in battery is made. In contrast, Oshiro and Masui (2014) analyze the Japan market and show that BEV would take most of the passenger car market in 2050 while the share of FCEV would remain marginal.

In all these studies the trajectory for the FCEV transition takes place over several decades. In a number of them the trajectory is exogenously determined and the cost dynamics follows this trajectory. In others the trajectory and the cost dynamics are linked in an intricate way so that the results are not easily implemented by policy makers. Our methodology formalizes this interdependence. For an exogenously given trajectory it characterizes the social cost of carbon that would be consistent with the proposed launching date of the trajectory. For a given cost dynamics it allows comparing the proposed trajectory with the optimal one, as long as the cost dynamics is properly modelled by our assumptions. The methodology is illustrated for the German market using a calibration of updated data from (McKinsey & Company, 2010). The proposed launching date is 2015 and we show that this date would be consistent with a carbon price at 53 €/t. This figure is much lower than estimates obtained through standard methodology which range around 800 to 1,000 €/t (e.g. Beeker, 2014). A local exploration of the proposed trajectory allows for deriving market or cost conditions under which the adjusted marginal abatement cost would decrease from 53 to 30 €/t.

From a theoretical standpoint our model can be seen as a particular specification of similar models developed in the literature. It delivers the standard result that along the optimal trajectory the CO_2 price should be equal to the sum of two terms: the difference between the cost of the marginal green goods and a polluting goods; and the learning benefits over the future. This result, well known in the literature on climate policy and induced technical change (e.g. Goulder and Mathai, 2000; Bramoullée and Olson, 2005) illustrates the intertemporal consistency of the optimal trajectory. Our contribution provides conditions to overcome this difficulty through the characterization of a simple indicator to assess a technological option.

The convexity of the cost function plays a key role in the qualitative property of the transition. Several papers have discussed the role of cost convexity in absence of learning-by-doing. Vogt-Schilb et al. (2012) introduce convexities in the investment cost of clean capital in a multi-sector framework. They show that this convexity incites to spread investment in clean capital over time and comfort observed transition dynamics. Similarly, Amigues, Ayong Le Kama and Moreaux (2015) introduce convexity in the form of adjustment cost in clean capital accumulation to study a transition from non-renewable to renewable resources. Amigues, Lafforgue and Moreaux (2015) analyse the optimal timing of carbon capture and storage policies under decreasing returns to scale. They show that the carbon capture of the emissions should start earlier than under an assumption of constant average cost. The role of convexity has also been stressed by Bramoullée and Olson (2005) in their study of the role of learning-by-doing in sectoral arbitrage. Without convexities, learning-by-doing alone does not justify a ramping of the clean option and learning cost should be postponed as far as possible. This feature is also present in our model.

Our approach can also be related to other streams of literature, as macro models on innovation and green technologies, on one side, and large scale computable models on the other. Analytical macro models that recommend early deployment of green technologies remain imprecise on the specific sectoral cost assumptions that would justify their conclusions (e.g. Grimaud and Rouge, 2008; Acemoglu et al., 2012). Top-down computable general equilibrium (CGE) models (as for instance GEM-E3, GREEN, PACE and MITEPPA) are typically based on exogenous technological change, where roadmaps from polluting to carbon free technologies are used. The associated cost function of the carbon free technologies are time dependent. They compare long-term scenarios under various environmental constraints. Bottom-up models are almost exclusively technology snapshot models that examine a suite of technological alternatives over time. A number of bottom-up models have integrated endogenous technological change that assumes the existence of learning by doing. Examples are MESSAGE, MARKAL and POLES. Both bottom-up and top-down large-scale models provide valuable numerical results, but their complexity limits their use, both for scenario explorations and conceptual thinking.

Our analysis and its application to the hydrogen car deployment provide a link between these two streams of literature. It facilitates the conceptual analysis of the main cost assumptions and its interpretability for decision makers.

The Role of Learning-by-Doing in the Adoption of a New Green Technology: the Case of Linear LBD

Green technologies often require initial sunk investments in physical and human capital and are subject to a significant LBD, which should be taken into account while assessing decarbonisation effort. The idea behind LBD is that initially high production cost may decline rapidly with cumulative experience in this new activity. In other words, the act of producing more goods increases the stock of cumulative experience and thus leads to decline in future cost.

The learning curve expresses the hypothesis that the unit cost decreases by a constant fraction with every doubling of cumulative production.

LBD effect on the timing of emissions abatement is however unclear. On one hand, LBD reduces the costs of future abatement. This suggests delaying abatement activities. On the other hand, there is added value to current abatement. It contributes to cumulative experience and hence helps reducing the costs of future abatement. It is unclear which of these two effects dominates (Goulder and Mathai 2000).

In addition to LBD, the convexity of the cost function plays a crucial role in defining properties of the transition towards a new green technology. Cost convexity encourages redistributing the investment in clean capital over a longer period. Bramoullé and Olson (2005) showed that without convexity, LBD alone does not justify a progressive switching to the clean option. Moreover, they show that LBD strongly affects the form of the deployment trajectory.

FCEV is subject to a significant LBD, which is generally derived from learning curves. Different studies model FCEV cost function with a steep learning curve within national (Lebutsch and Weeda 2011), European (HyWays 2008; McKinsey 2010; Zachmann et al. 2012), and worldwide (IEA 2015) deployment contexts.

McKinsey (2010) used a combined forecasting and backcasting approach to model FCEV cost: from 2010 to 2020, global cost was forecasted, based on proprietary industry data; after 2020, on projected learning rates. The learning rate is equal to 15%. All conclusions are shown to be robust with respect to significant variations in learning rates: by 2030, there is only a small difference in Total Cost of Ownership of FCEV and ICE-gasoline of –1 to 3 cents per kilometre even with important variation in FCEV learning rate after 2020.

Zachmann et al. (2012) adopts a slightly different methodology for FCEV cost function modelling and uses two-factor learning curves. This reflects the fact that both capacity deployment and R&D may impact the rate of technical progress and cost reduction. Learning effects come from learning-by-doing or learning-by-research. The authors use the industry assumptions on learning rates (15%) reported in (McKinsey 2010) for their modelling purposes. They use Marktmodell Elektromobilität simulation model based on discrete choice modelling to forecast the evolution of different automotive technologies on the German market. This paper does not provide details on the robustness check of the results with respect to the change in the learning rate. However, the model supposes a negative feedback loop between slow market uptake, insufficient learning-by-doing cost reductions and, hence, high fuel and purchase costs and low consumer acceptance, which would cause a far lower market penetration trajectory.

The studies described above do not explicitly introduce convexity in the FCEV cost function and treat mostly learning effect, which is certainly very important in FCEV cost reduction. This study aims analysing the characteristics of the optimal deployment and study a mutual impact of both convexity and learning. The case of a linear LBD cost function allows a complete analytical characterization of the deployment trajectory and, notably, defining the transition launching date and its duration. The partial equilibrium model of (Creti et al. 2015b) is used as a starting point.

The analysis shows that a high learning induces an earlier switch towards green cars in the case of low convexity and suggests delaying deployment of green cars in the case of high convexity. A higher learning also lowers the corresponding deployment cost.

This insight is used to revisit the hydrogen mobility deployment project in Germany. In the initial model of Creti et al. (2015a) the deployment trajectory was exogenously determined. We show that it would be beneficial to speed it up.

The questions treated in these three papers contribute to the analysis of the energy transition in the transport sector. All models are calibrated for the case of FCEV. However, the challenges of different ZEV such as adapted policy instruments during early deployment stages, tough cost competition with incumbent polluting technology and infrastructure deployment issue are similar to FCEV and BEV. Some insights developed in this thesis for FCEV can be applied for other ZEV types.

Chapter I

Transition towards a hydrogen-based passenger car transport: comparative policy analysis

Transition towards a hydrogen-based passenger car transport: comparative policy analysis

Alena Kotelnikova*
*Ecole Polytechnique

June, 2016

Abstract

Major OECD countries including Germany and Japan have put in place a wide range of policy instruments addressing Zero Emission Vehicle (ZEV) deployment. This paper draws a cross-country comparison between those instruments that support in particular the deployment of Fuel Cell Electric Vehicle (FCEV). We analyse the existing policy framework in favour of FCEV and hydrogen infrastructure deployment. We develop and calculate ex-post policy efficiency indicators and rank countries, which are the most active in promoting FCEV. The comparison stands on a series of complementary indicators including vehicle Affordability, Annual Advantage in TCO, State Financial Participation and infrastructure Coverage and Availability. We show that FCEV possession price is lower in Denmark, Norway and Japan, and is higher elsewhere. A high possession price of FCEV could be compensated with advantage in running cost within ten years notably in France, Sweden and California. Analysis shows that the most generous incentives to promote hydrogen vehicles deployment are available in countries using price- based policy instruments design (like subsidies in Japan or tax exemptions in Denmark). These instruments allow maximising short-term FCEV deployment rate. Denmark and Japan emerge as the best providers of favourable conditions for the hydrogen mobility deployment. These countries lead according to both vehicle- and infrastructure-related indicators and concentrate their efforts on coordinated ramp-up of vehicles and infrastructure.

JEL Classification: H23, Q58, R40

Keywords: Decarbonisation of the transport sector; ZEV deployment; fuel cell electric vehicles (FCEV); policy analysis; policy indicators; consumer incentives; State technology policy.

1. Introduction

The transport sector is the second biggest emitter of greenhouse gas (GHG) emissions after energy industries. While other sectors reduce their emissions, emissions of the transport sector continue to increase. Among all transport modes passenger transport contributes most to that growth. That is why introduction of zero emission vehicles (ZEV) in the passenger car sector is important. Even if the passenger car market in developed countries is not expected to increase, there is a need for programs reducing the corresponding GHG emissions in order to achieve the global GHG targets for 2050. The benefits from these programs will spread out to non-OECD countries where road emissions are bound to increase. Recent research shows that both Fuel Cell Electric Vehicles (FCEV) and Battery Electric Vehicles (BEV) can play a critical role in decarbonising the transport sector both on global (Anandarajah, McDowall, & Ekins, 2013; Oshiro & Masui, 2014; Franc, 2015) and national (Grahn & Williander, 2009) levels.

The market force alone is not sufficient to initiate the transition towards the ZEV technology and thus public support is crucial during initial deployment stages. ZEV deployment suffers from economies of scale market failure. Economies of scale (particularly increasing returns to scale) refer to a situation where the average cost of producing a unit decreases as the rate of output increases (due to a fixed cost for example). Along with economies of scale, there is a “chicken-and-egg” problem, whereby multiple actors that must simultaneously invest and ramp up production in order to commercialize a new technology. This problem is extremely relevant for FCEV, which requires deployment of a new costly infrastructure. Such investment project requires inter-industry cooperation, which delays necessary investment. Moreover, under certain conditions the initial sunk costs cannot be recouped through pure market equilibrium behaviours. Many authors have highlighted a necessity of public intervention during early deployment stages (Beltramello, 2012; Bleijenberg et al.; 2013; Egenhofer, 2011; Saugun, 2013; Bruegel institute, 2012). Public support at the beginning of the deployment period helps to attain an initial critical mass of stations and vehicle stock.

Once a critical mass is reached the need for public intervention will be significantly reduced thanks to learning-by-doing effect. The idea behind learning-by-doing is that the cost of producing goods declines with the cumulative production of goods. In other words, the act of producing more ZEV increases the stock of cumulative experience of the car manufacturer and thus leads to decline in future costs. However, the learning-by-doing ensures a long-term cost reduction only when the problem of economies of scale has been overcome due to public support and when a market kick-off has taken place.

In order to initiate a market kick-off, the critical mass of stations and vehicle stock could be attained through two mechanisms: first, vehicle deployment push; second, infrastructure deployment pull. Indeed, State could implement policy instruments targeting either vehicles or infrastructure deployment in order to solve chicken-and-egg dilemma (Plotkin, 2007; Bento, 2008). In the first case, State acts mainly on the demand side of the problem and addresses consumers by creating monetary and non-fiscal incentives in order to make FCEV possession more attractive. The associated demand for refuelling is supposed to push the corresponding infrastructure deployment. In the second case, State acts more on the supply side of the problem by inducing infrastructure deployment through subsidies or coordinated public-private partnerships, which in its turn will pull the demand for vehicles.

A complementarity between State support for vehicles supply and infrastructure deployment is supposed. The intuition to be verified within this analysis is that a coordinated ramp-up of vehicles and infrastructure deployment is the most complete approach to deal with chicken-and-egg dilemma.

The present study focuses on a short-term policy impact and evaluates a relative advantage within a set of different countries. Today, the deployment of ZEV has started thanks to a voluntary policy action. There is no common target, policy or strategy for the FCEV and BEV deployment. The long-term structural effects such as creation of new products in response to legislation (for, example, emergence of Nissan Leaf to comply with ZEV regulation in California) are not considered in this paper.

Recent papers provide a qualitative overview of policies promoting BEV worldwide (Leurent & Windisch, 2011; Tietge, Mock, Lutsey, & Campestrini, 2016; Trigg, Telleen, Boyd, & Cuenot, 2013). Some works (ACEA, 2014; ICCT, 2014) focus more generally on ZEV and overview existing CO_2-based vehicle taxation schemes, which could be applicable to both BEV and FCEV. This paper suggests a classification, which allows a quantitative analysis of existing policy instruments. Identified classes of Quotas, Monetary, Fiscal and Non-Fiscal incentives for vehicle deployment are further divided in price-based and quantity-based policy instruments groups. This classification enables to develop a set of indicators, which could be used in future ex-post policy analysis, when enough empirical data on FCEV deployment will be available.

This study focuses on large and luxury cars segments, for which FCEV is the lowest-carbon solution for long trips (McKinsey & Company, 2010). FCEV ensures a long-range autonomy and a short refuelling time compared to BEV and makes the use of FCEV similar to its gasoline substitute.

This paper focuses on FCEV and gives a perspective on a supportive policy framework for a new FCEV model launch on the example of Toyota Mirai. Toyota launched the sales of Mirai in Japan in December 2015. Initially, sales were limited to government and corporate customers and were not available to individual customers. As of December 2014, domestic orders had already reached over 400 Mirais, surpassing Japan's first-year sales target, and as a result, there was a waiting list of more than a year. It will be interesting to evaluate future diffusion of this technology within the framework of current analysis.

Two deployment strategies have been used for FCEV. The first one consists in deploying a captive fleet. A captive fleet is a group of vehicles possessed by one large entity (e.g. companies, governmental agencies with large delivery fleet). This approach greatly facilitates forecast of fuel consumptions, and the deployment needs for the network. The second strategy relies on public subsidies to quickly set up a large infrastructure, with a possible first focus on clusters and later expansions to interregional roads. In this case, State proves its engagement in ZEV deployment for car manufacturers and customers and reduces the uncertainty related to mass market FCEV deployment.

Indicators developed in this paper are inspired by classical industrial indicators (such as Capex, Opex, Pay Back Period, and Cumulated State Subsidy). The proposed set includes vehicle-related indicators such as *Affordability*, *Annual Advantage in Running Cost*, *Total Cost of Ownership (TCO) Convergence*, *Advantage in TCO, Static CO_2 price* and *State Financial Participation*; and infrastructure-related indicators such as *Coverage* and *Availability*. These indicators allow comparing incentives targeting consumers at the moment of vehicle purchase and maintenance; evaluating State financial implication; and making an assessment of hydrogen refuelling infrastructure deployment. Countries with the highest values of these indicators appear at the top of the final ranking and are supposed to provide the most favourable conditions for the FCEV deployment.

A few papers focus on FCEV and make a qualitative overview of public policies supporting its deployment (Bleischwitz & Bader, 2010; Ogden, Yang, Nicholas, & Fulton, 2014). The quantitative framework developed in this paper enables ranking of national policies according to the developed indicators and identifying countries with the most favourable FCEV deployment conditions. The scope of this paper covers France, Germany, Denmark, Norway, Japan, and California.

The most favourable policy framework for hydrogen mobility deployment is observed in Denmark and Japan. These countries are leaders according to both vehicle- and infrastructure-related indicators and concentrate their efforts on coordinated ramp-up of vehicles and infrastructure.

The paper is structured as follows. Section 2 describes the methodology of cross-country comparison of policy instruments supporting FCEV. Section 3 describes the framework of the FCEV deployment in different countries; quantifies incentives targeting the consumer at the moment of vehicle purchase and maintenance; and evaluates State financial Participation. It also compares price- and quantity-based approaches for policy instruments design. Section 4 makes an assessment of hydrogen refuelling infrastructure deployment. Section 5 provides a ranking of national policies in seven countries according to the set of developed indicators and identifies countries leading the FCEV deployment. Section 6 concludes.

2. Methodology

The aim of this paper is to provide a quantitative analysis of public policy instruments in favour of FCEV deployment and to identify countries with the most favourable conditions for this deployment. The paper analysis follows thee steps:

(i) analysis of existing policy framework in favour of ZEV (and notably FCEV) and infrastructure deployment;

(ii) calculation of ex-post policy efficiency indicators; and

(iii) ranking of national policies in seven countries (France, Germany, Denmark, Norway, Japan, and California).

Because there is no common binding policy target for ZEV deployment and the policy action is voluntary, this paper focuses on a short-term analysis and evaluates a relative ranking of seven countries. The top three countries, with the highest value of indicators, are selected for every indicator. The leaders of FCEV deployment are defined as countries, which appear at the top of the ranking in the summary table.

2.1 Vehicle comparison

In order to better quantify policy incentives, representative vehicles from luxury car segment were selected for a comparison exercise: Toyota Mirai for FCEV and Mercedes CLS for Internal Combustion Engine (ICE) vehicle. Technical characteristics of these vehicles could be found in Appendix A.

In order to allow for a fair comparison of incentives across countries, the following assumption is made: the selected vehicle models are available in all countries under consideration and vehicle prices (excluding taxes and subsidies) are identical to the vehicle base price in Germany. But really, the vehicle prices and availability vary in different countries according to the manufacturers' model and pricing strategies.

The comparison of incentives is based on simulation of vehicle-related costs for the two representative vehicles within existing legislation in favour of ZEV.[3] The summarised data on CO_2-related vehicle costs are available in tax overviews (ACEA, 2014; ICCT, 2014) and ZEV legislation, which is specific for each country.[4]

2.2 Impact on the consumer

In order to address consumer, State put in place a wide range of incentives at the moment of vehicle purchase and maintenance. The consumer could perceive the effort of State promoting ZEV by attributing the advantage to the initial investment (possession price) or to the dynamic component of TCO (running cost):

Total Cost of Ownership (TCO) = Possession price + Running cost

TCO is calculated according to a standard approach and is equal to the sum of annualized *Possession price* and annual *Running cost*.

Possession Price is the sum of vehicle base price, VAT and registration tax. The annualized *Possession price (I)* is calculated as: $I = Posession\, price * \frac{(1-\delta)}{(1-\delta^{15})}$, where $\delta = \frac{1}{1+r}$ is a discount factor. The discount rate r is assumed to be equal to 4%. The vehicle lifetime is assumed to be fifteen years.

Running Cost includes maintenance cost in parts and servicing, fuel cost based on the vehicle fuel economy and mileage, and vehicle annual taxes. The annual insurance cost is supposed to be the same for ZEV and ICE.[5] The annual *Running Cost* is estimated for one year of vehicle use (10,000 km). Assumptions on technical characteristics of vehicles (notably, fuel consumption) and on fuel prices are detailed in Appendix A. The maintenance of FCEV is supposed to be 20% less expensive than the one of ICE, because of less rotating mechanism in the electric engine and absence of oil (McKinsey, 2010).

This static evaluation suffers less from the uncertainty related to future policy evolution and future fuel market prices, compared to studies evaluating dynamic indicators, like 4-years total cost of ownership (Mock & Yang, 2014). Indeed, it is

[3] Note that all incentives examined in this article are as in September 2015.

[4] An overview of policy incentives addressing FCEV and BEV deployment in different countries could be found in an earlier technical report (Brunet, Kotelnikova, & Ponssard, 2015).

[5] This assumption is made due to lack of data on FCEV insurance in different countries. The market deployment of FCEV will allow revaluating this hypothesis.

difficult to predict the exact date and nature of change in future policies targeting ZEV and its medium- and long-term impact. Moreover, fuel price itself is subject to a high uncertainty related to volatile market conditions and hardly predictable exogenous shocks.

2.3 State intervention

The effort of the State promoting FCEV could be evaluated with its financial participation. This financial effort often aims to balance TCO between FCEV and its ICE substitute. TCO could be affected through the following policy instruments:

- Direct subsidy in order to increase ZEV affordability and reduce a price gap between FCEV and its ICE substitute. It could be evaluated with the amount of subsidy or ecological bonus;
- Advantage in one-time purchase or registration taxes. It could be evaluated with an opportunity cost: amount of ICE taxes or TVA in certain countries, which could be received if ICE vehicle was introduced instead of FCEV;
-Advantage in annual taxation. It could be evaluated in the same way as advantage in one-time vehicle-related taxes.

One of the main motivations of State introducing FCEV is to reduce current and future CO_2 emissions. For this reason *Static CO_2 Price* could be a suitable indicator to evaluate an initial State's commitment to promote FCEV. However, this indicator does not take into account all the advantages of state promoting ZEV: job creation, oil import independence, etc. (Cambridge Econometrics, 2013).

2.4 Definition of indicators

The following table summarises vehicle- and infrastructure-related indicators, developed for a cross-country comparison of policy instruments:

		Name of indicator	Definition
Vehicle-related	Impact on the consumer	Affordability	Difference in purchase price including VAT and registration taxes between FCEV and its gasoline analogy divided by the average salary
Vehicle-related	Impact on the consumer	Annual Running Cost advantage	Sum of maintenance, fuel cost, and vehicle-related annual taxes divided by the average salary
Vehicle-related	Impact on the consumer	Convergence of TCO	Time period to balance the difference in initial Possession Price by advantage in Running Cost
Vehicle-related	Impact on the consumer	Advantage in TCO	Difference in TCO between ICE and FCEV divided by the average salary
Vehicle-related	State support	State Financial Participation	Sum of direct subsidies and advantages in ZEV taxation divided by the average salary
Vehicle-related	State support	Static CO_2 price	*State Financial Participation* divided by the amount of CO_2 avoided over vehicle lifetime (18t for FECV[6])
Infrastructure-related		Coverage	Number of Hydrogen Refuelling Stations (HRS) per 1,000 km^2
Infrastructure-related		Availability	Number of HRS per 100 vehicles

Table 1 Definition of indicators developed for policy analysis (author's elaboration)

These indicators enable to compare incentives addressing consumer at the moment of vehicle purchase or maintenance; to evaluate State financial implication; and to make an assessment of hydrogen refuelling infrastructure deployment.

Indicators above are calculated with respect to the average salary, which allows accounting for differences in purchase power in different countries:

Country	Average salary
France	35652
Germany	54500
Denmark	54542
Sweden	32495
Norway	40881
California	60810
Japan	29138

Table 2 Average salaries in different countries (OCDE[7], 2015)

[6] The hydrogen production mix is supposed to be 50% of steam methane reforming and 50% of decarbonised production (electrolysis, biogas). This hypothesis is in line with gas industry programs, which aim to decarbonise hydrogen production (for example, 'Blue Hydrogen' programme of Air Liquide).

[7] OECD Statistics, 2015 *https://stats.oecd.org/Index.aspx?DataSetCode=AV_AN_WAGE*

Even if a person gaining the average salary is not the main target for luxury cars deployment strategy, the average salary accounts for differences in standard of living and purchase power in different countries. It allows reflecting a relative difference within the set of chosen countries. Indeed, it this analysis only a relative advantage within the set of seven countries does matter for the final ranking. Possibly TOP-10 fortunes data will be more adapted for the indicators calculation (even if these people are not especially targeted for a ZEV priced at €60 k). However, the cross-country difference for this data is supposed to follow the same trend as the cross-country difference for the average salary and give the same results for the final relative ranking.

3. Policy instruments addressing vehicles deployment

3.1 Targets for ZEV deployment

Countries have different ambitions for ZEV deployment in the mid-term. Initial policy motivation varies from decarbonising transport sector and improving air quality to gaining oil independency and recovering automotive industry. A brief overview of main policy motivations and targets for ZEV deployment (objective for total number of vehicles deployed and in percentage of the corresponding passenger car park) in different countries is represented in the table below:

Country	Main motivation	Targets	By year	Plan or legislation	Market share (Sep, 2015)
France	Accompanying the recovery of automotive industry in France	2M (6%) BEV	2020	'Plan automobile' of French government, Montebourg & Sapin, 2012	BEV .0271%
		No national target for FCEV			FCEV .0002%
Germany	'Energy concept', 2010: securing of a reliable, economically viable and environmentally friendly energy supply to make Germany one of the most energy-efficient and green economies in the world.	1M (2%) BEV	2020	National Development Plan for Electric Mobility, 2009	BEV .0064%
		250k (0.6%) FCEV 1.8M (4%) FCEV	2023 2030		FCEV .0003%
Denmark	Independence from oil by 2050	250k (12%) BEV	2020	Danish Energy Agreement, 2008	BEV .0808%
		110k (5%) FCEV	2025		FCEV .0014%
Sweden	Fossil independent transport sector by 2030, a climate-neutral transport sector by 2050	600k (13%) BEV	2020	Nordic Energy Perspectives, 2009	BEV .0674% FCEV .00004%
Norway	Reduction of GHG emissions of transport sector	50k (2%) ZEV (objective achieved in April 2015)	2018	The Norwegian government	BEV .2483% FCEV .0009%
California	Achieving California's air quality, climate and energy goals	1.5M (6%) ZEV	2025	The American Recovery and Reinvestment Act (ARRA), 2009	BEV .0102%
		18.5k (.08%) FCEV	2020		FCEV .0013%
Japan	Low Carbon Technology Plan with a long-term goal of reducing the level of emissions in 2008 by 60 to 80% until 2050.	0.8-1.1M (15-20%) of ZEV in new car registrations	2020	Ministry of Economy, Trade and Industry (METI), 2011	BEV .0190% FCEV .00002%

Table 3 Overview of main policy motivations and targets for ZEV (author's elaboration)

The top three of the most ambitious countries in terms of ZEV deployment with respect to the total passenger car park up to 2018 are Japan, Sweden and Denmark. Ambition of the deployment target may play a role in the current state of deployment.

FCEV market share is calculated as a total number of FCEV available over the total amount of passenger cars in the country. Both luxury FCEV and electric vehicles with hydrogen extender (example, of Hykangoo in France, described in subsection 3.5.1) are taken into account. The dataset available for FCEV numbers in different countries does not allow however distinguishing vehicles deployed within niche or national approaches.

A direct comparison based on the table above is however difficult because there is neither common time frame (the target periods vary between short term 2018 and long term 2030), nor common policy objective. The deployment of ZEV is voluntary policy action, and there is no common binding policy standard (as for example, 20-20-20 environmental targets in the EU). Given the fact that there is no common target for ZEV deployment, the present analysis focuses on a short-term policy impact and evaluates a relative advantage within a set of seven countries.

In the following sections a positive correlation between current FCEV market share and indicators measuring policy support for ZEV is observed.

3.2 Overview and classification of existing policy instruments

Policy instruments aimed to increase the affordability of ZEV may impact both an initial investment in vehicle possession (purchase price, VAT purchase and one time registration taxes) or dynamic component of total cost of ownership (maintenance and fuel cost, annual taxes). Additionally to this kind of monetary and fiscal incentives, State could put in place non-fiscal incentives, which include free parking, free toll roads, access to bus lanes, etc. The following table represents an overview of policy incentives available in different countries promoting ZEV:

Incentives			**France**	**California**	**Denmark**	**Germany**	**Sweden**	**Norway**	**Japan**
Q	**Quotas**	ZEV manufacturing quota		x					
P	**Monetary incentives**	Purchase subsidy	x	x			x		x
	Fiscal incentives on Possession price	VAT purchase tax						x	
		One-time registration tax	x		x	x		x	x
	Fiscal incentives on Running cost	Annual vehicle tax			x	x	x	x	x
		CO2 emission based vehicle tax				x	x		
	Non fiscal incentives	Free parking	x	x	x	x	x	x	
		Free toll road		x	x			x	
		Access to bus lanes						x	
		HOV[8] lanes		x					
		LEZ[9]				x	x	x	

Table 4 Overview of policy incentives promoting ZEV (author's elaboration)

Countries across the world put in place a wide range of policy instruments in order to promote ZEV deployment. The policy instruments target either car manufacturers (address the supply) or consumers (address the demand). In order to encourage car manufacturers to integrate ZEV in their production, State may put in place explicit quotas to ensure a minimal share of ZEV in their fleet (as it is the case in California) or attribute significant subsidies for FCEV purchase (as it is the case in Japan or France).

Countries use both price-based (P) and quantity-based (Q) policy instruments. In this paper instruments addressing demand for ZEV are price-based instruments: monetary incentives, fiscal incentives impacting possession price and running cost. The supply of ZEV is ensured through quantity-based instruments such as ZEV manufacturing quotas. A discussion of these two approaches facing technology

[8] Each vehicle that travels on a High Occupancy Vehicle (HOV) lane must carry the minimum number of people posted at the entrance signs. Violators are subject to a minimum $481 fine. The central concept for HOV lanes is to move more people rather than more cars.

[9] Low Emission Zones (LEZ) are areas or roads where the most polluting vehicles are restricted from entering. The vehicles are banned or in some cases charged.

uncertainty concludes this section.

3.3 Evaluation of impact on the consumer

3.3.1 Policy incentives with an impact on vehicle possession price

First, let us evaluate policy impact on the consumer at the moment of car purchase. Policy incentives, which have an impact on vehicle possession price, include monetary incentives in form of direct subsidies and fiscal incentives in form of exemption of one-time vehicle related taxes (VAT purchase tax and one-time registration tax). The following figure depicts *Possession Price* of both FCEV and ICE in different countries:

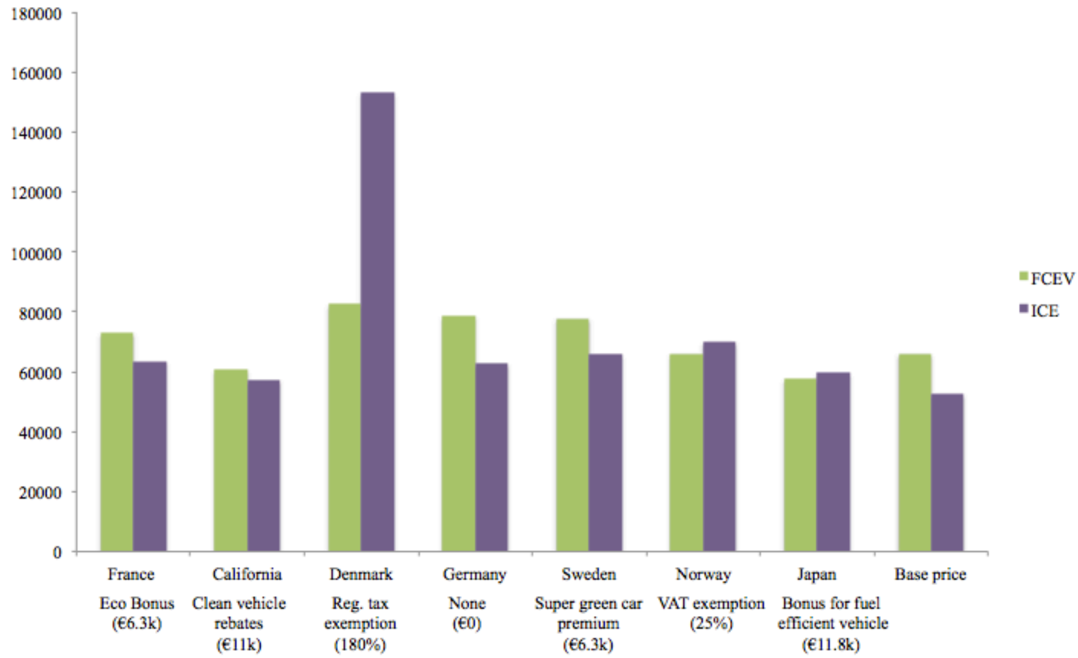

Figure 1 Difference in initial *Possession Price* between FCEV and ICE as in September 2015 (author's elaboration based on countries legislation concerning ZEV)

The figure shows that within existing policy framework FCEV *Possession Price* (purchase price including VAT and registration taxes) is lower than the one of ICE in Denmark, Norway and Japan (by 46%, 6% and 3% respectively).

Second, the *Affordability* indicator quantifies effort of State in reducing the gap in initial possession price between FCEV and its ICE substitute. *Affordability* equals to the difference in the possession price between ICE and FCEV divided by the average salary. The following figure represents the *Affordability* indicator and FCEV market share:

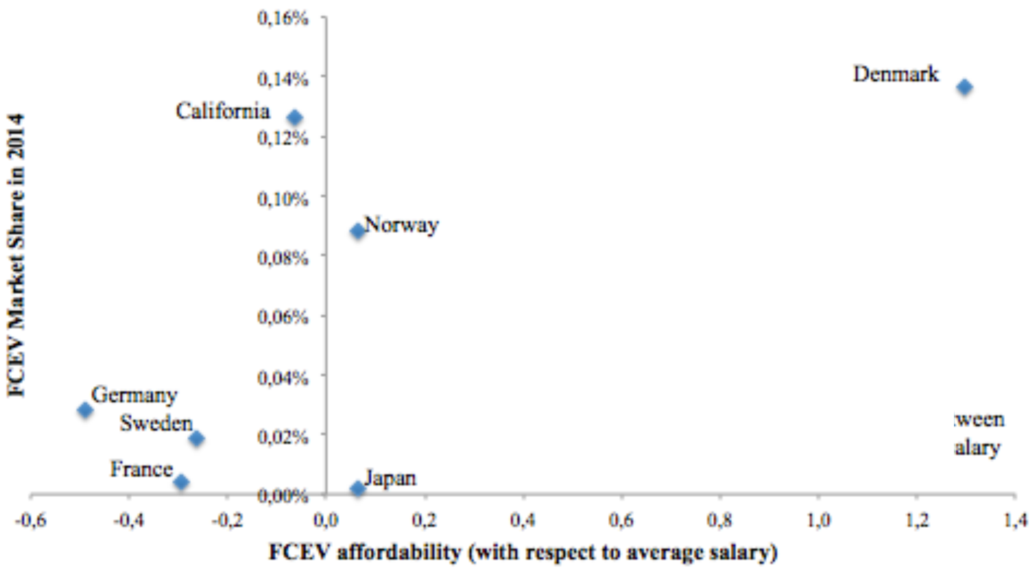

Figure 2 FCEV market share in 2015 with respect to the *Affordability* indicator (author's elaboration based of data on number of FCEV in different countries)

The vertical axe stands for the situation when the possession price of FCEV is equal to the one of ICE. Points to the right of this axe represent the countries, where FCEV possession price is lower than the one of ICE.

According to the *Affordability* indicator Denmark, Norway and Japan offers the most affordable FCEV. These countries provide the most generous incentives by introducing tax exemptions for FCEV (180% registration tax in Denmark and 25% VAT in Norway) and important purchase subsidies (€14.8k in Japan). Purchase subsidies and tax rebates in California are also strong enough (total of €11k) to significantly reduce the difference in *Possession Price* between FCEV and ICE for the consumer (*Affordability* of -0.06 with respect to an average salary).

3.3.2 Policy incentives with an impact on vehicle running cost

Running Cost could offset the difference in initial *Possession Price* between FCEV and ICE in a certain period of time. This time period (*Convergence*) is represented for different countries in the following table:

FCEV vs ICE							
Country	**Initial delta price after bonus, €**	**Annual fuel cost savings, €**	**Annual taxation advantage, €**	**Annual maintenance advantage, €**	**Annual running cost advantage, €**	**Annual running cost advantage, %**	**Convergence, years**
Japan	1906	275	429	569	1273	**4,4%**	**0,0**
Denmark	70668	560	718	569	1847	**3,4%**	**0,0**
Germany	-15853	374	148	569	1091	**3,4%**	**14,5**
Sweden	-12053	452	161	569	1182	**2,9%**	**10,2**
France	-9448	364	0	569	933	**2,6%**	**10,1**
Norway	3948	619	298	569	1486	**2,4%**	**0,0**
California	-3441	-214	0	569	355	**0,7%**	**9,7**

Table 5 Expected time needed to equilibrate the difference in the initial FCEV *Possession Price* by the annual *Running Cost* savings (author's elaboration)

Assumptions made for different fuel prices (Appendix A) result in relatively important annual fuel savings for FCEV compared to ICE in many countries. Annual fuel savings represent between 10% and 20% compared to the annualised vehicle price in all countries except for California, where gasoline price is extremely low.

Japan, Germany and Demark provide the most significant *Advantage in Annual Running Cost*, which is estimated to be about 3-5%. *Advantage in Annual Running Cost* is equal to the sum of fuel cost, vehicle-related annual taxes and maintenance advantages divided by the average annual salary.

Convergence indicates time period necessary to balance the difference in initial *Possession Price* by advantage in *Running Cost*. According to this indicator, the use of FCEV is less expensive in Denmark, Norway and Japan from the very first year (0 years before convergence) because of the positive difference in the initial *Possession Price* (see the previous subsection). In California, France and Sweden FCEV are more expensive at purchase but lower *Running Cost* can offset this difference within ten years. This period extends to fourteen years in Germany and approaches the vehicle lifetime, which is estimated to be around fifteen years.

3.3.3 Policy incentives with an impact on TCO

The impact on vehicle *Possession price* via monetary incentives, fiscal incentives on *Possession price* and *Running cost* are summarised within global impact on *Advantage in TCO*:

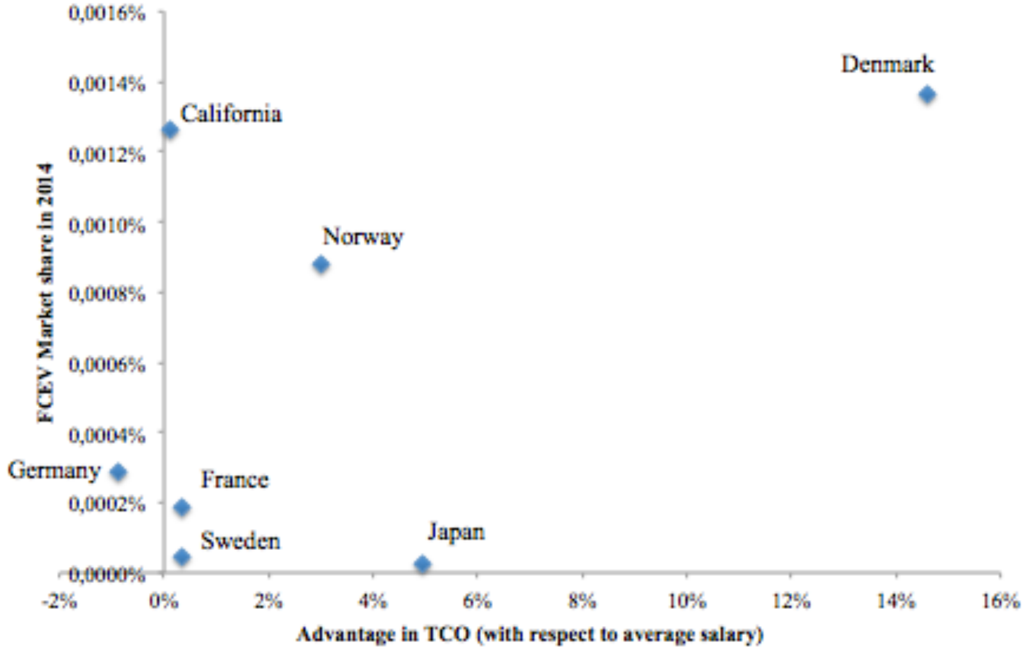

Figure 3 FCEV market share in 2015 with respect to the *Advantage in TCO* indicator (author's elaboration)

Denmark, Norway and Japan lead according to the *Advantage in TCO* indicator, which summarises impact of two indicators developed in the previous subsections. The contribution of annualised *Possession price* to final TCO is significantly more important that of annual *Running cost*. For this reason the ranking according the *Advantage in TCO* indicator coincides with ranking according to the *Affordability* indicator (subsection 3.3.1).

3.4 Evaluation of State intervention

The *Static CO_2 price* indicator, which equals to *State Financial Participation* divided by CO_2 economy over vehicle lifetime, gives a tool to evaluate a comparative level of the State intervention. The following figure represents FCEV market share in 2014 with respect to the intrinsic *Static CO_2 Price*:

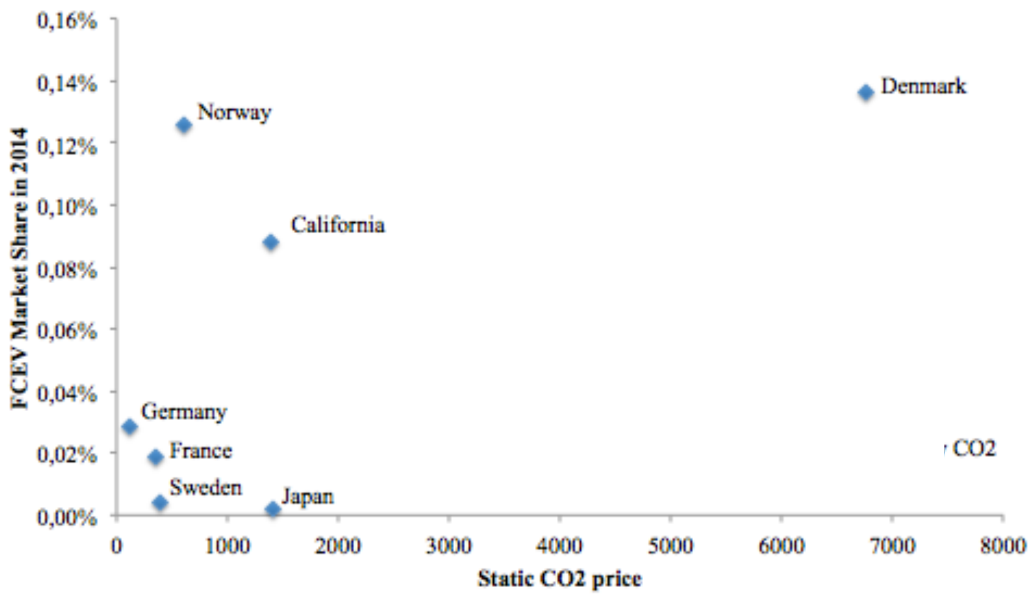

Figure 4 FCEV market share in 2014 with respect to *Static CO_2 Price* (author's elaboration based on countries legislation concerning ZEV)

This figure shows that countries with volunteer state intervention have achieved larger FCEV market share. On one hand, Denmark is a good example of a volunteer State action. Denmark's government provides 180% registration tax exemption for ZEV, which is equivalent to €111k bonus for FCEV. Moreover, it completes this by a significant advantage in annual taxation (about €700 per year). By indirectly pricing avoided CO_2 emissions at the highest price Denmark ensures the highest FCEV market penetration rate. On the other hand, in Germany the volunteer State's intervention is low. The German government provides an exemption of insignificant annual tax, which is equivalent to €150 per year bonus for FCEV. However, one should note that the effort of German government is concentrated on hydrogen infrastructure deployment (see section 4).

The top three countries in terms of volunteer *State Financial Participation* are Denmark, Japan and Norway. Japan provides significant direct subsidy (about €15k), advantages in registration (about €2k) and annual (about €400 per year) taxation. Norway provides a TVA (25%) exemption completed by advantages in annual taxation (about €300 per year).

It is interesting to notice that there is no single instrument that solves the policymaker's trade-off between maximising the ZEV penetration rate and minimising the policy budget. Denmark ensures the highest FCEV market share but related policy cost is also the highest among the seven countries under consideration. California government seems to solve this trade-off differently by ensuring a relatively high FCEV penetration rate while getting policy cost down. The Californian government use both price- (subsidies, tax rebates) and quantity-based (ZEV regulation) instruments with long-term effect, which are described in the following subsection.

Note that the static approach to calculate abatement cost described above does not consider the evolution of costs and compute the abatement cost associated to a vehicle each year given the costs of that year. Beeker (2014) estimates static abatement cost for hydrogen mobility to be about 1,000 €/t in 2014 in France and concludes that this high abatement cost does not justify substitution of ICE by FCEV. Within the similar set of initial hypothesis (similar FCEV and ICE fuel consumption, hydrogen and gasoline price, and related emissions), in the model of Creti et al. (2015) the corresponding abatement cost starts around 1,600 €/t in 2020, is comparable to (Beeker 2014) and this study estimations. However, it decreases to zero in 2043, when the relative total cost of ownership becomes positive for FCEV and then becomes negative. Not much can be inferred from this sequence of static abatement costs. In contrast dynamic approach, which computes the abatement cost of the whole deployment, is detailed in (Creti et al. 2015) and takes into account learning-by-doing effect along the FCEV deployment trajectory and gives a relevant proxy for policy analysis.

3.5 Discussion: Subsidies VS Quotas for hydrogen vehicle deployment

In order to promote vehicle deployment, State could use subsidy- or quota-based approaches. In the context of ZEV deployment, the differences between price- and quantity-based approaches highlight a classical (Weitzman, 1974) problem of securing predefined penetration rate targets while keeping program cost down. The following subsections discuss the specificity of price- and quantity-based instruments in the context of uncertainty related to the FCEV deployment.

The quota-based instruments target the supply side of the chicken-and-egg dilemma and increase the offer of FCEV. The price-based instruments act on the demand side of the deployment problem and increase financial attractiveness of FCEV for the consumer.

3.5.1 Subsidies, or price-based approach (example of France)

A price-based approach relies on the adoption of a schedule of decreasing government subsidies (or tax credits), distributed to ZEV buyers upon vehicle purchase. This schedule is defined in a way that equilibrates the difference in TCO between FCEV and its conventional substitute. The schedule decreases over time, as scale and learning effects on cost reduction take place.

From the policy maker's perspective, the main advantage of this price-based approach is that it enables to predict program costs and prevent them from drifting. Its main drawback is that it is complicated to define in advance a subsidy envelope and schedule that will match uncertain car market development. The uncertainty could be related to ZEV leading technology, technological break-through, economies of scale effects, FCEV learning curve or future penetration rates.

Implementing a discretionary scheme could reduce this last uncertainty factor; subsidy levels could be adjusted through time to match a targeted penetration rate. This approach, however, generates additional risk for investors, which are sensitive to uncertain environments. Limiting variability in the subsidy schedule, which is announced beforehand, may tackle this problem.

The price-based approach is used in France where French government introduced a 'bonus/malus' scheme. Since 2012, a €4,000 to €6,300 bonus is granted for the purchase of a new car when its emissions are 105 gCO_2/km or less (the amount depends on emissions level).[10] The bonus for FCEV is €6,300[11] (the amount of bonus is limited to 27% of car purchase price). Conversely, the malus can be compared to a carbon tax on the higher emission vehicles: between 130g/km and 200g/km it amounts to an additional €150 to €8,000 at car purchase.

To finance this scheme, €405m in rebates were given to consumers buying efficient vehicles, with 90% of that amount from fees on inefficient vehicles. Remaining 10% (€45m) was a direct subsidy (Trigg et al., 2013).

3.5.2 Quotas or quantity-based approach (example of California)

A quantity-based approach imposes a predefined share of quota for ZEV production and sales to large car manufacturers. In order to help the car manufacturers overcome the expensive initial deployment stage, when ICE are still cheaper than FCEV, subsidies could accompany the quota requirements.

The main advantage of the quantity-based approach compared to the price-based approach is that it reduces uncertainty by planning a FCEV penetration rate. Its main drawback is that it assumes a predefined rhythm for FCEV R&D over a long period. This puts large pressure on all car manufacturers to reach that goal in time and simultaneously, regardless of their respective learning curves and development goals. Companies unable to reach these goals may suffer large financial losses.

A credit-trading scheme could therefore be implemented allowing firms to trade credits for FCEV (or, more broadly, for ZEV). The car manufacturers with higher FCEV production costs could purchase credits from better performing ones to avoid burdensome investments.

The quantity-based approach is used in California, where the State Government imposed a ZEV production quota. Car manufacturers with annual sales higher than 60,000 vehicles must deploy a minimum percentage of ZEV for each period between 2010 and 2017.[12] The quotas are increasing through time from 12% in 2012-2014 to 14% 2015-2017.

Starting from 2018 the quota accounting procedure is based on the minimum ZEV credit percentage requirement for each manufacturer. The ZEV credit percentage requirement starts at 4.5% in 2018 and increases by 2.5 percentage points per year up to 22% in 2025.[13] The amount of ZEV credits generated from the sale of a ZEV is determined by the vehicle's range. For example, a vehicle with a range of 100 miles (160 km) generates 1.5 ZEV credits. Vehicles with longer ranges can generate more credits.

If the manufacturer failed to comply, financial penalties would apply (as outlined in the Health and Safety Code 43211) including $5k (€3.7k) penalty for each ZEV credit not produced.

The manufacturers can generate ZEV credits by exceeding minimum standards

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[10] French Ministry of Ecology, Sustainable Development and Energy *http://www.developpement-durable.gouv.fr/Bonus-Malus-definitions-et-baremes.html*

[11] French Ministry of Ecology, Sustainable Development and Energy *http://www.developpement-durable.gouv.fr/Bonus-Malus-2014.html*

[12] 13 Cal. Code Regs. § 1962.1

[13] Air Resources Board *http://www.arb.ca.gov/msprog/zevprog/zevregs/1962.2_Clean.pdf*

and are allowed to transfer the credits earned. For example, in 2014[14] Nissan and Tesla producing mainly BEV transferred over 500 ZEV credits out while Honda and Mercedes Benz (producing mainly ICE) transferred over 500 credits in. The trading scheme generates extra revenue models for companies producing mainly ZEV. For instance, in 2013, Tesla's sales of ZEV credits generated $194.4m, or about 9.7% of its annual revenue.[15]

Under current ZEV regulation one Toyota Mirai may worth up to seven ZEV credits. With a ZEV credit market price around $4,000 (€3,700) in 2014, one Mirai can generate an extra profit of about €26,000 for Toyota car manufacturer. A part of this profit may be redistributed to consumer in order to lower Mirai market price and increase its cost advantage.

In order to achieve ambitious ZEV deployment targets countries often combine both price- and quantity-based approaches, for example, by combining quotas with subsidies or by implementing captive fleet projects.

4. Policies addressing infrastructure deployment

FCEV fleet deployment requires a simultaneous introduction of minimal coverage of hydrogen refuelling infrastructure. The *Coverage* and *Availability* indicators enable to distinguish 'local' (niche) and 'global' (nationwide) approaches and to make an assessment of hydrogen refuelling infrastructure deployment.

4.1 Targets for infrastructure deployment

Ambition for hydrogen infrastructure deployment varies across countries. The following table describes the projected and current deployment state of network of Hydrogen Refuelling Stations (HRS):

[14] Air Resources Board, 2015, "2013 Zero Emission Vehicle Credits"

[15] Bloomberg *http://www.bloomberg.com/news/articles/2014-04-04/tesla-to-get-fewer-eco-credits-as-california-tweaks-rules*

Country	Targets for HRS stock	By year	Nb targeted HRS/ nb of gas stations	Budget per targeted HRS, €M	HRS stock as in Sep 2015	HRS penetration rate, %
Denmark	185	2025	**9%**	1,23	7	**0,35%**
Norway	1100	2050	**62%**	1,4	6	**0,34%**
California	100	2020	**1%**	1,76	22	**0,22%**
Germany	400	2023	**3%**	0,88	15	**0,10%**
Japan	100	2016	**0%**	3,38	31	**0,09%**
France	n/a		**n/a**	n/a	5	**0,04%**
Sweden	23		**1%**	1,7	1	**0,04%**

Table 6 Hydrogen infrastructure targets, dedicated budget and current deployment state (author's elaboration based national plans for H2 deployment in different countries)

Japan, California and Germany have the most ambitious targets in terms of HRS to be deployed. These countries also dedicate a very important budget per station compared to other countries and lead the current deployment. A high budget per station could be explained by the fact that these three countries began the hydrogen infrastructure deployment earlier and purchased HRS for relatively high cost. Moreover, security constraints in Japan are among the toughest. Nevertheless, early deployment of initially costly HRS contributes to the future decrease of HRS cost because of learning and scale effect and creates a benefit for following countries, which would be able to purchase HRS for a lower price.

The ratio of targeted HRS number over the total number of gasoline stations is the highest for Norway (62%). This fact is in line with ambition of Norway to be a leader in infrastructure for BEV and FCEV towards 2020.[16]

HRS penetration rate, defined as the ratio of HRS stock over number of gasoline stations, is relatively high in Denmark (0.35%), Norway (0.34%) and California (0.22%). The hydrogen infrastructure is the most developed in these countries.

The current state (as in September 2015) of hydrogen infrastructure and vehicles deployment is represented in the following figure:

[16] White Paper, 2012
http://fores.se/assets/763/ZERO_Incentives_zeroemissioncars_in_Norway_ZERO-?-3.pdf

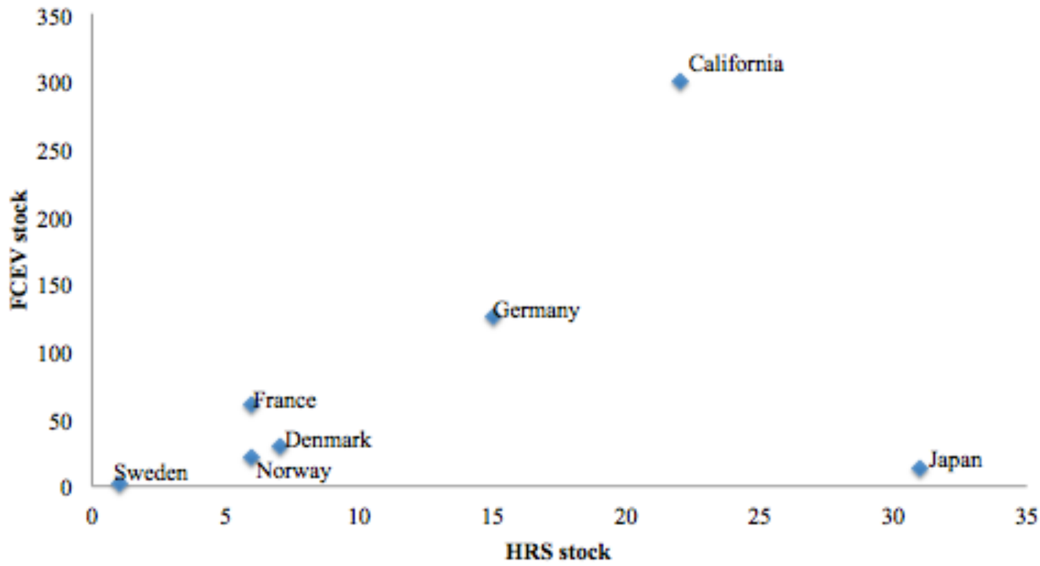

Figure 5 Current state of HRS network and FCEV stock deployed (author's elaboration base on H2 Mobility consortium communications in different countries)

According to this figure Japan lead in terms of HRS stock available and California in terms of number of FCEV deployed.

4.2 Coverage indicator

The *Coverage* indicator is especially relevant during the early stages of infrastructure deployment. It measures the effort of a country to cover the whole territory and provide a hydrogen supply service in both densely populated and rural areas.

The following table represents the *Coverage* indicator for seven countries under consideration:

Coverage = number of stations per 1,000 km^2		
Country	**ICE**	**FCEV today**
Denmark	47	**0,16**
Japan	90	**0,08**
Norway	5	**0,07**
California	24	**0,05**
Germany	40	**0,04**
France	22	**0,01**
Sweden	6	**0,002**

Table 7 *Coverage* indicator for infrastructure (author's elaboration)

The countries leading in terms of the *Coverage* indicator are Denmark, Japan and California. Denmark leads with seven HRS introduced on relatively small territory (43k km^2). Japan and California began the deployment of HRS infrastructure earlier than other countries. They massively invest in hydrogen infrastructure deployment to attain their very ambitious target (see table 5).

The *Coverage* indicator could be further improved in order to take into account population density of an area, where HRS is introduced. Indeed, deployment of HRS is supposed to start in areas with higher population and traffic flow density. This will leverage initial investment in a shorter period and ensure a cost reduction for HRS introduced lately in a rural area.

A high value of *Coverage* could indicate a nationwide approach of infrastructure deployment. High *Coverage* value of 1.07 in 2023 characterises ambitious HRS deployment plan in Germany, where in 2009 German government founded 'H2 Mobility' partnership with major industry companies (Air Liquide, Daimler, Linde, OMV, Shell and Total). This public private partnership aims to ensure synchronized ramp-up of hydrogen stations and vehicle deployment. It also creates a risk sharing mechanisms across industry and public actors. The objective of H2 Mobility project is to offer a HRS at least every 90 kilometres of highway between densely populated areas. By 2023, the current public network of 15 HRS is expected to expand to about 400 HRS, with a long-term target of 1,000 HRS in 2030. The total investment until 2023 is estimated of around €350m. In 2015 representatives of all the partners involved have signed a memorandum of understanding. Thanks to partnership with major car manufacturers (Hyundai, Toyota, Honda, BMW, Volkswagen, Nissan), this project would ensure a synchronised introduction of FCEV into the market in the coming years.

4.3 Availability indicator

The following table represents values for the *Availability* indicator:

Availability = number of stations per 100 vehicles		
Country	**ICE**	**FCEV**
Japan	340	**0,31**
California	100	**0,22**
Germany	144	**0,15**
Denmark	20	**0,07**
Norway	18	**0,06**
France	121	**0,05**
Sweden	28	**0,01**

Table 8 *Availability* indicator for infrastructure (author's elaboration)

As can be seen from the table above hydrogen infrastructure is in its early deployment stage. *Availability* of gasoline stations is in average 1,000 higher than *Availability* of HRS.

Availability indicator enables to distinguish 'local' (niche) and 'global' (nationwide) strategies of hydrogen infrastructure deployment. High Availability is characteristic for the nationwide strategy. Indeed, Japan (*Availability* of 0.31) as well as California (0.22) and Germany (0.15) adopt the national infrastructure deployment approach and ensure high availability of infrastructure for future vehicle deployment. Low *Availability* is characteristic for the niche deployment strategy. This approach is represented by the French case (*Availability* of 0.05), where local authorities have adopted the strategy of niche deployment.

The niche deployment approach in France could be illustrated with example of La Manche project in Normandy[17], where local authorities launch a FCEV delivery service. This project benefits from €4m funding to install 15 HRS (12 HRS of 10-15 kg/day capacity and 3 HRS of 50-60 kg/day capacity) by 2015-2018.[18] The car fleet in place counts approximately 12 battery electric vehicles with hydrogen fuel cell range extender - the Hykangoo vehicles manufactured by SymbioFcell. Thanks to the French ecological bonus (€6,300) and a financial support from the FCH-JU (€10,000) the Hykangoo is sold for €33,000 (before VAT). This is still higher than a diesel alternative, but the electricity-hydrogen energy mix is cheaper than diesel fuel. Because Hykangoo can run partly on electricity, the deployment of HRS infrastructure can be progressive.

5. Countries ranking and analysis of the results

The overall top-three ranking of countries leading FCEV deployment according to different indicators is represented in the following table:

	Indicator	**1st**	**2d**	**3d**
Vehicle deployment	Affordability	Denmark* (1.3)	Japan (0.07)	Norway (0.06)
	Annual Running Cost Advantage	Japan** (4.4%)	Germany (3.39%)	Denmark (3.36%)
	TCO Convergence (years)	California (9.7)	France (10.1)	Sweden (10.2)
	Advantage in TCO	Denmark (14.6%)	Japan (4.9%)	Norway (3.0%)
	Static CO2 price (k€)	Denmark (6.7)	Japan (1.41)	Norway (1.38)
Infrastructure deployment	Coverage (# HRS/100km)	Denmark (0.16)	Japan (0.08)	Norway (0.07)
	Availability (# HRS/100 cars)	Japan (0.31)	Sweden (0.22)	Norway (0.15)
Deployment results	FCEV market share	Denmark (0.14%)	California (0.13%)	Norway (0.09%)
	HRS penetration rate	Denmark (0.35%)	Norway (0.34%)	California (0.22%)

Table 9 Top-three ranking of countries according to the indicators developed in the paper (author's elaboration)

Note that the table summarizing values of all indicators for all countries is provided in Appendix B.

According to the *Affordability* indicator, the difference in *Possession Price* between FCEV and ICE is positive in Denmark, Norway and Japan. These countries

[17] For more details on La Manche project see an earlier technical report (Brunet et al., 2015)

[18] Press release from Region Basse-Normandie

* How to read: in Denmark FCEV is more affordable than ICE. The difference in purchase price (including VAT and registration taxes) between FCEV and its gasoline analogy is equal to 1.3 times average salary.

** How to read: in Japan annual running cost of FCEV is lower than the one of ICE. The difference in annual running cost (sum of maintenance, fuel cost, and vehicle-related annual taxes) between FCEV and ICE is equal to 4.4% of average salary.

provide the most generous incentives with respect to national average annual salary by introducing tax exemptions for ZEV (Denmark and Norway) and important purchase subsidies (Japan). Denmark leads according to this indicator by providing a 180% registration tax exemption for ZEV. Because the amount of registration tax varies in proportion to the vehicle base price, the luxury ZEV segment covered in the present analysis (Mirai) benefits from a bonus equivalent of €111,000 for FCEV, which makes its price very attractive compared to its ICE analogue (Mercedes CLS).

According to the *TCO Convergence* indicator, the initial negative difference in possession price in France, Sweden and California could be balanced in ten years period by advantage in ZEV running cost. The advantage in ZEV running cost includes fuel saving, advantage in annual taxation and maintenance. According to the *Annual Running Cost Advantage* indicator, Japan, Germany and Demark provides the most significant annual advantage in running cost which is estimated to be about 4-5% compared to the average annual salary.

The top-three ranking according the *Advantage in TCO* indicator coincides with ranking according to the *Affordability* indicator. Indeed, this indicator summarises impact of *Affordability* and *Annual Running Cost Advantage* indicators, with the highest contribution of the former. Denmark, Norway and Japan are again among the leaders.

According to the *Static CO2 Price* indicator, which evaluates State financial intervention to promote ZEV, Denmark, Japan and Norway provide the most generous financial participation in total cost of ownership of FCEV. These countries put in place price-based incentives: €11,800 subsidies for FCEV in Japan and exemptions of 25% VAT in Norway and 180% registration tax in Denmark.

Denmark ensures the highest *Affordability* of FCEV and FCEV market share. However, the related policy cost is also highest among the seven countries of the present analysis. No particular instrument is defined to solve the policymaker's trade-off between maximising the ZEV penetration rate and minimising the policy budget.

Analysis shows countries tend to favour price-based instruments (subsidies, tax rebates, annual and registration tax exemption). They choose to define program costs in advance and prevent them from drifting while facing FCEV technology uncertainty related to ZEV leading technology, technological break-through, economies of scale effects, FCEV learning curve or future penetration rates.

Assessment of hydrogen refuelling infrastructure deployment enable to distinguish 'local' (niche) and 'global' (nationwide) strategies according to the *Coverage* and *Availability* indicators. Japan (with the highest *Availability*) adopts the national infrastructure deployment approach and ensures coordinated infrastructure and vehicle ramp-up. In this case the number of HRS is relatively high compared to the number of vehicles on the roads. The other approach is represented by the French case (with the lowest *Availability*), where local authorities have adopted the strategy of niche deployment. This approach is characterized by introduction of few HRS to feed a captive fleet. However, there is no leading strategy and both approaches are used equally.

As can be seen from the table above, Denmark and Japan[19] appear the most often among the top leaders. They put an accent on the coordinated ramp-up of vehicles and infrastructure and lead the hydrogen mobility deployment according to both vehicle- and infrastructure- related indicators.

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[19] Note that the situation for FCEV market penetration rate will change in Japan in the end of 2015, when the delivery of 400 ordered Mirai will take place.

The surprising result of this analysis is that California and Germany are not among the leaders even if they ensure high FCEV and HRS penetration rates. California put in place an aggressive environmental policy. It combines both quantity-based instruments (ZEV regulation quotas) and price-instruments (subsidies and tax rebates). The fact that California does not lead the deployment according to the developed indicators could be explained by the strong competition from ICE technology and comparatively low gasoline prices. Germany, in turn, addressed in the first place infrastructure deployment and invests massively in nationwide HRS network (vehicle incentives are negligible and equivalent to €150 per year for FCEV). The current infrastructure deployment is in its early stage. Future analysis of German case could shed some light on the efficiency of prior infrastructure deployment in solving chicken-and-egg dilemma. Both the quantity-based approach of ZEV regulation in California and the German focus on the infrastructure deployment are expected to produce effects in the longer term.

This analysis also suggests that there is a complementarity between State support for vehicles supply and infrastructure deployment. There is a positive correlation between the FCEV market share and high values of both vehicle- and infrastructure-related indicators for the countries leading FCEV deployment. Germany, which was initially focused on infrastructure deployment, recently introduced direct subsidies for ZEV[20]. This fact confirms the intuition that a coordinated ramp-up of vehicles and infrastructure deployment is the most complete approach to deal with chicken-and-egg dilemma.

6. Conclusion

ZEV, such as hydrogen and electric vehicles will play a critical role in decarbonising the transport sector, for which related emissions continue to increase. Market forces alone will not trigger the transition towards ZEV; thus public support is crucial during initial deployment stages. Major OECD countries have put in place a wide range of policy instruments addressing simultaneously vehicle and infrastructure deployment. These policy instruments aim to solve the chicken-and-egg dilemma and reach a 'critical mass' from which the need for public intervention will be significantly reduced. This paper draws a cross-country comparison between existing policy instruments in favour of the FCEV deployment.

Countries with voluntary State support such as Denmark, Norway and California have achieved larger FCEV market share (0.02% vs 0.001%). Our analysis shows that most generous incentives are available in countries that put in place price-based instruments (like subsidies in Japan or tax exemptions in Denmark). The differences between price- and quantity-based approaches highlight a problem of securing predefined penetration rate targets while keeping program cost down. The price-based instruments such as monetary and fiscal incentives are actually more often used in the studied set of the countries. The price-based instruments act on demand side of the deployment problem and make FCEV more attractive for consumers (lower purchase and possession prices, more competitive TCO). Moreover, from State viewpoint, this type of instruments allows defining program costs in advance and preventing them from drifting.

[20] The Guardian, April 2016 *https://www.theguardian.com/world/2016/apr/28/germany-subsidy-boost-electric-car-sales*

As for infrastructure deployment, the Coverage and Availability indicators enable to distinguish two strategies: 'local' (niche approach in France) and 'global' (nationwide approach in Japan, Germany).

According to the present analysis, Denmark and Japan lead the hydrogen mobility deployment with respect to a large number of indicators. Vehicle deployment benefits from strong price-based incentives (important direct subsidies, exemption of registration tax). Infrastructure deployment is ensured on the national territory (according to the Coverage indicator) and satisfies needs of the FCEV fleet in place (according to the Availability indicator).

We show that Denmark and Japan seem to solve the problem of maximisation of ZEV penetration rate and not minimisation of the policy cost. Indeed the State Financial Participation is among the highest for these two countries. Meanwhile, Californian government insures relatively high ZEV penetration rate and get policy cost down by combining both price- (subsidies, tax rebates) and quantity-based (ZEV regulation) instruments. Both Californian ZEV regulation and German focus on the infrastructure deployment are expected to produce effects in the longer term.

The results of this analysis, which is focused on FCEV, are applicable to the ZEV deployment in general except for the second part, which is infrastructure analysis (indeed, the FCEV and BEV are not substitutes and need a deployment of a specific infrastructure). The methodology developed in this analysis and vehicle-related conclusions can be partly transposed to BEV addressing the luxury car segment. However, the most advanced BEV (e.g. full electric Tesla), which targets the same car segment, provides a 30% shorter autonomy range; moreover, recurring long trajectories significantly degrade batteries.

There are several limits to the present paper. First, very little data on ZEV is available to make a proper econometric analysis. Second, it could be interesting to understand how each stakeholder across the hydrogen value chain is affected independently by ZEV deployment. The introduction of ZEV contributes to increasing social welfare (mainly by decreasing CO2 emissions in the transport sector). Hence, the utility of consumers, car manufacturers and State should increase in the sum. Third, this analysis can be further extended to a larger set of countries, which actively support ZEV deployment (China, UK, South Korea, etc).

ZEV technologies (both FCEV and BEV) face similar deployment challenges: on one hand, the production cost of ZEV is higher than that of ICE; on the other hand, there is a need for complete infrastructure deployment that requires massive investments with a long payback period. Public support is therefore crucial during initial deployment stages in order to address both challenges of vehicles and infrastructure deployment. The present analysis shows that most countries implement price-based instruments to encourage vehicles deployment in the first place and reduce ZEV TCO. As for infrastructure, the nationwide introduction of minimal coverage network compared to the niche approach ensures a long-term effect for sustainable ZEV market deployment. However, no particular instrument is defined to solve the chicken-and-egg dilemma without strong financial commitment from State.

Appendix A

To better quantify the incentives, vehicles representing a luxury car segment in each fuel category were selected for a comparison exercise. The FCEV is represented by Toyota Mirai, and ICE vehicle by Mercedes CLS 400. The technical characteristics of these vehicles could be found in the following table:

	Mirai	**Mercedes CLS 400**
Vehicle type	FCEV	ICE (gasoline)
Engine Power, kW	114	245
Engine displacement, cm^3	n/a	3,498
Acceleration time 0-100 km/h, s	9.6	5.4
Curb weight, kg	1,850	1,775
Transmission type	automatic	automatic
Local CO2 emission, g/km	0	169
Fuel consumption	0.9 kg/100km	9.8 l/100 km
Energy consumption (equivalent)	30 kWh/100km	124.5 kWh/100km
Autonomy, km	500	785
Vehicle base price excl. VAT, €	66,000	52,678

Table 10 Technical characteristics of representative FCEV and ICE vehicles (author’s elaboration based on Toyota and Mercedes communication in Germany)

The following assumptions are made for the different fuels prices:

Country	**Gasoline price, €/l**	**Hydrogen price, €/kg**
France	1,29	10
California	0,59	8,8
Denmark	1,49	10
Germany	1,3	10
Sweden	1,38	10
Norway	1,55	10
Japan	0,96	7,4

Table 11 Fuels (gasoline and hydrogen) prices (Global Petrol Prices, 2015)

Appendix B

		Name of indicator	Definition	France	California	Denmark	Germany	Sweden	Norway	Japan
Vehicle-related	Impact on the consumer	Affordability	Difference in purchase price including VAT and registration taxes between FCEV and its gasoline analogy divided by the average salary	-0,27	-0,06	1,30	-0,49	-0,29	0,06	0,07
		Annual Running Cost advantage	Sum of maintenance, fuel cost, and vehicle-related annual taxes divided by the average salary	2,6%	0,7%	3,4%	3,4%	2,9%	2,4%	4,4%
		Convergence of Total Cost of Ownership (TCO)	Time period to balance the difference in initial Possession Price by advantage in Running Cost	10,1	9,7	0	14,5	10,2	0	0
		Advantage in TCO	Difference in TCO between ICE and FCEV divided by the average salary	0,3%	0,1%	14,6%	-0,9%	0,3%	3,0%	4,9%
	State intervention	State Financial Participation	Sum of direct subsidies and advantages in ZEV taxation divided by the average salary	0,2	0,2	2,2	0,1	0,2	0,4	0,9
		Static CO2 price	*State Financial Participation* divided by the amount of CO2 avoided over vehicle lifetime (18t for FECV)	362	609	6759	123	389	1388	1415
Infrastructure-related		Coverage	Number of Hydrogen Refuelling Satiations (HRS) per 1,000 km2	0,01	0,05	0,16	0,04	0,002	0,07	0,08
		Availability	Number of HRS per 100 vehicles	0,05	0,22	0,07	0,15	0,01	0,06	0,31

Table 12 Values of indicators developed in the paper for the final ranking of countries (author's elaboration)

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Chapter II

Defining the Abatement Cost in Presence of Learning-by-doing: Application to the Fuel Cell Electric Vehicle

Defining the Abatement Cost in Presence of Learning-by-doing: Application to the Fuel Cell Electric Vehicle.*

Anna Creti[a,b], Alena Kotelnikova[a], Guy Meunier[a,c†] , Jean-Pierre Ponssard[a,d]

[a] Ecole Polytechnique
[b] Université Paris Dauphine
[c] INRA-UR1303 ALISS
[d] CESifo, CIRANO and CNRS

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Abstract

We consider a partial equilibrium model to study the optimal phasing out of polluting goods by green goods. The unit production cost of the green goods involves convexities and learning-by-doing. The total cost for the social planner includes the private cost of production and the social cost of carbon. Under some assumptions we show that the problem can be addressed by defining an "adjusted" abatement cost in which the whole transition trajectory is considered as a one shot decision. The case of Fuel Cell Electric Vehicles offers an illustration of our results. Using data from the German market we show that the trajectory foreseen by the German H2 project, if launched in 2015 would be consistent with a carbon price at 53 €/t. This figure is much lower than estimates obtained through standard abatement methodology, which range around 800 to 1000 €/t. The relationships of our model with other models in the literature that analyze induced technical change are also discussed.

JEL Classification: Q55, Q42, C61

Keywords: Dynamic abatement costs; learning by doing; fuel cell electric vehicles

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†Corresponding author, e_mail: guy.meunier@ivry.inra.fr, INRA, 65 bd de Brandebourg, 94200 Ivry-sur-Seine, France.

1 Introduction

Marginal abatement costs (MACs) are practical indicators used in policy discussions. The MAC is the cost to reduce polluting emissions at the margin, by a factory, a firm, a sector or a country. MACs are notably used to critically assess decarbonization efforts among sectors and arbitrage between technical options (Marcantonini and Ellerman, 2014; Archsmith et al., 2015). This apparently simple indicator may hide some traps. Although conceptually valid, MACs are difficult to compute in a dynamic context, for reductions that require sunk investment in human and physical capital. The objective of this paper is to propose an extension of the standard concept of static abatement costs in a context in which features such as learning-by-doing cannot be neglected.[1]

More precisely, we consider a partial equilibrium model, the objective is to minimize the cost of phasing out polluting goods from a market in presence of learning spill-overs over time. The market size is fixed and initially served by polluting goods that must be produced at every point in time at constant marginal cost. The cost of the green goods depends on the rate of production, which rationalizes a smooth phase-out. It also depends on the cumulated past output, introducing a learning-by-doing effect to the model. The total cost for the social planner includes the private cost of production and the social cost of carbon. The latter has an exogenous upward trend; the pollution problem is not otherwise modeled but for this trend in the social cost.

Under these assumptions we show that the optimization problem can be decomposed into two questions: (i) at which rate the transition should be completed, that is, the design of a transition trajectory as such; (ii) when to launch a given trajectory. Interestingly the second question can be answered also for suboptimal trajectories, which provides interesting insights. We define an Adjusted Abatement Cost (AAC) associated to a trajectory, possibly suboptimal. This AAC can be interpreted as the MAC of the whole trajectory and gives the date at which the transition should start (Proposition 1). Our model also allows to compare a given trajectory with the optimal one (Proposition 2). If the deployment cost is not minimized or the total number of green goods produced during deployment is larger than the optimal one, the launching date should be postponed. If the total number of green goods produced during deployment is lower than the optimal one, the launching should instead take place earlier.

The case of Fuel Cell Electric Vehicles (FCEV) for the substitution of the mature ignition combustion engine (ICE) provided the primary motivation for our methodology. There exists a number of studies on this subject. A study sponsored by industrials (McKinsey & Company, 2010) developed scenarios for the deployment of PHEV, BEV and FCEV in Europe based on the assumption that the total cost of ownership (TCO) for all power-trains are expected to converge around 2040. Bruegel and the European School for Management and Technology revisit the economic rationale for public action for FCEV (Zachmann et al., 2012). Harrison (2014) provides an extensive analysis of the environmental and macroeconomic impacts (growth, employment, trade) of alternative motor ways (ICE, BEV, FCEV) at the European level at the 2050 horizon. Rösler et al. (2014) carry an in depth investigation

[1] A survey of learning-by-doing rates for different energy technology can be found in IEA (2000) and McDonald and Schrattenholzer (2001). Learning rates varies from 25% for photovoltaics, 11% for wind power, and 13% for fuel cell in the period 1975-2000.

using the energy bottom-up model TIAM-ECN (Loulou, 2008; Loulou and Labriet, 2008) to build scenarios up to 2100 for passenger car transportation in Europe. They show that FCEV could achieve most of the market in 2050 if no significant breakthrough in battery is made. In contrast, Oshiro and Masui (2014) analyze the Japan market and show that BEV would take most of the passenger car market in 2050 while the share of FCEV would remain marginal.

In all these studies the trajectory for the FCEV transition takes place over several tens of years. In a number of them the trajectory is exogenously determined and the cost dynamics follows from this trajectory. In other ones the trajectory and the cost dynamics are linked in an intricate way so that the results are not easily interpretable for policy makers. Our methodology formalizes this interdependence. For an exogenously given trajectory it characterizes the social cost of carbon that would be consistent with the proposed launching date of the trajectory. For a given cost dynamics it allows for comparing the proposed trajectory with the optimal one, as long as the cost dynamics is properly modeled by our assumptions. The methodology is illustrated for the German market using a calibration of updated data from (McKinsey & Company, 2010). The proposed launching date is 2015 and we show that this date would be consistent with a carbon price at 53 €/t (Corollary 2). This figure is much lower than estimates obtained through standard methodology which range around 800 to 1000 €/t (e.g. Beeker, 2014). The empirical analysis of German data allows for deriving market or cost conditions under which the adjusted marginal abatement cost would decrease from 53 to 30 €/t (Corollary 3).

From a theoretical standpoint our model can be seen as a particular specification of similar models developed in the literature. It delivers the standard result that along the optimal trajectory the CO_2 price should be equal to the sum of two terms: the difference between the cost of the marginal green good and a polluting good; and the learning benefits over the future (lemma 1). This result, well known in the literature on climate policy and induced technical change (e.g. Goulder and Mathai, 2000; Bramoullé and Olson, 2005) illustrates the inter-temporal consistency of the optimal trajectory. Still it is difficult to operationalize. Our contribution provides conditions to overcome this difficulty through the characterization of a simple indicator to assess a technological option.

The convexity of the cost function plays a key role in the qualitative property of the transition. Several papers have discussed the role of cost convexity in absence of learning-by-doing. Vogt-Schilb et al. (2012) introduce convexities in the investment cost of clean capital in a multi-sector framework. They show that this convexity incites to spread investment in clean capital over time and comfort observed transition dynamics. Similarly, Amigues, Ayong Le Kama and Moreaux (2015) introduce convexity in the form of adjustment cost in clean capital accumulation to study a transition from non-renewable to renewable resources. Amigues, Lafforgue and Moreaux (2015) analyze the optimal timing of carbon capture and storage policies under decreasing returns to scale. They show that the carbon capture of the emissions should start earlier than under a constant average cost assumption. The role of convexity has also been stressed by Bramoullé and Olson (2005) in their study of the role of learning-by-doing in sectoral arbitrage. Without convexities, learning-by-doing alone does not justify a ramping of the clean option and learning cost should be postponed as far as possible. This feature is also present in our model (lemma 2).

Our approach can also be related to other streams of literature, as macro models on innovation and green technologies, on one side, and large scale computable models on the other. Analytical macro models that recommend early deployment of green technologies remain imprecise on the specific sectoral cost assumptions that would justify their conclusions (e.g. Grimaud and Rouge, 2008; Acemoglu et al., 2012). Top-down computable general equilibrium (CGE) models (as for instance GEM-E3, GREEN, PACE and MITEPPA) are typically based on exogenous technological change, where roadmaps from polluting to carbon free technologies are used. The associated cost function of the carbon free technologies are time dependent. They compare long term scenarios under various environmental constraints.[2] Bottom-up models are almost exclusively technology snapshot models that examine a suite of technological alternatives over time. A number of bottom-up models have integrated endogenous technological change that assumes the existence of learning by doing. Examples are MESSAGE, MARKAL and POLES. Both bottom-up and top-down large-scale models provide valuable numerical results, but their complexity limits their use, both for scenario explorations and conceptual thinking. Our analysis and its application to the hydrogen car deployment provides a link between these two streams of literature. It facilitates the conceptual analysis of the main cost assumptions and its interpretability for decision makers.

The paper is organized as follows. Section 2 presents the analytical model and develops the first best and second best scenarios. Section 3 illustrate the application to the case of FCEV versus ICE, whereas Section 4 briefly concludes.

2 The analytical framework

2.1 The model

We consider a simple model of a sector, say the car sector, the size of which is constant. There are two varieties of vehicles: cars build by using an old polluting technology (ICE vehicle) and new ones which are carbon free (FCEV vehicle). The new technology is subject to learning by doing.

Time is continuous from 0 to $+\infty$. The discount rate is constant equal to r. We consider that cars last one unit of time. There are N cars among which x new "green" cars and $N-x$ polluting old cars. Units are normalized so that each old car emits one unit of CO_2, green cars do not pollute. The cost of a old car is constant: c_o. The cost of x new green cars is a function of the knowledge capital X: $C(X, x)$. At any time $t \in [0, +\infty[$ the knowledge capital X_t is equal to the total quantity of green cars previously built $X_t = \int_0^t x_t dt$.

The cost $C(X, x)$ is assumed twice differentiable and positive. It is null for $x = 0$, for all X: $C(X, 0) = 0, \forall X$, and strictly positive otherwise. The cost is increasing and convex with respect to x, the quantity of green cars produced. Knowledge reduces the production cost and this effect is lower for larger knowledge stock. The marginal production cost also

[2] See for instance Rösler et al. (2014) which relies the bottom-up energy systems ETSAP-TIAM family of models (Loulou and Labriet, 2008; Loulou, 2008).

decreases with knowledge. All this assumptions translate formally:[3]

$$C_x \geq 0, C_X \leq 0, C_{xx} > 0, C_{XX} > 0 \text{ and } C_{Xx} \leq 0. \tag{A1}$$

To ensure the convexity of the problem we assume that the following condition holds:

$$[C_{Xx}]^2 < C_{XX}C_{xx}. \tag{A2}$$

Finally, we assume that the effect of knowledge on the marginal cost, $-C_{Xx}$, is larger for larger production. Said differently, the derivative C_X is concave with respect to x, that is, $C_{Xxx} < 0$.

The price of CO_2 is p_t^{CO2}, it grows at the speed of the discount rate $p_t^{CO2} = e^{rt}p_0$ with $p_0 = 0$. This assumption will prove very useful to simplify dynamic considerations. It means that once discounted a CO_2 emissions has the same value whatever the date at which it is emitted. Such a price dynamics could be linked to the stock nature of CO_2 emissions and the low decay of CO_2 in the atmosphere. It would occur if there was a constraint on the total cumulated emissions (it would be a CO_2 Hotelling's rule).

A notation that will prove useful is the discounted cost of a fully green fleet with a initial knowledge stock X. This cost is the discounted sum of the costs of producing N green cars at each time. With this production schedule the knowledge stock at time t is $X + tN$ so this discounted cost, denoted $\Omega(X)$, is as follows:

$$\Omega(X) = \int_0^{+\infty} e^{-rt}C(X + tN, N)dt. \tag{1}$$

The objective of the social planner is to minimize the cost:

$$\Gamma = \int_0^{+\infty} e^{-rt} \left[(p_t^{CO2} + c_o).(N - x_t) + C(X_t, x_t)\right] dt \tag{2}$$

$$\textit{subject to}$$

$$\dot{X}_t = x_t, \ X_0 = 0 \tag{3}$$

$$0 \leq x_t \leq N \tag{4}$$

This is a standard problem, and the qualitative properties of the optimal trajectory have been already analyzed elsewhere, if not in the precise same framework in relatively similar ones. The following Lemma describes the features of the optimal trajectory.

Lemma 1 *The production of green cars increases over time. There are two dates T_s and T_e, with $T_s \leq T_e$, at which the transition respectively starts and ends:*

$$x_t = 0 \textit{ for } t \leq T_s$$

$$0 < x_t < N \textit{ for } T_s < t < T_e$$

[3] Partial derivatives are denoted with indexes (except if it could be confusing) for instance C_X stands for $\partial C/\partial X$.

$$x_t = N \text{ for } t \geq T_e$$

During the transition, that is, for $t \in [T_s, T_e)$ the following equation holds:

$$p_t^{CO2} = \underbrace{[C_x(X_t, x_t) - c_o]}_{\textit{static abatement cost}} + \underbrace{\int_t^{+\infty} e^{-r(\tau - t)} C_X(X_\tau, x_\tau) d\tau}_{\textit{learning benefit } (<0)} \tag{5}$$

The proof is in Appendix A. The optimal trajectory is a smooth transition in which green cars progressively replace old cars. At the end of the transition the fleet is completely green. During the transition, the fraction of the fleet that is green is determined by equation (5). This equation is the transcription within our framework of a well-known result in the literature on learning-by-doing whether related to climate policy (e.g. Goulder and Mathai, 2000; Bramoullé and Olson, 2005), or not (see Rosen, 1972 for an early discussion; and the survey by Thompson, 2010, eq. 3 p. 435): the marginal cost should be equal to the marginal revenue plus the learning benefits.

Indeed, the static marginal abatement cost, that is, the difference between the cost of the marginal green car and an old car, is not sufficient to determine the optimal number of green cars as a function of the CO_2 price. One should also compute the learning benefits, that is, the reduction of future cost due to the production of one more green car today. The "relevant " marginal abatement cost, the right hand side of equation (5), cannot be computed without knowing the whole future optimal path of production, which limits the practical use of equation (5).

Considering two extreme cases is useful to interpret the role of our assumptions on cost in the time dependency. On the one hand, without learning-by-doing, the static abatement cost is sufficient to determine the optimal number of green cars at each date. There is a smooth transition. Still, each date can be isolated from the rest of the trajectory: there is no interdependency between past, present and future decisions. On the other hand, without convexity, the transition takes place at once and its date can be determined through some generalization of the notion of abatement cost. Learning-by-doing alone, instead, does not imply a smooth transition. This is pointed out below.

Lemma 2 *If $C_{xx} = 0$ then the optimal strategy is to replace all old cars by new cars from a date $T_s = T_e$. At this date the CO_2 price is:*

$$p_{Ts}^{CO2} = \frac{r\Omega(0) - c_o N}{N}. \tag{6}$$

in which $\Omega(0)$ is given by equation (1).

The proof is in Appendix B. The threshold of CO_2 price in the equation (6) could be interpreted as a MAC for the whole technical option: it is the ratio of the difference between the levelized (static) cost of a fleet of green cars and a fleet of old cars to the quantity of emissions abated by the project. In the next subsection, this rule is extended to a general cost function and a ramping deployment scenario.

2.2 The "deployment" perspective

In the optimal case, the whole trajectory is consistent with the CO_2 price: the date at which the deployment starts and the pace at which green cars replace old cars are jointly determined. For a real world application, this theoretical analysis does not provide a simple rule to evaluate a technical option and a "launching date". Furthermore, for real world issues there are many components in the cost (e.g. investment in infrastructure) that do not easily translate into a specified version of $C(X, x)$ so that the determination of an optimal trajectory may be out of reach. It is more realistic to discuss suboptimal trajectories.

We propose to decompose the global problem into sub-problems easier to connect to practical examples, offering straightforward interpretations. We disentangle the choice of the production schedule of cars during the deployment phase from the choice of a date at which deployment should start (the date T_s in the optimal scenario). More precisely, the global problem could be decomposed as follow. There is a "deployment scenario" of the green option with a finite duration; during this deployment a exogenously given amount of green cars is produced each year. The "launching date" of this deployment should be determined. Once deployment is achieved, the whole fleet is replaced by green cars. The optimal trajectory can be found by choosing simultaneously and consistently not only the launching date, but also the deployment scenario characteristics. The optimal choice of the deployment scenario is discussed in the next subsection. We consider here a given scenario, regardless that optimal choice.

For a given deployment scenario, the only variable to be chosen is the launching date T_l that should balance the price of CO_2 with the abatement cost of the deployment. Waiting one year to launch the deployment increases emissions by an amount proportional to the fleet but postpones the costly deployment and implementation of the green fleet. The discounted cost of the fleet, given by equation (2), can be decomposed to reflect this trade-off. To do so, the costs of the deployment and the fully green fleet should be discounted to be independent of the launching date:

- The deployment scenario takes place over D years during which a total quantity of $\bar{X}$ cars are produced. The trajectory of accumulation is $(\xi_\tau)_{\tau \in [0,D]}$ in which ξ_τ is the number of green cars produced at stage τ of the deployment (i.e. τ years after the launching), and $\bar{X} = \int_0^D \xi_\tau d\tau$. The cost of this deployment is

$$I = \int_0^D e^{-r\tau}[C(\bar{X}_\tau, \xi_\tau) - c_o \xi_\tau] d\tau \text{ in which } \bar{X}_\tau = \int_0^\tau \xi_u du \tag{7}$$

- At the end of the deployment the fleet is completely green, and the discounted cost of the green fleet of cars solely depends on $\bar{X}$, the knowledge accumulated during the deployment. This cost, view from the date of the end of the deployment, is $\Omega(\bar{X})$ given by equation (1).

The discounted cost of the fleet, given by equation (2), can then be written (with a slight abuse of notation):

$$\Gamma(T_l) = \underbrace{\int_0^{T_l+D} e^{-rt}(c_o + p_t^{CO2})N dt}_{\text{fully old fleet}} + \underbrace{e^{-rT_l} I - p_0 \bar{X}}_{\text{deployment phase}} + \underbrace{e^{-r(T_l+D)}\Omega(\bar{X})}_{\text{fully green fleet}} . \tag{8}$$

This cost is the sum of three terms: the cost, including the CO_2 cost, of a fleet of old cars from today to the end of the deployment; the cost of the deployment minus the gain from abatement during deployment; once deployment is achieved the fleet is entirely green and the current cost of the fully green fleet only depends on the quantity of knowledge accumulated during the deployment.

The problem is now simply to determine the date T_l at which the deployment should be launched. The assumption that the CO_2 price grows at the interest rate plays a key role here because the precise date at which carbon reduction takes place does not impact welfare. The emissions abated during deployment, which are precisely equal to the quantity of cars accumulated during the deployment, do not impact the choice of the launching date. This nicely fits our decomposition, since the choice of the launching date only changes costs via discounting.

Proposition 1 *The optimal launching date T_l^* of the deployment scenario (ξ_τ) is such that the CO_2 price at the end of the deployment is equal to the Adjusted Abatement Cost of the deployment scenario:*

$$p_{T_l^*+D}^{CO2} = AAC(\xi(\tau)) =_{def} \frac{rI}{N} e^{rD} + \frac{r\Omega(\bar{X}) - c_0 N}{N} \tag{9}$$

equivalently, the price at the launching date is the Discounted Adjusted Abatement Cost:

$$p_{T_l^*}^{CO2} = DAAC(\xi(\tau)) =_{def} \frac{rI}{N} + \frac{r\Omega(\bar{X}) - c_0 N}{N} e^{-rD} \tag{10}$$

Proof. Taking the derivative of the discounted total cost Γ given by (8) with respect to the launching date gives:

$$\begin{aligned}\frac{\partial \Gamma}{\partial T_l} &= e^{-r(T_l+D)}(c_o + p_{T_l+D}^{CO2})N - rIe^{-rT_l} - r\Omega(\bar{X})e^{-r(T_l+D)} \\ &= e^{-r(T_l+D)} \left[p_{T_l+D}^{CO2} N + c_o N - rIe^{rD} - r\Omega(\bar{X}) \right]\end{aligned}$$

At the optimal launching date this derivative is null and, consequently, equation (9) is satisfied. ■

This rule can be easily interpreted: the launching date is chosen so that the abatement cost of the whole deployment is equal to the CO_2 price at the end of the deployment. The abatement cost of the project is the sum of two components: the sunk cost of the deployment that takes D years (rI/Ne^{rD}); and the relative over-cost of a green car at the end of the deployment ($(r\Omega(\bar{X}) - c_0)/N$). The cost $r\Omega(\bar{X})$ is the annualized cost of a fully green fleet, so $r\Omega(\bar{X})/N$ is the average current cost of a green car over the life of the green fleet. Note that, if at the end of the deployment the green car cost is linear and stable ($C(X, x) = \underline{c}x$) the second component becomes the difference between the cost of a green and an old car ($\underline{c} - c_0$). The AAC makes a clear parallel between a deployment trajectory and a huge clean plant. This is further discussed below, in subsection 2.3 on the growth rate of the CO_2 price. The discounted adjusted abatement cost (DAAC), defined by equation (10), is the indicator that the policy makers would be interested in, to know when the trajectory is worth launching.

The price obtained in Lemma 2 corresponds to the price of Proposition 1 for an extreme deployment scenario in which there is no ramping of the production, that is when $\bar{X} = 0$ and $D = 0$, we have that $I = 0$.

Corollary 1 *Consider two cost functions $C_1(X, x)$ and $C_2(X, x)$. If for all X and x, the cost function 1 is lower than the cost function 2, then for any given deployment scenario $(\xi_\tau)_{\tau \in [0,D]}$, the optimal launching date is earlier with C_1 than with C_2.*

The proof of this corollary is straightforward. For a given scenario, both the investment cost and the cost of a fully green fleet are lower with the cost C_1 and the associated launching date should then be earlier. For instance, an increase of the learning rate, for a given scenario, should induce an earlier launching. This might seem contradictory with the theoretical ambiguous effect of learning-by-doing on the timing of abatement found in the literature (e.g. Goulder and Mathai, 2000). This is so because both the CO_2 price and the production scheduled are fixed in the present framework, which suppress contrasting forces at play in other analysis.

First, with an endogenous CO_2 price, a lower abatement cost suggests to reduce the CO_2 price which would counteract the result of Corollary 1.[4] Second, a higher learning rate should modify the whole optimal deployment, and the sign of the change depends on the date in a non-trivial way, even with a fixed CO_2 price. The implication of a higher learning rate both on the level and the pace of abatement are difficult to determine without further specification. Abatement should increase at some dates and decrease at other, and the magnitude of such change is not monotonic. Equation (5) can help to have some intuition. Since a stronger learning rate decreases marginal static abatement costs, production should increase especially at a latter date. This would increase the level and the pace of abatement. However... However, the change of learning benefits is unclear; it seems likely than the learning benefits of earlier production are enhanced while they are reduced for latter production, and this would work in the opposite direction: it implies a reduction of the pace of abatement.

2.3 The impact of the CO_2 price growth rate

The model allows to understand the limits of the change of perspective (from a single car to the whole technological deployment) and of the parallel between a deployment scenario and a huge clean plant. The role of CO_2 price dynamic should be stressed. The adjusted abatement cost is theoretically valid only if the CO_2 price grows at the interest rate, which allows to neglect interim abatement. To assume that the CO_2 price grows at the interest rate

[4]Indeed, the appropriate change of the CO_2 price would depend on the policy objective, and the cost associated to emissions in the sector considered. If the objective is to keep constant cumulated emissions associated to the car fleet under consideration, the move of the CO_2 price would exactly compensate the direct effect of the reduction of cost and the launching would indeed be unchanged.

considerably simplifies the analysis of dynamic trajectory, by reducing to a single number p_0 the description of the whole CO_2 price path. With a different dynamic of the CO_2 price, interim abatements interact with the dynamic of the CO_2 price and impact the launching date. This effect is detailed in the following corollary.

Corollary 2 *If the CO_2 price grows at the rate $\rho \neq r$, $p_t^{CO2} = p_0 e^{\rho t}$, the optimal launching date of scenario $(\xi_\tau)_{\tau\in[0,D]}$ is such that:*

$$p_{T_l^*+D}^{CO2} = \frac{rIe^{rD} + (r\Omega(\bar{X}) - c_0 N)}{N - (\rho - r)\int_0^D e^{-(\rho-r)(D-\tau)}\xi(\tau)d\tau} \tag{11}$$

The proof is in Appendix C. If the CO_2 price does not grow at the interest rate, emissions have different present costs depending on the date at which they are emitted which explain that production during deployment should influence the launching date.

If production during deployment is negligible, $\xi \simeq 0$, the CO_2 price at the end of the deployment, described by equation (11), is equal to the AAC, and is not affected by the growth rate of the CO_2 price. In such a case, the parallel between a deployment scenario and a huge clean plant is still valid. The launching date is determined by the CO_2 price at the ending date. Indeed, the launching CO_2 price is no longer equal to the DAAC in that case, but to $AAC \times e^{-\rho D}$, which shows that the discount of AAC to obtain the DAAC is related to the dynamic of the CO_2 price.

With non negligible interim abatement, the comparison between the CO_2 price growth rate and the interest rate determines whether a latter emission is more costly than an earlier emission and the influence of interim abatement on the launching and ending dates. The CO_2 price at the ending date is described by equation (11), as could be seen the AAC should be corrected by subtracting a term to the yearly abatement N in the denominator. The sign of this term is determined by the comparison between the growth rate of the CO_2 price and the interest rate, it reflects the gain (if $\rho > r$), or cost (if $\rho < r$), to postpone interim abatement. Figure 1 illustrates the Corollary with $\rho > r$. If the growth rate of the CO_2 price is larger than the interest rate,[5] the ending CO_2 price is larger than in case of equality, reflecting that delaying interim abatement reduces costs. However, the launching CO_2 price is lower than in case of equality, and thus lower than the DAAC of Proposition (1) (cf Appendix C), because of the overall higher cost of emissions. More precisely, in Appendix C, it is shown that an increase of the growth rate of the CO_2 price would both reduce the launching CO_2 price and increase the ending CO_2 price.

2.4 The optimal trajectory revisited and some comparative statics

The deployment approach can be seen as a convenient procedure to compute the optimal trajectory. Indeed, in the optimal trajectory there is a deployment phase during which green cars progressively replace old cars, and after this phase the whole fleet is green (cf Lemma 1).

[5] This is the case if the objective is to stabilize the concentration of the CO_2 in the atmosphere, the CO_2 price should then grow at a higher rate than the interest rate because latter emissions have a stronger effect on the binding of the ceiling constraints (e.g. Amigues, Ayong Le Kama and Moreaux, 2015).

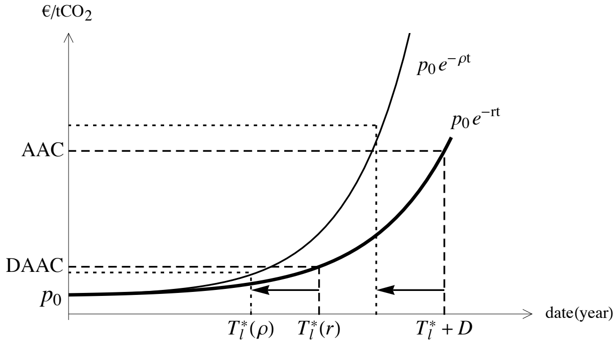


Figure 1: The CO_2 price growth rate impact on the launching and ending dates of deployment and the corresponding CO_2 prices, with $\rho > r$.

If the deployment scenario is precisely similar to the optimal deployment, then the launching dates coincide (T_s in Lemma 1 equals T_l in Proposition 1).

The optimal trajectory can be found with a deployment approach by proceeding as follows. For any quantity $\bar{X}$ and duration D there is a deployment scenario that minimizes the discounted cost I (given by equation 7). This deployment scenario is independent of the CO_2 price and the launching date. Let us denote $I^*(\bar{X}, D)$ the minimum deployment cost which is only defined for $D \geq \bar{X}/N$:

$$I^*(\bar{X}, D) = min_{x_\tau} \int_0^D e^{-r\tau}[C(X_\tau, x_\tau) - c_0 x_\tau]d\tau \quad (12)$$
$$\text{s.t. } \dot{X}_t = x_\tau;\ 0 \leq x_\tau \leq N \text{ and } X_D = \bar{X}.$$

The optimal solution is found by optimally choosing three variables: the launching date, the duration of deployment D and the quantity $\bar{X}$ of green cars produced during this deployment. The optimal trajectory corresponds to the trajectory found by minimizing with respect to T_l, $\bar{X}$ and D the following cost:

$$\Gamma = \int_0^{T_l+D} e^{-rt}(c_o + p_t^{CO2})Ndt + e^{-rT_l}I^*(\bar{X}, D) - p_0\bar{X} + e^{-r(T_l+D)}\Omega(\bar{X}). \quad (13)$$

The optimal quantity of green cars produced during deployment and the optimal duration of the deployment satisfy the pair of first order conditions:

$$p_0 e^{rT_l} = \frac{\partial I^*}{\partial \bar{X}} + e^{-rD}\frac{\partial \Omega}{\partial \bar{X}} \quad (14)$$

$$p_0 e^{rT_l}N - e^{-rD}[r\Omega - c_0 N] = -\frac{\partial I^*}{\partial D} \quad (15)$$

Consider first equation (14) that determines the choice of the optimal number of green cars during deployment. The left-hand-side is the gain due to the reduction of emissions during the deployment. This benefit should be equalized with the marginal cost of the overall project. This marginal cost is the sum of the marginal cost of the deployment and the marginal latter cost of the fully green, post-deployment, fleet. The former is positive and the latter is negative, since an increase of the quantity of green car produced during deployment reduces the cost of the fully green fleet.

The choice of the optimal duration as represented by equation (15), equalizes the gain from reducing the deployment duration with the corresponding marginal cost ($\partial I^*/\partial D < 0$). Reducing the duration of deployment allows to save N additional emissions but brings forward the replacement of the old fleet by a green one.

It is feasible to briefly examine how the sub-optimality of a deployment scenario impacts the launching date.[6]

Proposition 2 *An optimal trajectory can be described by an optimal deployment scenario and the associated optimal launching date. The optimal deployment scenario consists in* $\bar{X}^*$, D^* *and* $(\xi^*_\tau)_{\tau\in[0,D^*]}$.

If the deployment scenario is suboptimal :

- *If the deployment cost is not minimized (*$\xi_\tau \neq \xi^*_\tau$*), the launching should be postponed;*
- *If the total number of green cars produced during deployment is larger than the optimal one (*$\bar{X} > \bar{X}^*$*), the launching should be postponed;*
- *If the total number of green cars produced during deployment is slightly lower than the optimal one (*$\bar{X} < \bar{X}^*$*), the launching should take place earlier.*

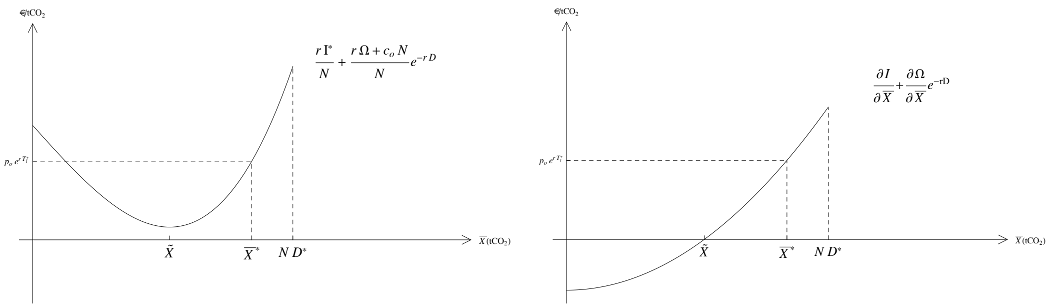
If, given $\bar{X}$ and duration D, the deployment cost I is not minimized, then the launching should be postponed. Indeed, the higher the cost of the project the higher the associated CO_2 price.

If the duration is fixed and the cost is minimized, the choice of $\bar{X}$ has a non monotonic effect on the choice of the launching date. Figure 2 illustrates the joint determination of the launching date and the quantity of accumulated cars. Figure 2(a) represents the result of Proposition 1: the abatement cost of the whole project should be equalized to the launching date. This is also true for a sub-optimal scenario, notably if $\bar{X} \neq \bar{X}^*$. Figure 2(b) depicts the choice of the quantity of green cars accumulated during deployment that should equalize the marginal cost of such accumulation with the CO_2 price at the launching date.

As illustrated by Figure 2(a), the accumulation $\bar{X}$ that would minimize the launching date is lower than the optimal accumulation. So, if more cars than optimal are accumulated, the launching should be postponed, because of the increased cost of the whole deployment. If the number of accumulated cars is smaller than the optimal one, but not far from it, the cost is actually reduced and launching should start earlier than the optimal date. This earlier deployment would partly compensates for the lower interim abatement.

The figure 2(b) also shows how the accumulation of green cars during deployment is modified by a sub-optimal launching date. The later the launching is the larger the accumulation should be.

[6]A formal proof of the following proposition is available upon request.



(a) The choice of the launching date T_l^* equalizes the CO_2 price with the levelized cost of the project

(b) The choice of the quantity of green cars produced during the deployment $\bar{X}^*$, equalizes the marginal cost with the CO_2 price

Figure 2: The joint determination of the launching date (a) and the quantity of cars produced during deployment (b).

3 Application to the case of FCEV versus ICE

We recall the key assumptions:

- An exogenous deployment for FCEV based on industry projections; this deployment is based on a number of technical and economic constraints such as the time to achieve the targeted cost projections, the time to build up the network, social constraints such as acceptability of the new technology by consumers...Once this deployment scenario is characterized it becomes meaningful to model the associated cost dynamics based on a limited number of parameters.

- A normative social price of carbon based on global general equilibrium models. More precisely we assume a CO_2 price sequence increasing at the social discount rate from a given initial value.

From these two assumptions we are able to answer the following two questions:

- What should be the threshold CO_2 price in 2015 so that it would be optimal to launch the proposed deployment of FCEV over the period 2015 to 2050? We shall refer to this price as the DAAC of the deployment trajectory.

- If the DAAC is higher than the current normative cost of carbon in 2015, what is the magnitude of the changes in the key parameters in our model that would make the abatement cost consistent with the normative value?

The corresponding results can be used to determine with industry experts the technical feasibility and uncertainties associated with different sets of assumptions.

3.1 The data and the associated static abatement costs

Table 1 gives the data. The geographic context is Germany, a country in which some significant moves have already been made in favor of FCEV. The cost dynamics underlying the deployment scenario involves three main components: manufacturing costs, infrastructure costs and fuel costs. The corresponding model is detailed in Creti et al. (2015). We briefly review the construction of the cost function.

The total passenger car fleet in Germany is assumed to increase from today's level of 47 million vehicles to 49.5 million in 2030. It is assumed to be stable from 2030 to 2050. Our exogenous deployment scenario assumes a very progressive ramp up starting in 2015 up to a 2.7% market share in 2030 and a targeted market share of 15% in 2050, that is 7.500 million units for the FCEV car park. Based on this scenario one constructs a unit manufacturing cost for a FCEV. Cars are expected to have a ten year life time, so that the actual yearly production takes account the renewal of the car park. Both ICE and FCEV cars are running 15 000 km per year. Fuel consumption is derived based on energy efficiency. Using unit fuel costs one gets the total fuel consumption. Fuel costs for hydrogen depend on the technology to produce hydrogen (development and capital expenditures of energy producers are integrated in this cost).[7]

The cost of infrastructure is derived from the number of hydrogen refueling stations (HRS) which is derived from the required network to deliver the total hydrogen consumption at every time period. Delivery cost to the stations is added to the infrastructure cost. Gasoline price is also the delivery price at the retail station. In the base case we assume that value added taxes on the cost components are not included but that the excise tax on imported petroleum is, since it represents an opportunity cost for importing oil. Note that the excise tax is in absolute value so its percentage of the gasoline price declines over time. The untaxed gasoline price follows the oil price in the world market, assumed to increase at a constant rate of 1.4%.[8] CO_2 emissions depend both on energy efficiency (which keeps improving for ICE and FCEV) and the progressive introduction of carbon free technologies for hydrogen production.

[7]In our scenario we shall consider three new technologies: carbon sequestration and capture, electrolysis based on renewable energies, and biogas.

[8]The average gasoline market price per litre in Germany in 2014 was equal to 1,6 €(including all taxes). While the recent drop in oil prices had a significant impact on this price, its long term impact for year 2030 and later is uncertain. The 1.4% annual growth rate is consistent with IEA long term projections.

	Unit	2015	2020	2025	2030	2050
Market size (car life time: 10 years, 15 000km/yr)	1000 cars	1	95	453	1350	7500
Vehicle manufacturing cost						
FCEV	k€	60.0	37.7	32.1	28.6	22.8
ICE	k€	22.0	21.4	21.3	21.1	20.5
Relative price FCEV vs ICE	%	173%	77%	53%	37%	13%
Fuel costs						
FCEV						
Hydrogen production cost (delivery cost to HRS included)	€/kg	7.0	5.8	6.1	6.3	6.8
Hydrogen consumption per 100 km	kg/100km	0.95	0.87	0.84	0.80	0.70
ICE						
Gasoline price	€/ l	1.30	1.35	1.40	1.46	1.71
of which state tax (w/o VAT)	%	50%	48%	47%	45%	38%
Gasoline consumption per 100 km	l/100km	7.04	6.2	4.97	4.88	4.8
Infrastructure costs						
Number of HRS	#	40	220	926	2234	9257
Capital cost per unit of car	k€	62.24	2.39	2.02	1.65	1.18
CO_2 emissions						
Hydrogen	$kgCO_2/100km$	9.0	6.2	5.0	3.8	1.7
Gasoline	$kgCO_2/100km$	19.8	17.4	14.0	13.7	13.5

Table 1: Simplified Data Sheet

For each cost component we introduced a learning by doing parameter and calibrated the model using costs estimates based on existing applied studies and interviews with industry experts. In this way we can analyze how the results are affected through small changes in the cost and environmental parameters. This will be convenient for sensitivity analysis.

Figure 3 gives the TCO at various dates with its cost components. Observe that introducing an excise tax on hydrogen in 2050 would not endanger its position relative to ICE. Figure 4 compares our values for TCO with those obtained in Rösler et al. (2014). Figure 5 depicts fuel efficiency for FCEV and ICE.[9] Figure 6 gives the respective CO2 emissions for FCEV and ICE.[10]

[9]For ICE the sources are coming from the EIA Annual Energy Outlook 2014 (http://www.eia.gov/forecasts/aeo/pdf).

[10]Note that for FCEV the level of carbon free electrolysis in the portfolio of technologies grows from 15% in 2020 to 40% in 2050 which explains the decline in CO2 emissions. The values for ICE are higher than the EU targets. These targets apply to the average portfolio of car manufacturers while FCEV would be more for large vehicles (C/D or J segments).

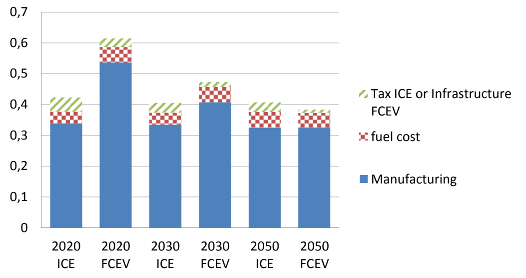


Figure 3: Analysis of the costs components for one car unit in € per km per year

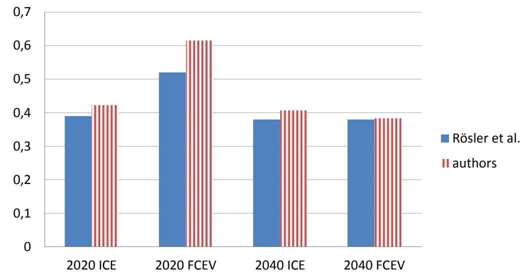


Figure 4: TCO authors versus Rösler et al. (2014), in € per km per year

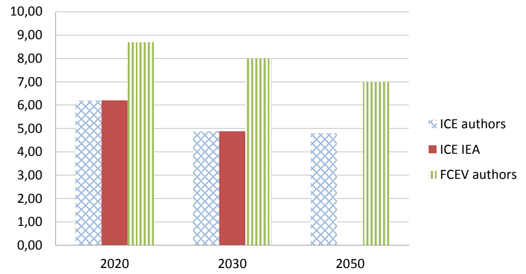


Figure 5: Fuel consumption ICE (l/100km) FCEV (kg/10km)

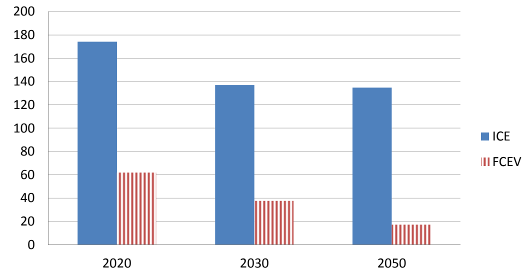


Figure 6: CO_2 emissions g/km

From the respective TCOs and from the respective yearly CO_2 emissions we can derive the yearly static abatement costs (Proposition 1). They are depicted Figure 7. It starts around 1600 €/t in 2020 and decreases to zero in 2043 (the year at which the relative total cost of ownership becomes positive for FCEV). Not much can be inferred from this sequence of abatement costs. In contrast our methodology provides a relevant proxy for policy analysis.

3.2 The adjusted abatement cost for the FCEV deployment trajectory

Recall the result of Proposition 1:

$$p_0 e^{rT_i^*} = DAAC = \frac{rI}{N} + \left[\frac{r\Omega}{N} - c_0\right] e^{-rD} \tag{16}$$

Our illustration directly fits for applying this result with one exception: the TCO and the CO2 emissions for ICE are not constant over time but slightly decreasing. Proposition 2 provides a first order estimate and a more refined approach should take this assumption into account. To calculate our first order estimate we proceed as follows.

- Time is discrete and not continuous;

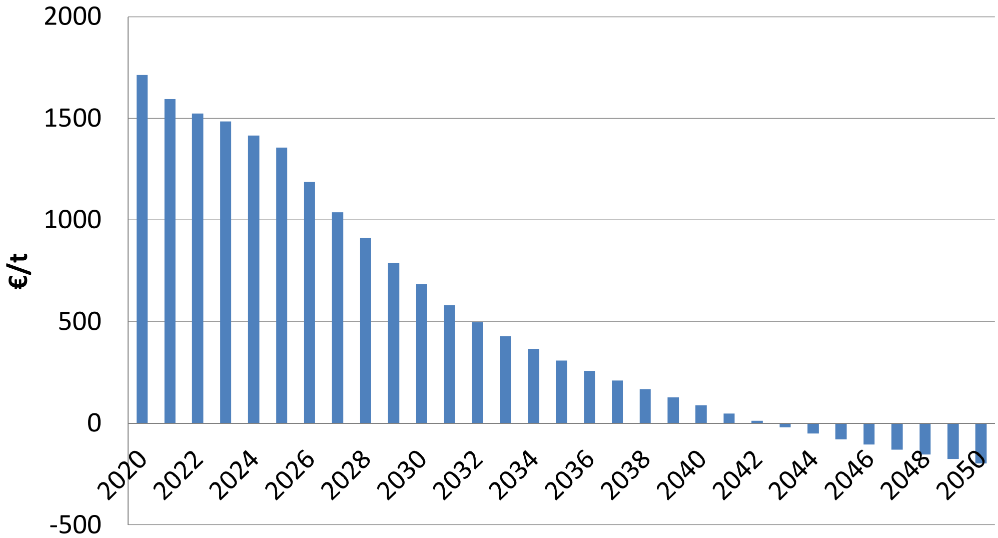


Figure 7: Static abatement cost (€ / t)

- The launching date is such that $T_l^* = 2015$ and the deployment is completed at $T_l^*+D = 2050$;
- TCOs are assumed to converge at the end of the deployment phase which implies $\left[\frac{r\Omega}{N} - c_0\right] = 0$;
- The CO2 avoided emissions for year 2050 and further is not N but the park times the difference in emissions per unit of car, all values being taken at date 2050.

Altogether this gives the following result.

Corollary 3 *The DAAC p_{2015}^{CO2} for the reference scenario is such that:*

$$p_{2015}^{CO2} = ((1-\delta)/\delta) I_{2015-2050}/A_{2050} \tag{17}$$

in which:
- $I_{2015-2050}$ *is the total discounted cost of the trajectory over the period 2015-2050;*
- A_{2050} *denotes the yearly avoided emissions at full deployment that is in year 2050;*
- $\delta = 1/(1+r)$ *with r standing for the social discount rate.*

This expression can be interpreted as an extension of the static abatement cost in which a once and for all investment with a capex of $I_{2015-2050}$ at date 2050 with an infinite life time will balance a recurring amount A_{2050} of avoided CO_2 emissions.

Based on the data of Table 1 and using a 4 % social discount rate we obtain a numerical value for $p_{2015}^{CO2} = 53$ €/t. If we assume an initial social cost of carbon around 30 €/t for 2015, as suggested by Quinet (2009) and Quinet (2013) for France, this suggests that our reference scenario should be postponed until 2030. Since this scenario starts quite slowly it is more meaningful to investigate how one could strengthen some parameters of our model to achieve an optimal launching date at 2015. This leads to the following target analysis.

3.3 Target analysis

Our deployment approach cannot directly deliver the optimal trajectory: too many assumptions such as regarding customer's acceptability and innovation in hydrogen production remain implicit. Still a local exploration can be made by marginally changing the proposed trajectory. This exploration is conducted so as to achieve a targeted adjusted abatement cost, say of 30 €/t in 2015

Corollary 4 *To achieve a DAAC p_{2015}^{CO2} consistent with a social cost of carbon of 30 €/t in 2015 one may either target for*

- *a market share of 27 % rather than 15 % in the total car park in 2050;*
- *a growth rate of 2.9 % instead of 1.4 % in the increase in the oil price;*
- *a higher learning rate for manufacturing costs so that the unit cost of a FCEV car be only 6.7 % instead of 13 % higher than the one of a ICE car in 2050;*
- *a higher learning rate for H2 production costs so that the unit cost of H2 production be 33 % lower than the expected value with the reference scenario in 2050.*

Consider the following four parameters as well as a combination of changes in these four parameters. The detailed results of this exploration are given Table 2. Note that all one parameter changes impact the total investment cost while a change in the targeted market size and in the hydrogen production cost (modeled as a decrease in the cost of the electrolysis process combined with a more intensive use of this technology) also impact the level of CO_2 avoided in 2050. The changes may appear quite large but the effort can be substantially reduced if they are combined. Indeed as shown in Table 2 the targeted abatement cost could be achieved with:

- a market share of 20 % in the total car park in 2050;
- a growth rate of 1.8 % in the increase in the oil price;
- a unit cost of a FCEV car 9.8 % higher than the one of a ICE car in 2050;
- a unit cost of H2 production 8 % lower than the expected value with the reference scenario in 2050.

In Figure 8 the effort of the combined change relative to the one parameter changes is depicted.

	unit	Base Case	Market size in % of total car park	Gasoline price (yearly rate of increase)	Manufacturing cost (FCEV vs ICE in 2050)	Hydrogen production cost in 2050	4 parameter target
Market size (in % of total car park)	%	15%	**27**%	15%	15%	15%	**20**%
Gasoline price (yearly rate of increase)	%	1.4%	1.4%	**2.9**%	1.4%	1.4%	**1.8**%
Manufacturing cost (FCEV vs ICE in 2050)	%	11.3%	11.%	11.3%	**6.7**%	11.3%	**9.8**%
Hydrogen production cost	€/kg	6.8	6.8	6.8	6.8	**4.5**	**6.2**
avoided CO_2 emissions in 2050	Mt/year	13.2	18.9	13.2	13.2	13.8	14.1
Discounted cost for the scenario up to 2050	M€	17 511	14 001	9 719	9 965	10 528	10 582
adjusted abatement cost	€/t	53	30	30	30	30	30

Table 2: Target analysis, each column correspond to a scenario in which a parameter is changed to get a DAAC of 30€/t, in the last column all four parameters are changed.

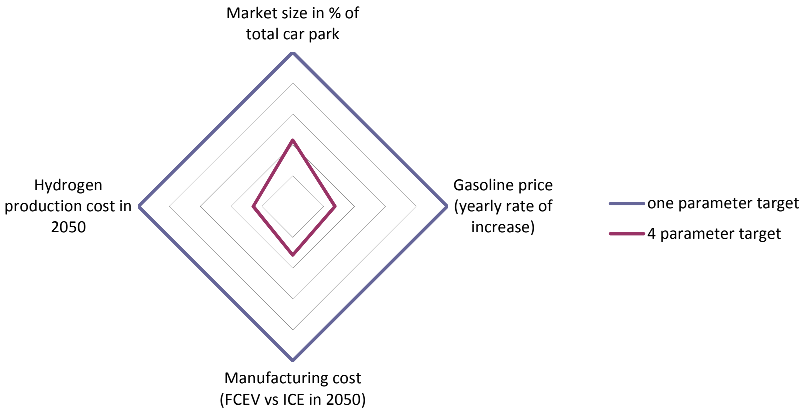


Figure 8: The four parameters target in % of the one parameter ones

4 Conclusion

The main contribution of the paper consists in designing a decomposition methodology to disentangle the choice of the production schedule from the choice of launching date in the search of the optimal trajectory. This leads to two interesting results. Firstly we extend the standard static notion of abatement cost associated to the substitution of a dirty unit by a clean one at some point of time to a dynamic one in which the all deployment trajectory is globally considered from its launching date. Second this adjusted abatement cost is also meaningful for a second best trajectory, which is often the case in applications where trajectories are defined through industrial and social considerations outside the scope of the modeling exercise. These results provide a simple framework for policy guidance. This is illustrated through an analysis of a trajectory in which ICE are progressively replaced by FCEV.

It would be interesting to extend this approach in several directions. From a theoretical point of view the dependence of the launching date on the learning rate for the optimal trajectory is worth to clarify (possible generalization of Corollary 2). Our decomposition methodology relies on a number of stationarity assumptions which may be revisited in search for possible theoretical extensions. Indeed in the FECV case we have assumed that the minor efficiency gains in ICE and the time increase in gasoline fuel costs do not invalidate the derivation of an adjusted marginal abatement cost; this would be worth further work. A more elaborate extension would consider the simultaneous deployment of alternative clean technologies such as BEV and FCEV to be substituted to ICE. This may possibly involve the introduction of consumers' preferences in which the role of product differentiation could be analyzed.

Another interesting extension would be to consider the decentralization issue of the optimal trajectory to the various players (manufacturers, H2 producers, network operators). These players need operate under a positive profit constraint assumptions. We have assumed an exogenous normative CO_2 price. There is no guaranty that the transfer of externality benefit to the players can be enough to accommodate the positive profit constraints. Defining more operational policy instruments could be examined such as imposing a minimal rate of clean cars in the portfolio of manufacturers. We think that some answers to these various questions could be obtained while preserving the simplicity of our approach.

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Appendix

A Proof of Lemma 1

Proof. To minimize the total cost (2), let us introduce λ_t the co-state variable associated to the relation (3), and θ_t and δ_t the Lagrange multipliers associated to the two constraints (4) on x_t: it is positive (θ_t) and smaller that the total fleet size (δ_t). The first order conditions (together with the complementarity slackness conditions) are:

$$C_x(X_t, x_t) - c_o = p_t^{CO2} + \lambda_t + \theta_t - \delta_t \tag{18}$$
$$\dot{\lambda}_t - r\lambda_t = C_X(X_t, x_t). \tag{19}$$

The main step of the proof consists in proving that x_t is increasing if $x_t \in (0, N)$. This condition ensures that once $x_t > 0$ the number of green cars cannot come back to zero, and that x_t does not move when $x_t = N$. If x_t is strictly positive ($\theta_t = 0$) and lower than the total car fleet ($\delta_t = 0$), equation (18) becomes

$$C_x(X_t, x_t) - c_o = p_t^{CO2} + \lambda_t$$

If $x_t \in (0, N)$, taking the time derivative of the first equation gives:

$$\begin{aligned} C_{xX}\dot{X}_t + C_{xx}\dot{x}_t &= \dot{p}_t^{CO2} + \dot{\lambda}_t \\ C_{xX}x_t + C_{xx}\dot{x}_t &= \dot{p}_t^{CO2} + r\lambda_t + C_X && \text{thanks to eq. 19} \\ C_{xx}\dot{x}_t &= \dot{p}_t^{CO2} + r\lambda_t + [C_X(X_t, x_t) - C_{xX}x] \end{aligned}$$

The last term of the right hand side is positive because $C_X(X, x)$ is concave with respect to x and $C_X(X, 0) = 0$ (since $C(X, 0) = 0, \forall X$). Since C_{xx}, p_t^{CO2} and r are all positive, $\dot{x}$ is also positive so that x_t is increasing through time.

Then, since the CO_2 price increases exponentially, x_t cannot be always null along an optimal trajectory. Then either $x_0 = 0$ or $x_0 > 0$. In the latter case $T_s = 0$, whereas in the former case T_s is the inf of the dates at which $x_t > 0$.

The ending date is finite, $T_e < +\infty$: From the above proof, when x_t is strictly positive its time derivative is bounded below by a strictly positive number, so x_t necessarily reaches N in a finite time.

Finally, equation (5) is obtained by integrating equation (19), between t and $+\infty$ (and using the boundary conditions $\lim_{t\to+\infty} e^{-rt}\lambda_t = 0$):

$$\lambda_t = -\int_t^{+\infty} e^{-r(\tau-t)} C_X(X_\tau, x_\tau)d\tau \tag{20}$$

and injecting this expression into equation (18).

■

B Proof of Lemma 2

Proof. If $C_{xx} = 0$, given that $C(X, 0) = 0$, $C_X(X, x) = C_{Xx}(X, x)x$. Then, we resort by reductio ad absurdum assuming $T_s < T_e$. Between the two dates the equation (5) is satisfied and taking its derivative with respect to t gives:

$$\begin{aligned}
\dot{p}_t^{CO2} &= C_{Xx}\dot{X}_t + C_{xx}\dot{x}_t - \dot{\lambda}_t \\
&= C_{Xx}x_t + 0 - [r\lambda_t + C_X] && \text{using eq. (19)} \\
&= C_{Xx}x_t - C_X(X_t, x_t) + r\left[\int_t^{+\infty} e^{-r(\tau-t)} C_X(X_\tau, x_\tau)d\tau\right] && \text{from (20)}
\end{aligned}$$

Therefore, using that $C_X(X, x) = C_{Xx}(X, x)x$ in that case,

$$0 < \dot{p}_t^{CO2} = r\left[\int_t^{+\infty} e^{-r(\tau-t)} C_X(X_\tau, x_\tau)d\tau\right] \leq 0$$

a contradiction.

Therefore, the number of green cars jumps from 0 to N at date $T_s = T_e$, and the total discounted cost Γ could be written as a function of the date T_s:

$$\Gamma = \int_0^{T_s} e^{-rt}\left[(p_t^{CO2} + c_o).N\right]dt + e^{-rT_s}\Omega(0)$$

Along the optimal trajectory, T_s should minimize this function. Taking the derivative with respect to T_s in the equation above and setting it equal to zero gives the equation (6). ■

C Growth rate of the CO_2 price

Proof of Corollary 2.
Proof. The total discounted cost should be written:

$$\begin{aligned}
\Gamma(T_l) = &\int_0^{T_l+D} e^{-rt}(c_o + p_t^{CO2})Ndt + e^{-rT_l}I + e^{-r(T_l+D)}\Omega(\bar{X}) \\
&- p_0\int_{T_l}^{T_l+D} e^{(\rho-r)t}\xi(t - T_l)dt
\end{aligned}$$

which is similar to (8) except that the second line above, the value of interim abatement, replaces $p_0\bar{X}$. The derivative of the second line with respect to T_l is (after an integration by parts):

$$-p_0 \int_{T_l}^{T_l+D} (\rho - r)e^{(\rho-r)t}\xi(t - T_l)dt = -(\rho - r)p^{CO2}_{T_l+D}e^{-r(T_l+D)} \int_0^D e^{(\rho-r)(t-D)}\xi(t)dt$$

so that the derivative of the discounted cost with respect to T_l is

$$\frac{\partial\Gamma}{\partial T_l} = e^{-r(T_l+D)} \left[(c_o + p^{CO2}_{T_l+D})N - rIe^{rD} - r\Omega(\bar{X}) - p^{CO2}_{T_l+D}(\rho - r) \int_0^D e^{(\rho-r)(t-D)}\xi(t)\right] dt$$

This derivative is equal to zero at the optimal launching date (the second order condition is satisfied) which gives equation (11). ■

The following result is proved:

Result The ending (resp. launching) CO_2 price of scenario $(\xi_\tau)_{\tau\in[0,D]}$ is increasing (resp. decreasing) with respect to ρ if $\xi(0) = 0$ and $\xi' > 0$.

Proof.

The ending CO_2 price is given by equation (11). The derivative of its denominator with respect to ρ is:

$$\begin{aligned}
&\int_0^D ((\rho - r)(D - \tau) - 1)e^{-(\rho-r)(D-\tau)}\xi(\tau)d\tau \\
= &\underbrace{\left[(D - \tau)e^{-(\rho-r)(D-\tau)}\xi(\tau)\right]_0^D}_{=0} \underbrace{- \int_0^D (D - \tau)e^{-(\rho-r)(D-\tau)}\xi'(\tau)d\tau}_{<0}
\end{aligned}$$

so the ending CO_2 price is increasing with respect to ρ.

The launching CO_2 price is:

$$p^{CO2}_{T_l^*} = \frac{rI + (r\Omega(\bar{X}) - c_0N)e^{-rD}}{Ne^{(\rho-r)D} - (\rho - r)\int_0^D e^{(\rho-r)\tau}\xi(\tau)d\tau} \tag{21}$$

The derivative of the denominator with respect to ρ is

$$\begin{aligned}
&DNe^{(\rho-r)D} - \left[\tau e^{(\rho-r)\tau}\xi\right]_0^D + \int_0^D \tau e^{(\rho-r)\tau}\xi'(\tau)d\tau \\
=&D(N - \xi(D))e^{(\rho-r)D} + \int_0^D \tau e^{(\rho-r)\tau}\xi'(\tau)d\tau > 0
\end{aligned}$$

so, the launching CO_2 price is decreasing with respect to ρ. ■

Chapter III

The Role of Learning-by-Doing in the Adoption of a New Green Technology: the case of linear LBD.

The Role of Learning-by-Doing in the Adoption of a New Green Technology: the case of linear LBD.

Alena Kotelnikova[a,b]

[a] Ecole Polytechnique
[b] Energy and Prosperity Chair

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Abstract

New green technologies are often subject to a significant learning-by-doing (LBD), i.e. production costs rapidly decline with cumulative experience. The impact of LBD on the timing and costs of emission abatement is, however, ambiguous. In addition to LBD, the convexity of the cost function plays a crucial role in defining properties of the transition towards a new green technology. This paper studies the optimal characteristics of the transition towards green vehicles in the transport sector when both LBD and convexity are present in the cost function. The partial equilibrium model of (Creti et al. 2015) is used as a starting point. For the case of linear LBD the optimal deployment trajectory can be analytically obtained. This allows to conclude that a high learning induces an earlier switch towards green cars in the case of low convexity, and a later switch in the case of high convexity. This insight is used to revisit the hydrogen mobility project in Germany. The analysis assesses impact of both convexity and LBD on characteristics of the optimal deployment, such as transition cost and investment 'death valley'. The initial exogenous deployment trajectory for H2 Mobility project is shown to be suboptimal and it would be beneficial to speed it up, notably through State support for the infrastructure deployment on the early deployment stages.

Key words: Energy transition, optimal deployment trajectory; learning-by-doing; fuel cell electric vehicles

1 Introduction

Green technologies often require initial sunk investments in physical and human capital and are subject to a significant learning-by-doing (LBD), which should be taken into account while assessing decarbonisation effort. The idea behind LBD is that initially high production cost may decline rapidly with cumulative experience in this new activity. In other words, the act of producing more goods increases the stock of cumulative experience and thus leads to decline in future cost.

The learning curve expresses the hypothesis that the unit cost decreases by a constant fraction with every doubling of cumulative production. For instance, unit cost follows the relation: $C_t = C_0(N_t/N_0)^{-l}$, in which C_t is the cost at time t, C_0 its initial cost, N_t the cumulative production at time t, N_0 the initial cumulative number of produced goods, and l the learning rate.

LBD effect on the timing of emissions abatement is however unclear. On one hand, LBD reduces the costs of future abatement. This suggests delaying abatement activities. On the other hand, there is added value to current abatement. It contributes to cumulative experience and hence helps reducing the costs of future abatement. It is unclear which of these two effects dominates (Goulder and Mathai 2000).

In addition to LBD, the convexity of the cost function plays a crucial role in defining properties of the transition towards a new green technology. Cost convexity encourages redistributing the investment in clean capital over a longer period. Bramoullé and Olson (2005) showed that without convexity, LBD alone does not justify a progressive switching to the clean option. Moreover, they show that LBD strongly affects the form of the deployment trajectory.

Fuel Cell Electric Vehicles (FCEV) are subject to a significant LBD, which is generally derived from learning curves. Different studies model FCEV cost function with a steep learning curve within national (Lebutsch and Weeda 2011), European (HyWays 2008; McKinsey 2010; Zachmann et al. 2012), and worldwide (IEA 2015) deployment contexts.

McKinsey (2010) used a combined forecasting and backcasting approach to model FCEV cost: from 2010 to 2020, global cost was forecasted, based on proprietary industry data; after 2020, on projected learning rates. The learning rate is assumed to be equal to 15%. All conclusions are shown to be robust with respect to significant variations in learning rates: by 2030, there is only a small difference in Total Cost of Ownership of FCEV and Internal Combustion Engine (ICE)-gasoline of –1 to 3 cents per kilometer even with important variation in FCEV learning rate after 2020.

Zachmann et al. (2012) adopts a slightly different methodology for FCEV cost function modelling and uses two-factor learning curves. This reflects the fact that both capacity deployment and R&D may impact the rate of technical progress and cost reduction. Learning effects come from learning-by-doing or learning-by-research. The authors use the industry assumptions on learning rates (15%) reported in (McKinsey 2010) for their modelling purposes. They use Marktmodell Elektromobilität simulation model based on discrete choice modelling to forecast the evolution of different automotive technologies on the German market. This paper does not provide details on the robustness check of the results with respect to the change in the learning rate. However, the model supposes a negative feedback loop between slow market uptake, insufficient learning-by-doing cost reductions and, hence, high fuel and purchase costs and low consumer acceptance, which would cause a far lower market penetration trajectory.

The studies described above do not explicitly introduce convexity in the FCEV cost function and treat mostly learning effect, which is certainly very important in FCEV cost reduction. This study aims to analyse the characteristics of the optimal deployment and studies a mutual impact of both convexity and learning. The case of a linear LBD cost function allows a complete analytical characterization of the deployment trajectory and, notably, defining the transition launching date and its duration. The partial equilibrium model of (Creti et al. 2015b) is used as a starting point.

The analysis shows that a high learning induces an earlier switch towards green cars in the case of low convexity and suggests delaying deployment of green cars in the case of high convexity. A higher learning also lowers the corresponding deployment cost.

This insight is used to revisit the hydrogen mobility deployment project in Germany. In the initial model of Creti et al. (2015a) the deployment trajectory was exogenously determined. We show that it would be beneficial to speed it up.

The paper is structured as follows. Section 2 recalls the partial equilibrium model of Creti et al. (2015b). It also introduces the case of linear LBD cost function and studies the impact of LBD on the shape of the optimal deployment trajectory and its characteristics. A simple numerical illustration is used to obtain the impact of LBD on the transition cost. Section 3 revisits the H2 Mobility project in Germany. Section 4 concludes.

2 The Creti et al. model revisited

This section aims to evaluate impact of both convexity and LBD on the characteristics of optimal deployment trajectory within the setting of partial equilibrium model of Creti et al. (2015b) and to obtain an analytical solution for the case of a linear LBD cost function.

2.1 Assumptions and analytical model

Let us briefly recall the original (Creti et al. 2015b) model. A car market of a constant size N is composed of two types of vehicles: mature polluting technology, represented by Internal Combustion Engine (ICE) gasoline vehicles, and carbon free technology, represented by Fuel Cell Electric Vehicles (FCEV). Units are normalized so that each gasoline car emits one unit of CO_2, while green cars do not pollute. At the date t there are x new green cars and $N-x$ polluting cars. The polluting cars have a constant cost of c_o, while the cost of x green cars $C(X,x)$ is subject to learning-by-doing, in which $X_t = \int_0^t x_t dt$ is a knowledge capital. The cars lifetime is supposed to be one unit of time.

The cost of green cars $C(X,x)$ is assumed twice differentiable and positive. It is null for $x=0$, for all X: $C(X,0)=0, \forall X$, and strictly positive otherwise. The cost is increasing and convex with respect to x, the quantity of green cars produced. Knowledge reduces the production cost and this effect is lower for larger knowledge stock. The marginal production cost also decreases with knowledge. All these assumptions translate formally: $C_x \geq 0, C_X \leq 0, C_{xx} > 0$ and $C_{Xx} \leq 0$.

The gradual substitution of the polluting vehicles by the green ones is due to an exogenously growing CO_2 price. The price of CO_2 is p_t^{CO2}, and it grows at the speed of the discount rate r: $p_t^{CO2} = e^{rt}p_0$ with $p_0 > 0$. This means that once discounted a CO_2 emissions has the same value whatever the date at which it is emitted. This assumption simplifies the dynamic analysis.

2.2 Properties of the optimal deployment scenario

The objective of the social planner is to minimize the discounted cost of operating a fleet of N cars over time:

$$\Gamma = \int_0^{+\infty} e^{-rt} \left[(p_t^{CO2} + c_o).(N - x_t) + C(X_t, x_t) \right] dt \tag{1}$$

$$s.t.$$

$$\dot{X}_t = x_t$$
$$0 \leq x_t \leq N$$

This optimization problem determines the optimal deployment trajectory for the new green vehicles. The optimal trajectory is a smooth transition in which green cars progressively replace polluting cars. Initially the fleet is entirely composed of polluting cars. At the end of the transition the fleet is completely green (see Lemma 1 in Creti et al. 2015b).

Denote respectively T_s and T_e the starting and ending dates of the transition. The optimal deployment trajectory during the transition period is defined by the system of first order conditions associated to the Lagrangian for (1) and takes the form of the following second order differential equation (see proof in the Appendix):

$$C_{xx}\ddot{X}_t + C_{xX}\dot{X}_t - rC_x - C_X + rc_o = 0 \tag{2}$$

The optimal trajectory satisfies therefore the following fundamental equation:

$$p_t^{CO2} = \underbrace{[C_x(X_t, x_t) - c_o]}_{\text{static abatement cost}} + \underbrace{\int_t^{+\infty} e^{-r(\tau - t)} C_X(X_\tau, x_\tau) d\tau}_{\text{learning benefit } (< 0)} \tag{3}$$

According to this equation, at a time t the price of CO_2 should be equal to the sum of two terms: first, the "static" marginal abatement cost, that is the difference between the cost of the marginal green car and an old car; second, the learning benefit (which is negative), that is the reduction of future cost due to the production of one more green car today. Thus, the relevant marginal abatement cost at a particular date should take into account the whole trajectory.

In the case of suboptimal trajectory (see subsection 3), a subsidy can be introduced during early deployment stages to support the deployment of zero-emission cars. The optimal subsidy S can be directly derived form (3) in order to internalize long-term learning and environmental benefits, which often are not considered by short-term profit maximizing companies. It should be equal to the second component, which is learning benefit.

It can be seen that LBD affects two components of equation (3) in opposite directions. On one hand, an increase in X triggers a decrease in $C_x(X_t, x_t)$, which is positive. This means that within any conditions being equal x should decrease to equilibrate the static abatement cost component. On the other hand, an increase in X triggers an increase in $C_X(X_\tau, x_\tau)$, which is negative. Thus x should increase in order to equilibrate the learning benefit component of equation (3). These two effects of comparative statistics produce a contradictory impact and it is not possible to conclude on the impact of LBD within general setting. This ambiguity, which was first defined in (Goulder and Mathai 2000), is usual in this type of models.

The contribution of this paper is to uncover this ambiguity in the case of a particular cost function. In the following subsections we solve model of Creti et al. (2015b) for the case of a linear LBD cost function and obtain analytical expressions for the transition cost (Γ), the launching date (T_s) and the transition duration (D) as the LBD varies in the case of linear LBD.

2.3 Optimal deployment characteristics in the case of the linear LBD

The model setting of Creti et al. (2015b) can be analytically solved for the case of a linear LBD cost function, which is defined as:

$$C(X, x) = ax_t + \frac{1}{2}bx_t^2 - cX_t x_t \tag{4}$$

This cost function accounts for both effects of learning and convexity and follows the intuition behind green cars deployment. At the beginning of the deployment, when the cumulated experience X is small, the related weight of the convexity parameter b is high and therefore the corresponding rate of the deployment is slow. The impact of the convexity parameter diminishes with growing X (when X is large the FCEV cost is small with respect to c_o) and the corresponding rate of the deployment increases. These properties are in line with characteristics of exogenous deployment trajectory studied in (Creti et al. 2015). The convexity parameter is more associated to the cost of infrastructure deployment, while the learning parameter to the vehicle cost.

In the case of the linear LBD cost function the second order differential equation (2), which defines the optimal deployment trajectory, can be analytically solved. The solution to identify the characteristics of the optimal deployment combines three steps. First, we define the number of deployed green cars x_t as a function of T_s. Second, the expression for the transition duration D is obtained. Finally, we derive an analytical expression for the launching date T_s. Complex analytical expressions can be simplified in the case of a sufficiently small c and the solution is shown to be continuous in the case of no learning ($c = 0$).

Let us first define the shape of the optimal deployment trajectory x_t as a function of T_s. For cost function (4), equation (2), which defines the optimal deployment trajectory, takes the form of:

$$\ddot{X}_t - r\dot{X}_t + \frac{rc}{b}X_t = \frac{r(a-c_0)}{b} \tag{5}$$

For $0 < c < \frac{rb}{4}$, the solution of this equation is a sum of two exponential functions:

$$X_t = C_1 e^{\alpha t} + C_2 e^{\beta t} + \frac{a-c_0}{c} \tag{6}$$

where $\alpha = \frac{1}{2}r(1-\sqrt{1-\frac{4c}{br}})$ and $\beta = \frac{1}{2}r(1+\sqrt{1-\frac{4c}{br}})$. Note that $\alpha\beta = \frac{rc}{b}$ and $\beta - \alpha = r\sqrt{1-\frac{4c}{br}}$. The existence of the analytical solution is therefore constrained by $c < \frac{br}{4}$.

The optimal trajectory and cumulative experience during the transition are defined in the following Lemma:

Lemma 1 *The cumulative experience and the optimal deployment trajectory of green cars during the transition are respectively:*

$$X_t = \frac{a-c_0}{c(\beta-\alpha)}(\alpha e^{\beta(t-T_s)} - \beta e^{\alpha(t-T_s)} + 1) \tag{7}$$

$$x_t = \frac{a-c_0}{c}\frac{\alpha\beta}{\beta-\alpha}(e^{\beta(t-T_s)} - e^{\alpha(t-T_s)}) \tag{8}$$

Proof. The constants C_1 and C_2 in the expression (6) can be obtained by solving the system of linear equations for the trajectory conditions at the beginning of deployment: $\dot{X}_{T_s} = x_{T_s} = 0$ and $X_{T_s} = 0$. The solution of the corresponding system results in $C_1 = -\frac{a-c_0}{c}\frac{\beta}{\beta-\alpha}e^{-\alpha T_s}$ and $C_2 = \frac{a-c_0}{c}\frac{\alpha}{\beta-\alpha}e^{-\beta T_s}$. Once these values are introduced into (6) this gives (7). Applying to (7) the fact that $x_t = \dot{X}_t$ results in (8). ■

Using Lemma 1, the marginal production cost at the end of the deployment is $C_x(X_D, N) = a + bN - cX_D$. The difference in marginal production costs between FCEV and ICE is therefore equal to

$$C_x(X_D, N) - c_o = \frac{a-c_0}{\beta-\alpha}(\beta e^{\alpha D} - \alpha e^{\beta D}) + bN \tag{9}$$

This expression can be simplified in the case of a sufficiently small c. If c is sufficiently small, then $\alpha \simeq \frac{c}{b}$ and $\beta \simeq r - \frac{c}{b} = r - \alpha$. In this case the expression below turns to $C_x(X_D, N) - c_o = a - c_0 + bN$, which is always positive for $a > c_0$. In this case the marginal production cost at the end of deployment $C_x(X_D, N)$ is, therefore, positive at all times and we assume that there is no further LBD after some given cumulative experience $\overline{X}$:

$$C_x(X_D, N) > 0 \tag{10}$$

The optimal trajectory can be isolated from the CO_2 price. Indeed, the optimal trajectory does not depend on the CO_2 price and grows exponentially according to the equation (3). The CO_2 price defines the starting date. This means that for two different CO_2 prices p_0 the deployment will start at two different dates; however, the corresponding deployment trajectories will be the same.

Let us now obtain analytical expressions for characteristics of the optimal deployment such as duration D and launching date T_s. Assume that the deployment lasts for D years ($D = T_e - T_s$). D and T_s are such that:

Lemma 2 *The duration D and the launching date T_s are respectively:*

$$e^{\beta D} - e^{\alpha D} = \frac{cN}{a - c_0}\frac{\beta - \alpha}{\alpha\beta} \tag{11}$$

$$e^{rT_s}p_0 = \frac{a - c_0}{\beta - \alpha}(\beta e^{-\alpha D} - \alpha e^{-\beta D}) - cN\frac{e^{-rD}}{r} \tag{12}$$

Proof. At the end of the deployment the fleet is completely green $x_{T_e} = N$. Introducing this condition into the optimal trajectory (8) gives $e^{\beta D} - e^{\alpha D} = \frac{cN}{a-c_0}\frac{\beta-\alpha}{\alpha\beta}$ and defines the optimal duration (9).

The CO_2 price at the beginning of the deployment T_s is defined by (3): $e^{rT_s}p_0 = C_x(0,0) - c_o + \int_{T_s}^{+\infty} e^{-r(\tau-T_s)}C_X(X_\tau, x_\tau)d\tau =$
$= a - c_o - c\int_{T_s}^{T_e} e^{-r(\tau-T_s)}x_t d\tau - c\int_{T_e}^{+\infty} e^{-r(\tau-T_s)}N d\tau =$
$= a - c_o - c\frac{a-c_0}{c}\frac{\alpha\beta}{\beta-\alpha}\int_{T_s}^{T_e} e^{-r(\tau-T_s)}(e^{\beta(t-T_s)} - e^{\alpha(t-T_s)})d\tau - cN\int_{T_e}^{+\infty} e^{-r(\tau-T_s)}d\tau =$
$= a - c_o - (a - c_0)\frac{\alpha\beta}{\beta-\alpha}\int_{T_s}^{T_e}(e^{(\beta-r)(\tau-T_s)} - e^{(\alpha-r)(\tau-T_s)})d\tau - cN\int_{T_e}^{+\infty} e^{-r(\tau-T_s)}d\tau =$
$= a - c_o - (a - c_0)\frac{\alpha\beta}{\beta-\alpha}(\frac{1}{\beta-r}(e^{(\beta-r)D} - 1) - \frac{1}{\alpha-r}(e^{(\alpha-r)D} - 1)) - cN\frac{e^{-rD}}{r}$
Using the fact that $\beta \simeq r - \alpha$ and $\alpha \simeq r - \beta$
$e^{rT_s}p_0 = \frac{a-c_0}{\beta-\alpha}(\beta e^{-\alpha D} - \alpha e^{-\beta D}) - cN\frac{e^{-rD}}{r}$ ■

The complex expressions for characteristics of the optimal deployment trajectory defined in Lemma 2 can be simplified in the case of a sufficiently small c. In the case of a sufficiently small c, expression (11) and (12) turn to

$$D \simeq \frac{bN}{r(a - c_0)} \tag{13}$$

$$e^{rT_s}p_0 \simeq a - c_o - c\frac{N}{r}(1 - rD) \tag{14}$$

Let us show that the solution is continuos in the case of no learning ($c = 0$). If $c = 0$ the cost function (4) takes the form of $C(x) = ax_t + b/2x_t^2$. The launching date is directly defined by (3) and is equal to $e^{rT_s}p_0 = C_x(0) - c_o = a - c_o$. It is straightforward to see, that for $c = 0$ expression (14) takes the same form. The ending date directly defined by (3) is $e^{rT_e}p_0 = C_x(N) - c_o = a + bN - c_o$. The duration of the transition is therefore $e^{rD} = e^{r(T_e-T_s)} = \frac{a-c_o+bN}{a-c_o} = 1 + \frac{bN}{a-c_o}$. For small r, this expression turns to $D \simeq \frac{bN}{r(a-c_0)}$ and coincides with (13). This proves that the solution is continuous at $c = 0$.

Let us finally evaluate the interaction between convexity and learning effects and its impact on the optimal deployment trajectory. The following proposition describes the behavior of characteristics of the optimal deployment trajectory with respect to the variation of the learning parameter:

Proposition 1 *A higher learning induces an earlier transition towards green vehicles in the case of a low convexity of the cost function (*$0 < b < \frac{a-c_o}{N}$*). In the case of a high convexity (*$b > \frac{a-c_o}{N}$*), the higher learning, the later launch of the optimal deployment trajectory.*

Proof. As can be directly seen from (9.2), the learning parameter does not affect the approximative expression for the transition duration: $\frac{dD}{dc} = 0$.

Introducing (9.2) into (10.2) gives $\frac{dT_s}{dc} = -\frac{N}{r}(1 - \frac{bN}{a-c_o})$. This expression is negative for $b < \frac{a-c_o}{N}$ and positive otherwise. This means that for $b < \frac{a-c_o}{N}$, a higher learning results in an earlier launching date. For $b > \frac{a-c_o}{N}$, the higher the learning, the later the start of the optimal deployment trajectory. ■

The result above can be compared with the results obtained by Bramoulle and Olson (2005). The authors develop an analytical model of pollution abatement across different technologies to achieve a target level of abatement by some specific future date. Each technology is characterized by LBD and the costs of abatement decline as experience with the technology increases. Technologies are heterogeneous in two ways: with respect to costs of abatement and rate at which costs decline with experience. The authors examine how LBD affects the allocation of pollution abatement between heterogeneous technologies over time.

Bramoulle and Olson (2005) analyze the general case where marginal abatement costs are increasing in abatement. For the case of convex abatement cost and the abatement with one technology,cumulative abatement is postponed as LBD parameter increases. Also, LBD strongly affects the shape of optimal abatement trajectory: the optimal abatement is usually convex in time when there is low or high learning, but it might become concave for intermediate levels of learning. This finding is in line with Proposition 1 and highlights the fact that the characteristics of the optimal trajectory depend both on convexity and learning parameters. Fig 2 on page 1946 shows that the higher learning α, the sharper the optimal abatement trajectory $a(t)$. This result is consistent with our findings, showing that the higher learning c induces a sharper deployment trajectory for the green cars $x(t)$.

2.4 Numerical illustration

This subsection aims to develop numerical simulations to quantify the impact of the learning parameter on characteristics of the optimal deployment as defined in subsection 2.3. We quantify the impact in the case of different values of the convexity parameter above and below its critical value as defined in Proposition 1.

We analyze the characteristics of the optimal deployment trajectory in two cases: (i) low convexity $b < \frac{a-c_o}{N}$; and (ii) high convexity $b > \frac{a-c_o}{N}$. We notably evaluate numerically the impact of LBD on the cost of the transition (1). This point was not treated in the previous subsection due to the complexity of the corresponding analytical expression.

The cost of the transition is computed in the following way. As is showed in (1), the cost of the transition is equal to a discounted sum of the costs related to the operation of polluting cars (production and emissions costs) and green cars (production costs, which decrease with cumulative experience). A fleet of green cars is supposed to have a linear LBD cost function (4). In this numerical example, we introduce $\overline{X}$, which defines the limit of learning, and is chosen in such a way that the cumulative experience X attains $\overline{X}$ after the end of deployment (after x attains N) for all possible values of c. The cost of transition is equal to the sum of the total discounted cost of the transition at the date when X attains $\overline{X}$ plus the cost of the stabilized stage (after X attains $\overline{X}$) discounted at infinity. Note that the interval for possible values of learning parameter c is restricted by constraints related to existence of the solution for the differential equation (7), and a positive launching date (12).

The numeric illustrations analyzed below are obtained for the parameters inspired by the earlier technical report for the H2 Mobility project in Germany (Creti et al., 2015a). The 'Energy concept' plan of the German government targets FCEV achieving 4% of German projected vehicle fleet in 2030. This trend is projected to decarbonise 10% of the total German car fleet in 2050: namely 7.5 million of FCEV in 2050 ($N = 10$).The price a pollutant car is in the range between 20 and 30 thousand euros ($c_0 = 30$), while the cost for a hydrogen substitute vehicle, on the example of Toyota Mirai on the German market, was announced around 66 thousand ($a = 66$). The normative cost of carbon as expressed in Quinet (2009 and 2013) is around 30 euros per ton in 2015 ($p_0 = 30$). The discount rate is 4% ($r = 0.04$).

Let us now analyse cases of low and high convexity b and quantify impact of LBD on characteristics of the optimal deployment.

2.4.1 Low convexity

From Proposition 1 we know that in the case of low convexity ($0 < b < \frac{a-c_o}{N}$), a higher learning induces an earlier transition towards green vehicles. In our numerical example the critical value for the convexity parameter is $b = \frac{a-c_o}{N} = 3.6$. Let us consider the case of low convexity $b = 3$. In this case possible values of c are from the interval of $(0; 0,03)$.

The following table provides comparative statistics for this numerical example:

c	0,001	0,005	0,03
T_s	5	5	4
D	15	15	15
Γ	17,612	17,518	16,904

Table 1 Comparative statistics for the change in the learning parameter in the case of low convexity

As can be seen from the table above, the higher the learning parameter the earlier the launching date is. This is in line with theoretical results described in the previous section. It can also be seen that the higher the learning parameter, the lower the associated cost of the deployment. However, variations are extremely small.

Interest of low convexity case is, however, limited because of small possible values for learning. LBD is limited by the constraint related to the existence of second order differential equation (2), which defines the optimal deployment trajectory. Let us examine in details the case of high convexity in order to be able to consider higher learning, which is characteristic for the FCEV technology.

2.4.2 High convexity

From Proposition 1 we know that in the case of high convexity ($b > \frac{a-c_o}{N}$), a higher learning induces a later transition towards green vehicles. Let us consider the case of high convexity $b = 10$. In this case possible values of c are from the interval of $(0; 0, 09)$.

The optimal deployment trajectory with respect to the learning parameter is represented in the following figure:

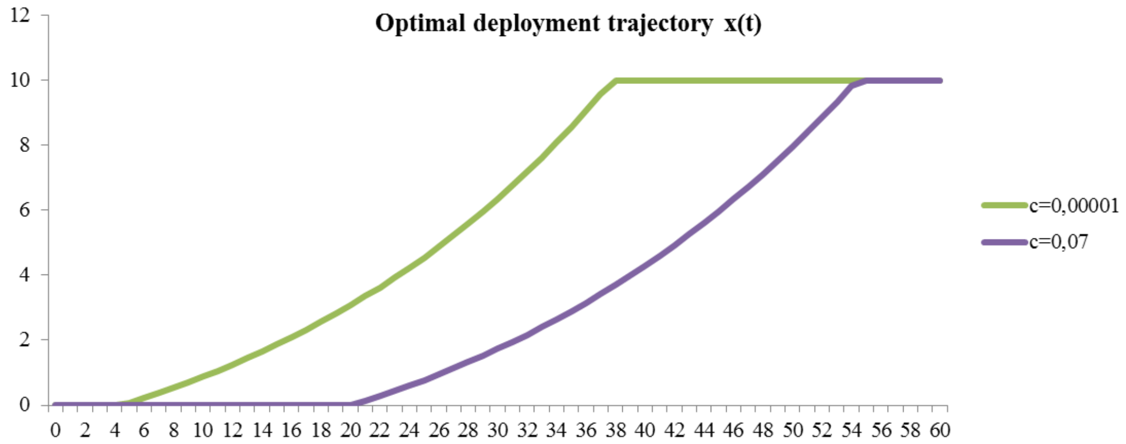

Figure 1: Optimal deployment trajectory with respect to the LBD parameter in the case of high convexity ($b = 10$)

The following table provides comparative statistics for this numerical example:

c	0,01	0,02	0,07
T_s	8	11	21
D	33	33	33
Γ	46,897	46,827	46,721

Table 2 Comparative statistics for the change in the LBD parameter in the case of high convexity

It can be seen that in the case of high convexity the higher LBD, the later transition launching date is. This confirms the findings of Proposition 1. In the case of high convexity, the effect of future cost reduction due to LBD dominates the effect of its contribution to the cumulative experience and hence suggests delaying abatement activities.

Learning has no impact on the duration of the transition, as was expected in (13).

The table above indicates that the higher learning, the lower the associated cost of the transition, however, its impact is still small. The following figure represents the profile of the cash flow for the transition cost through time with respect to the learning parameter:

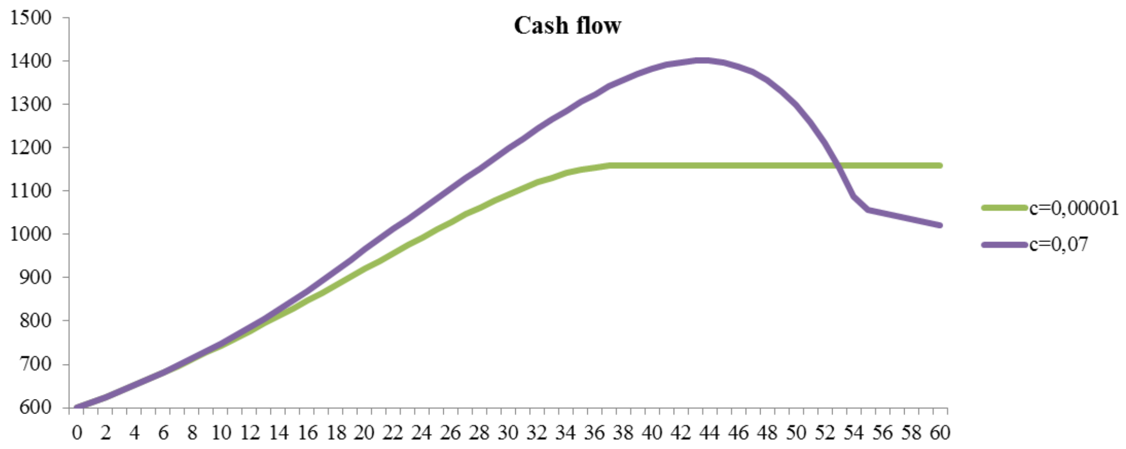

Figure 2: Cash flow with respect to the LBD parameter in the case of high convexity ($b = 10$)

A higher learning parameter results in a higher associated cost during the second decade of the deployment trajectory which is, however, compensated by a lower cost during stabilized period. Therefore, the total cost of the transition is lower for higher values of learning parameter. This numerical intuition is in line with findings of (Manne and Richels 2004), who develop an intertemporal general equilibrium model (MERGE) of the global economy, which provides a bottom-up perspective of the energy supply. While focusing on the timing and the costs of emissions abatement, the authors find that LBD can substantially reduce (by 40-70%) the total cost of emission abatement.

In our simulation the impact of the learning on the transition cost is extremely low because of difference in modelling approaches. While model of (Manne and Richels 2004) is constrained by a particular ceiling on atmospheric CO_2 concentration, our model (Creti et al. 2015b) integrates the pathway of exogenously growing CO_2 price. A large part of learning advantage, which is particular important at the end of the deployment is compensated by a relatively high external CO_2 price.

3 Application for the H2 Mobility project in Germany

Theoretical results described above give some useful insights for industrial projects of hydrogen mobility deployment. Industrial literature on FCEV mainly studies learning effect and omits convexity in its explicit form. It previous subsections it was shown that there is an interaction between convexity and LBD, which can change the way they impact the optimal deployment trajectory. In the case of linear LBD, the convexity parameter accounts more for the infrastructure part of hydrogen mobility deployment, while learning for vehicle cost reduction. In two following subsections we quantify impact of both convexity and learning on characteristics of the optimal deployment trajectory for the H2 Mobility project in Germany.

The H2 Mobility project in Germany is a public private partnership,which aims to ensure synchronized ramp-up of hydrogen stations and vehicle deployment on the national territory. The corresponding model is detailed in (Creti et al. 2015a). The deployment trajectory is defined exogenously and is based on industry forecast (Shell, 2009; McKinsey 2010). It starts in 2015 with 1 thousand FCEV and progressively ramps up to 7.5 million FCEV in 2015. The cost function is composed of three components: car manufacturing cost, infrastructure investment and fuel cost. First, car manufacturing cost is subject to a classical learning curve as in (IEA 2015; Zachmann et al. 2012; Lebutsch and Weeda 2011; Schoots, Kramer, and van der Zwaan 2010; HyWays 2008). Second, infrastructure investment follows the exogenous trajectory of vehicle deployment in order to satisfy the expanding demand for hydrogen. Third, the fuel cost is derived from projections for energy efficiency of both FCEV and ICE and corresponding fuel prices (IEA 2013). There is no explicit convexity parameter in the initial cost function, it is nevertheless embedded in exogenously defined deployment trajectory. The learning parameter is introduced for each cost component and calibrated according to applied studies and interviews with industry experts.

The technical report (Creti et al. 2015a) concludes on a reasonable range for H2 Mobility abatement cost which varies from 50 to 60 euros per ton of CO_2 abated. These results are robust with respect to a large set of scenarios, and notably to the dominant technological choice for a decarbonized hydrogen production and to assumptions on the learning parameter for hydrogen production and infrastructure deployment. The results are however sensitive with respect to the learning parameter for the FCEV manufacturing cost.

3.1 Impact of learning on characteristics of the deployment trajectory

This section provides a more detailed analysis of the transition cost for the social planner compared to the original study (Creti et al. 2015a) and evaluates impact of the learning parameter of the cash flow profile, and notably on the deepness of the investment 'death valley'. The 'death valley' is a negative cash flow during initial deployment stages, which discourages private investors and reinforces first-mover disadvantage to unlock new business opportunities.

The analytical model developed in subsection 2.3 and intuition obtained for numerical simulations analyzed in subsection 2.4 provide an interesting framework for a more rigorous analysis of the impact of the learning parameter on the cost of transition towards hydrogen mobility in Germany. In the theoretical setting of the linear LBD cost, the learning has no impact on the transition duration and only affects the launching date. According to Proposition 1 and numerical illustration 2.4, we expect higher learning to reduce the associated transition cost.

The learning parameter l for FCEV manufacturing cost varies between 0.10 for base case scenario and 0.12 for very high learning rate scenario. The following figure represents the evolution of FCEV manufacturing cost compared to ICE cost projection:

Depending on the learning parameter FCEV manufacturing cost in the long term reaches or stays above the ICE manufacturing cost. Even a slight change in the learning parameter has an important impact on the cash flow profile (note that in this section we talk about transition-related benefit and not the cost):

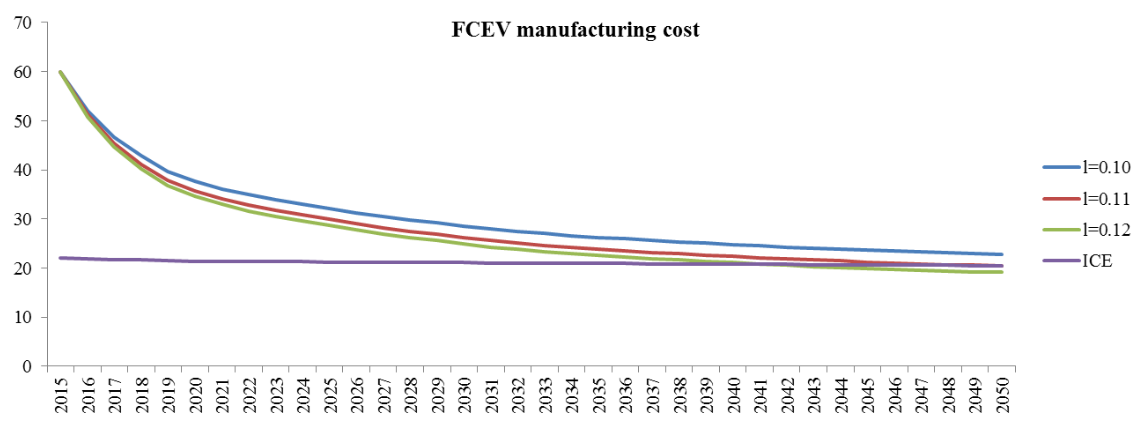

Figure 3: FCEV manufacturing cost with respect to the LBD parameter for the H2 Mobility project in Germany

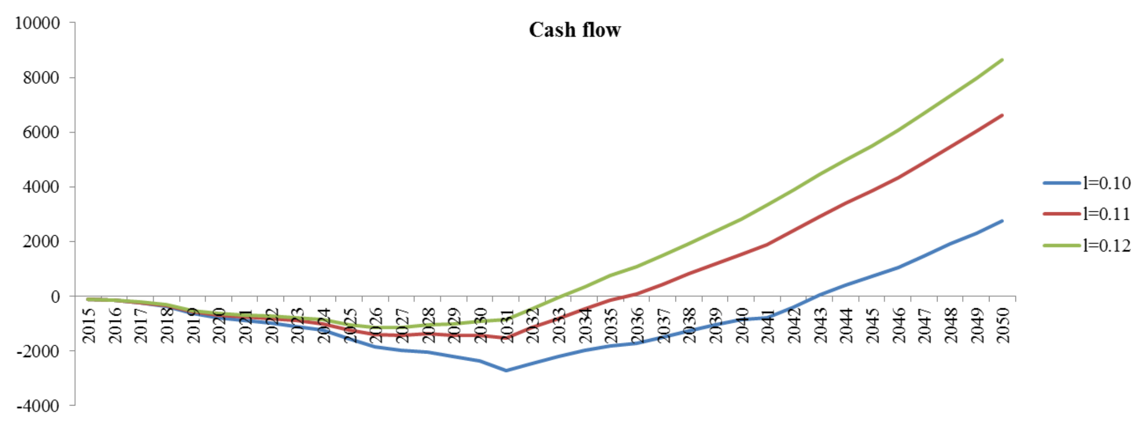

Figure 4: Cash flow with respect to the LBD parameter in for the H2 Mobility project in Germany

As can be seen from the figure above a higher learning parameter diminishes the deepness of the 'death valley' and reduces its duration. The deepness of 'death valley' is calculated as total discounted cost of the period with a negative cash flow. The discount rate is 4%. The following table provides comparative statistics for this numerical simulation:

l	0.10	0.11	0.12
NPV from 2014 to 2050	-17 511	2 112	12 564
Deepness of death valley	20 313	11 089	8 042
Duration of death valley	27 years	19 years	16 years

Table 3 Comparative statistics for the change in the LBD parameter for the H2 Mobility project in Germany

Indeed, 1% higher learning makes the H2 Mobility project profitable and halves the associated deepness of 'death valley' while reducing its duration. This finding confirms the results obtained above: a higher learning reduces the associated transition cost and creates incentives to start the transition towards hydrogen mobility earlier. Indeed, the higher learning, the lower the transition cost and the corresponding dynamic CO_2 price. The lower this dynamic CO_2 price of the H2 Mobility project, the earlier the date when the exogenously growing CO_2 price reaches this value.

The deployment of zero-emission cars can be supported by the social planner through optimal subsidy S during initial deployment stage. The optimal subsidy can be directly derived form (3) in order to internalize long-term learning and environmental benefits, which often are not considered by short-term profit maximizing companies. The optimal subsidy per vehicle is calculated in a way to compensate negative cash flow:

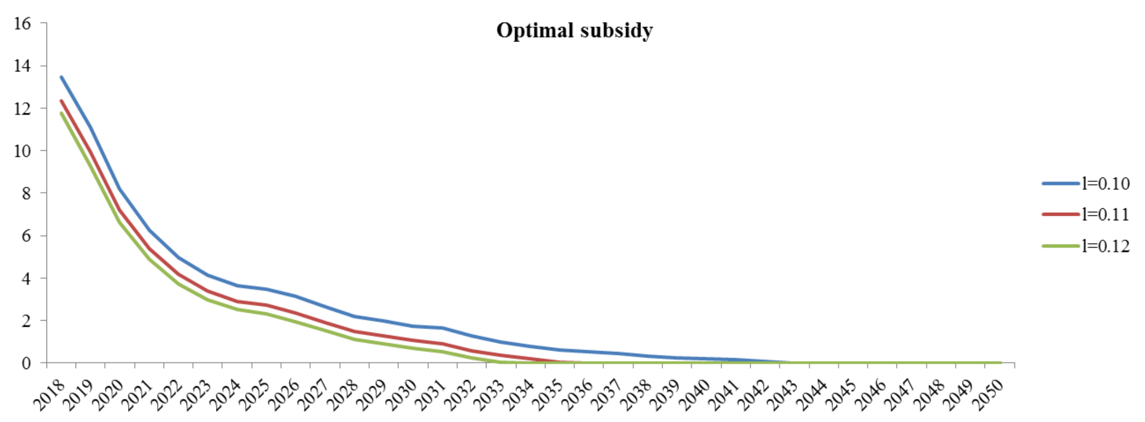

Figure 5: Optimal subsidy per vehicle with respect to the LBD parameter for the H2 Mobility project in Germany

The subsidy starts at level of $12 - 13,000$ euros per vehicle and drops by approximately 20% every year. This range is constituent with the level of subsidies for zero-emission vehicle available in California ($11,000$ euros per vehicle), Japan ($11,800$ euros per vehicle) or Sweden ($6,300$ euros per vehicle). During the first three years the optimal subsidy per vehicle according to this methodology should be extremely high due to a very limited number of vehicles deployed and so small environmental advantage. However, this extra cost for a very few vehicles can be co-financed by car manufacturers developing and deploying zero-emission vehicles.

3.2 The exogenous trajectory revisited

This subsections aims using theoretical results of Section 2 to challenge exogenously defined deployment trajectory analyzed in the earlier work of Creti et al. (2015a). Is the chosen trajectory suboptimal? Would it be optimal to accelerate the deployment?

The convexity parameter which has an important influence on the transition duration is more linked to the infrastructure ramp up rather then to the learning effect of vehicle cost reduction. Let us study the impact of a lower convexity and a shorter duration on the deployment characteristics, an notably on the deployment cost. It can be directly seen from (13) that a higher convexity increases the transition duration and encourages redistributing the investment in clean capital over a longer period.

Let us evaluate two alternative scenarios: initial base case scenario ($Ts = 2015; D = 35$) and scenario in which deployment is 10 years shorter ($Ts = 2015; D = 25$). The border conditions for (8) are verified for all scenarios: the deployment starts at zero and stabilizes once it achieves N (7.5 million FCEV in this example):

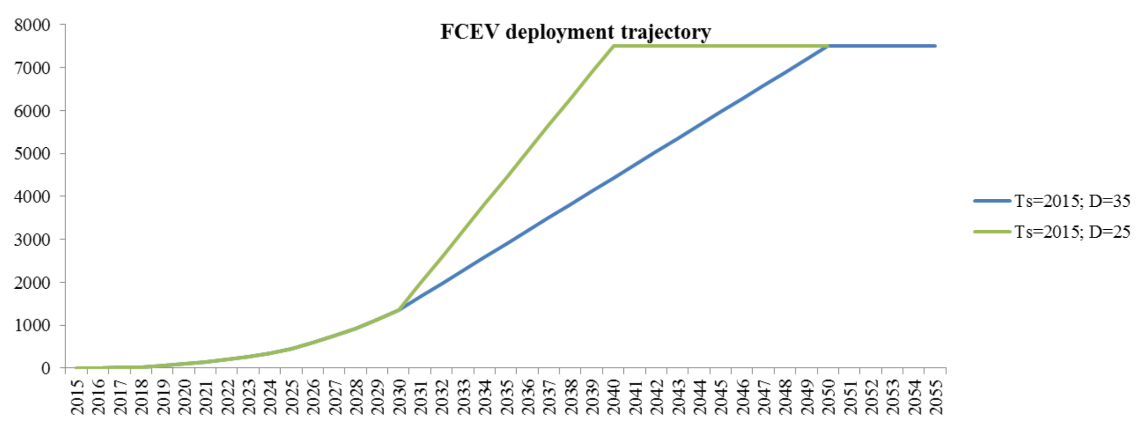

Figure 6: Deployment trajectories analyzed within H2Mobility model

The corresponding cash flows for these two scenarios are represented in the following figure:

As can be seen from the figure above the duration of the negative cash flow is shorter in the accelerated scenario, however, the investment 'death valley' is also deeper. The following table provides comparative statistics for this numerical simulation:

Deployment trajectory	$Ts = 2015; D = 35$	$Ts = 2015; D = 25$
NPV from 2014 to 2050	-17 511	-10 333
Deepness of death valley	20 313	23 490
Duration of death valley	27 years	19 years

Table 4 Comparative statistics for different deployment trajectories within the H2 Mobility project in Germany

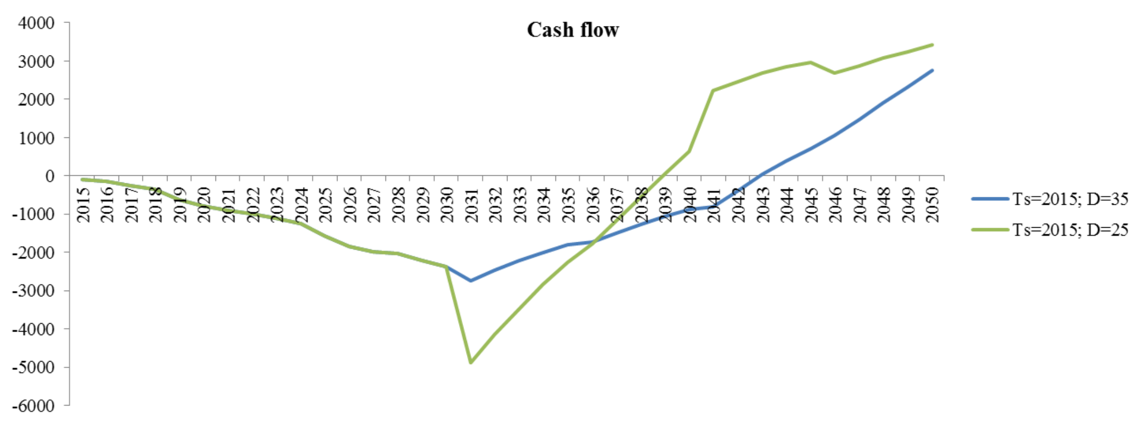

Figure 7: Cash flow for different deployment trajectories within the H2 Mobility project in Germany

A ten years faster deployment makes the 'death valley' 16% deeper. It significantly reduces, however, duration of negative cash flow. Moreover, it more then halves the corresponding transition cost.

Deployment acceleration does not significantly affect the optimal subsidy profile:

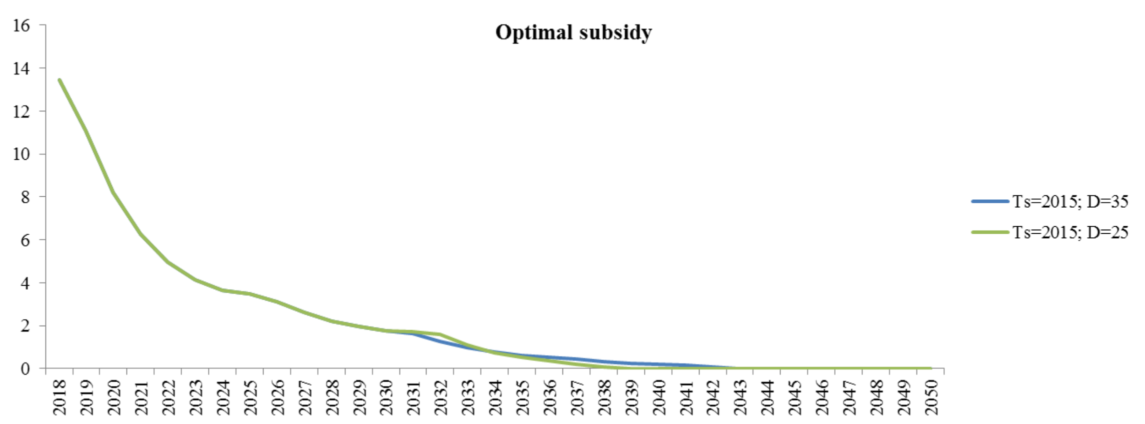

Figure 8: Optimal subsidy per vehicle for different deployment trajectories within the H2 Mobility project in Germany

The time period necessary for the optimal subsidy is two years longer in the accelerated scenario because of a deeper corresponding 'death valley'. However, the impact of the scenario acceleration on the total policy envelope is very small: total discounted subsidy for the total vehicle fleet in the accelerated scenario is only 4% higher. This means that the base case scenario chosen for hydrogen mobility deployment in Germany (based on car manufacturers' input) is suboptimal and there is an economic interest to accelerate the transition.

It can be seen that there is an economic interest to reduce the duration of the deployment. It can be done by reducing the impact of the convexity parameter and supporting infrastructure deployment. Indeed, insufficiently fast infrastructure ramp-up would slow down the hydrogen mobility deployment. This issue can be tackled through creation of State subsidy program for alternative infrastructures or through Public-Private Partnerships aiming to ensure a early stage infrastructure deployment.

4 Conclusion

This work contributes to clarify the impact of learning parameter and its interaction with convexity in the cost function in the case of a new green technology deployment. This paper introduces a linear LBD cost function, which explicitly accounts for convexity and learning, and allows analytical characterisation of a transition towards green vehicles in the transport sector. In this case a solution of the second order non-homogeneous differential equation, which defines the optimal deployment trajectory for green vehicles is analytically obtained. This simple form of the cost function also allows deriving analytical expressions for the characteristics of the optimal trajectory, such as transition duration and its launching date.

In the case of linear LBD, the convexity parameter accounts more for the state of infrastructure deployment, while the learning parameter for vehicles cost. This cost function follows the intuition behind green cars deployment. At the beginning of the deployment, when the cumulated experience is small, the convexity effect is important and slows the deployment of green vehicles. This impact diminishes with time and more important cumulated experience and accelerates the corresponding rate of vehicle deployment during late stages.

Within a partial equilibrium model of the earlier paper (Creti et al. 2015) framework, it was shown that for high values of convexity parameter, high learning induces a later transition toward green cars. In this case the effect of future cost reduction due to LBD dominates the effect of its contribution to the cumulative experience and hence suggests delaying abatement activities.

This paper also develops several numerical illustrations to quantify impact of learning and its interaction with convexity in the cost function. Obtained insights are used to revisit the H2 Mobility project in Germany: a high learning lowers the corresponding deployment cost and reduces deepness and duration of the 'death valley'. It was also shown that the exogenously defined scenario for H2 Mobility project is suboptimal and there is an economic interest to accelerate the deployment of FCEV. The convexity effect is shown to be extremely important and in order to account for it State is encouraged to support infrastructure deployment through subsidies programs or public-private partnerships during early deployment stages of hydrogen mobility.

The main limitation of this work is that the conclusions of this paper is developed for the case of linear LBD and may not however hold for other types of cost functions.

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6 Appendix

Proof for the equation (2) for the optimal deployment trajectory:

The objective of the social planner is to minimize the cost:

$$\Gamma = \int_0^{+\infty} e^{-rt} \left[(p_t^{CO2} + c_o).(N - x_t) + C(X_t, x_t) \right] dt$$

$$s.t.$$

$$\begin{array}{rcl} \dot{X}_t = x_t & \qquad\qquad & \lambda_t \\ 0 \leq x_t \leq N & & \theta_t, \delta_t. \end{array}$$

where λ_t are the Lagrange coefficients associated to each constraint.

For $0 < x_t < N$, using Pontryagin maximization principle we obtain
$0 = x_t - \dot{X}_t$
$0 = \lambda_t(x_t - \dot{X}_t)$
$0 = \int_0^{+\infty} e^{-rt}\lambda_t(x_t - \dot{X}_t)dt$
In this case the associated Lagrangian is
$L = \int_0^{+\infty} e^{-rt} \left[(p_t^{CO2} + c_o).(N - x_t) + C(X_t, x_t) \right] dt - \int_0^{+\infty} e^{-rt}\lambda_t(x_t - \dot{X}_t)dt$
$L = \int_0^{+\infty} e^{-rt} \left[(p_t^{CO2} + c_o).(N - x_t) + C(X_t, x_t) - \lambda_t x_t \right] dt + \int_0^{+\infty} e^{-rt}\lambda_t\dot{X}_t dt$

Let us consider the second integral and integrate it by parts
$\int_0^{+\infty} e^{-rt}\lambda_t\dot{X}_t dt = \lim\limits_{t\to+\infty} e^{-rt}\lambda_t X_t - \lambda_0 X_0 - \int_0^{+\infty}(e^{-rt}\lambda_t)' X_t dt = 0 - 0 - \int_0^{+\infty}(-re^{-rt}\lambda_t + e^{-rt}\dot{\lambda}_t)X_t dt = -\int_0^{+\infty} e^{-rt}(\dot{\lambda}_t - r\lambda_t)X_t dt$

So, the Lagrangian takes the following form
$L = \int_0^{+\infty} e^{-rt} \left[(p_t^{CO2} + c_o).(N - x_t) + C(X_t, x_t) - \lambda_t x_t \right] dt - \int_0^{+\infty} e^{-rt}(\dot{\lambda}_t - r\lambda_t)X_t dt$
FOCs
$\frac{\partial L}{\partial x_t} = -(p_t^{CO2} + c_o) + C_x(X_t, x_t) - \lambda_t = 0$
$\frac{\partial L}{\partial X_t} = C_X(X_t, x_t) - \dot{\lambda}_t + r\lambda_t = 0$

Or
$C_x(X_t, x_t) - c_o = p_t^{CO2} + \lambda_t$
$\dot{\lambda}_t - r\lambda_t = C_X(X_t, x_t)$

Derivation of the first equation gives: $C_{xX}\dot{X}_t + C_{xx}\dot{x}_t = \dot{p}_t^{CO2} + \dot{\lambda}_t$
Using the second equation from the FOCs results in: $C_{xX}x_t + C_{xx}\dot{x}_t = \dot{p}_t^{CO2} + r\lambda_t + C_X$

Using the first equation from the FOCs and remembering that $\dot{x}_t = \ddot{X}_t$ results in
$C_{xX}x_t + C_{xx}\ddot{X}_t = \dot{p}_t^{CO2} + r(C_x - c_o - p_t^{CO2}) + C_X$

We know exogenous exponential law of growth of carbon price: $p_t^{CO2} = e^{rt}p_0$, where $p_0 > 0$. Implementing this in the equation below results in:

$C_{xX}\dot{X}_t + C_{xx}\ddot{X}_t = \dot{p}_t^{CO2} + r(C_x - c_o - p_t^{CO2}) + C_X$

$C_{xx}\ddot{X}_t + C_{xX}\dot{X}_t = re^{rt}p_0 + rC_x - rc_o - re^{rt}p_0 + C_X$
After simplification we obtain the following differential equation

$$C_{xx}\ddot{X}_t + C_{xX}\dot{X}_t - rC_x - C_X + rc_o = 0$$

which defines the optimal deployment trajectory during the transition.

Academic Conclusion

The goal of this research is to identify economic and policy framework to decarbonise a part of transport sector in Europe in the long term (2030-50) via hydrogen mobility deployment. This research combines empirical and theoretical approaches and answers the following questions:

1. How to design appropriate policy instruments to solve inefficiencies in hydrogen mobility deployment?
2. How to define abatement cost and an optimal launching date in the presence of LBD?
3. How to define an optimal deployment trajectory in presence of LBD and convexity in investment costs?

The paper *'Transition Towards a Hydrogen-Based Passenger Car Transport: Comparative Policy Analysis'* draws a cross-country comparison between policy instruments that support the deployment of FCEV. A comparison, which stands on a series of complementary indicators including vehicle Affordability, Annual Advantage in Running Cost, Advantage in TCO, State Financial Participation, Infrastructure Availability and Coverage, allows ranking the most active countries, supporters of FCEV. The analysis shows that the most generous incentives are available under price-based policy instruments design, which allows maximising short-term FCEV deployment rate. Denmark and Japan currently emerge as the best providers of favourable conditions for the hydrogen mobility deployment: local authorities put in place price-based incentives (such as subsidies and tax exemptions) making FCEV more financially attractive than its gasoline substitute, and coordinate ramp-up of their hydrogen infrastructure nationally. Both Californian ZEV regulation, which addresses ZEV supply, and the focus of the German public private partnership H2 Mobility on the infrastructure deployment are expected to produce effects in the longer term.

This study focuses on large and luxury cars segments, for which FCEV is the lowest-carbon solution for long trips. FCEV ensures a long-range autonomy and a short refuelling time compared to BEV and makes the use of FCEV similar to its gasoline analogue.

The analysis of this paper can be further extended to other car segments within the same technological choice of FCEV (e.g. Hykangoo delivery vehicles deployed within niche approach in France), or other types of ZEV within the same car segment of luxury cars (e.g. full electric Tesla). Indeed, BEV and FCEV deployment face the same challenges: coordinated deployment of vehicles and infrastructure (also know as chicken-and-egg dilemma); and severe cost competition with incumbent gasoline technology. The methodology and some vehicle-related conclusions developed for FCEV in this paper can be transposed to luxury BEV (e.g., Tesla). Tesla, while targeting the same car segment, provides a 30% shorter autonomy range; moreover, recurrent long trajectories significantly degrade batteries. For this reason some methodological adjustment will be required.

The scope of this analysis can be extended to a larger set of countries, which actively support ZEV deployment, for example China, UK, South Korea, etc. in further works.

The paper *'Defining the Abatement Cost in Presence of Learning-by-doing: Application to the Fuel Cell Electric Vehicle'* models the process of substitution of pollutant cars by green ones, which are subject to LBD. Within a partial equilibrium model for a car sector of a constant size, the objective of the social planner is to minimize the cost of phasing out a stock of polluting cars. This cost includes the private cost of green cars production, which is subject to LBD, and the social cost of carbon, which has an exogenous upward trend. During the transition, the equalization of marginal costs takes into account the fact that the current action has an impact on future costs through LBD. This paper also describes a suboptimal plan and defines the optimal launching date for an exogenously given deployment trajectory. The paper provides a quantitative assessment of the FCEV case for the substitution of the mature ICE vehicles. The analysis concludes that the CO_2 price should reach 53€/t for the program to start and for FCEV to be a socially beneficial alternative for decarbonizing part of the projected German car park in the 2050 timeframe.

The methodology developed in this paper can be applied to other green technologies, which are subject to a significant LBD, for example BEV. An important set of assumptions should however be revisited: infrastructure deployment; decarbonisation of electricity production; certain components of TCO for BEV. First, BEV infrastructure requires a lower cost of charging points but a higher network density. Second, the cost and strategy of decarbonisation of electricity production is very country specific and depends both on global decarbonisation objective and current policy support for deployment and storage of renewable energies. Third, the BEV TCO is expected to be very sensitive to the progress in autonomy range (which is currently significantly smaller that of FCEV) and battery price reduction.

The question of impact of uncertainty about long-term data trends on the results may be further analysed. Indeed, there is a large uncertainty about long-term trends of data used in the model, notably about technical performance of vehicles, fuel prices and corresponding taxation schemes. Technological performance of both FCEV and ICE and especially corresponding emissions rate may evaluate drastically in the long term due to an unexpected technological breakthrough (e.g. ICE vehicle consuming 2 litres of gasoline per 100 km). Fuel price (both oil and hydrogen) is subject to a high uncertainty related to volatile market conditions and hardly predictable exogenous shocks. Moreover, it is difficult to predict the exact date and nature of change in future taxation policies targeting ZEV and its medium- and long-term impact. This uncertainty may be partly treated within target analysis context developed in the original paper. However, a more exhaustive sensitivity analysis of uncertainty impact would enrich the study.

A competition between different green technologies subject to LBD is also an interesting issue, which can be analysed in more details. In this study FCEV is the only decarbonised technology subject to LBD, and ICE has constant marginal production cost. Besides FCEV there are other technologies, such as BEV, that will contribute to the decarbonisation of transport sector. It will be insightful to evaluate learning and decarbonisation potential of different zero-emission technologies. Indeed, an assessment of decarbonisation potential for different green technologies is a starting point for a further policy debate and future technological choice. Today FCEV and BEV appear not as direct competitors but rather as complementary solutions: they address different car segments. However, delays in the development of FCEV infrastructure, possible breakthroughs in battery technology, and promotion of national preferable technological option may change the nature of this competition, making it more intense in the future.

The paper *'The Role of Learning-by-Doing in the Adoption of a Green Technology: the Case of Linear LBD'* clarifies the impact of LBD on the optimal characteristics of a transition towards green vehicles and studies its interaction with convexity in investment cost. Within the partial equilibrium model of the previous paper, the deployment trajectory is analytically obtained for the case of linear LBD. In this case a high learning induces an earlier switch towards green cars in the case of low convexity, and a later switch in the case of high convexity. This insight is used to revisit the hydrogen mobility project in Germany. A high learning lowers the corresponding deployment cost and reduces deepness and duration of the, investment 'death valley' (period of negative project's cash flow). An acceleration of exogenously defined scenario for FCEV deployment, based on the industry forecast, would be beneficial to reduce the associated transition cost.

In the case of linear LBD, the convexity parameter accounts more for the state of infrastructure deployment, while the learning parameter for vehicles cost. This cost function follows the intuition behind green cars deployment. At the beginning of the deployment, when the cumulated experience is small, the convexity effect is important and slows the deployment of green vehicles. This impact diminishes with time and more important cumulated experience and accelerates the corresponding rate of vehicle deployment during late stages.

The conclusions of this paper are developed for the case of linear LBD and may not however hold for other types of cost functions. Other types of cost functions, where both convexity and learning are present may be considered, for example, interdependent LBD and convexity within non-linear function or independent LBD and convexity. It will be interesting to generalise this approach.

This thesis analyses transport decarbonisation issue through economic and policy axes. The institutional axe is out of the scope of this work. A further extension may aim to understand and model strategic interactions among actors along hydrogen value chain. This may allow identifying 'an optimal' composition of public-private partnership to support hydrogen infrastructure deployment.

Traditionally, authors analyse competition between new technologies and more rarely complementarity of sectors contributing to the development of these new technologies. It will be interesting to focus on complementarity aspect and on questions of its impact on coordination of R&D or/and deployment trajectories. The approach may include analysis of adapted State intervention through specialised financial schemes (taxes on fossil fuels and CO2 emissions, subsidies, quotas, etc.) and competition policies (cooperation agreements, temporary allocation of exclusivity rights, etc.)

The industrial question to answer may be ‘With whom a gas producer should better cooperate: with producer of a complement good (car producer) or its substitute (another gas producer) while launching hydrogen mobility project?’ Comparing frameworks of vertical and horizontal integration may result in certain collaboration schemes that could create necessary economic motivation for private actors to participate in the hydrogen infrastructure deployment.

Industry Collaboration

This thesis was initiated within CIFRE framework of industry applied Ph.D. programs of National Association of Research and Technology (ANRT), supported by the French Ministry of Higher Education and Research. It was conducted at the Department of Economics at Ecole Polytechnique under scientific supervision of Jean-Pierre Ponssard and Anna Creti and at Air Liquide's Advanced Businesses and Technologies Department presided by Pierre-Etienne Franc. During its final year this research also benefited from six-month contract with Energy and Prosperity Chair.

Additionally to three academic papers presented in this manuscript, this research also gave rise to two industry oriented technical reports.

A cost benefit analysis of Fuel Cell Electric Vehicles, done in collaboration with Anna Creti, Guy Meunier and Jean-Pierre Ponssard (available at https://hal.archives-ouvertes.fr/hal-01116997)

This study aims to update the study of McKinsey & Company (2010) and to provide a simple model of the FCEV deployment over the period 2015-2050. This report compares hydrogen vehicles with its gasoline substitute for the German market, without taking into account neither indirect incentive tools (carbon tax on transport emissions) nor direct incentive tools for FCEV (tax reduction, subsidies, bonus) except fuel tax exemption for hydrogen fuel (such as TIPP in France). As such it provides a consistent framework for:

- The formulation of a proper cost benefit analysis, including the definition of the abatement cost for the hydrogen technology;
- The simulation of the results under various technological and cost assumptions;
- The identification of the major conceptual issues to be addressed in analytical developments.

The main conclusion of this work is that FCEV could be a socially beneficial alternative for decarbonizing part of a projected German car park by 2050. The corresponding abatement cost would fall in the range of 50 €/t CO2 to 60 €/t CO2. This range is higher than the current estimate for the normative cost of carbon as expressed in Quinet (2009 and 2013), which is around 30€/t in 2015. Still the gap is not out of hand. A set of market and cost conditions that would shorten the gap is identified in the target analysis.

This work contributed to support the debate between Air Liquide and France Strategy (Beeker 2014) over the appropriate abatement cost for the FCEV deployment. Indeed, there are two approaches to evaluate the abatement cost: a static and a dynamic one.

The static approach does not consider the evolution of costs and compute the abatement cost associated to a vehicle each year given the costs of that year. Beeker (2014) estimates static abatement cost for hydrogen mobility to be about 1,000 €/t in 2014 and concludes that this high abatement cost does not justify substitution of ICE by FCEV. Within the similar set of initial hypothesis (similar FCEV and ICE fuel consumption, hydrogen and gasoline price, and related emissions), in our model the corresponding abatement cost starts around 1,600 €/t in 2020, which is comparable to Beeker (2014) estimation. However, it decreases to zero in 2043, when the relative total cost of ownership becomes positive for FCEV and then becomes negative. Not much can be inferred from this sequence of static abatement costs.

In contrast dynamic abatement cost takes into account learning-by-doing effect along the FCEV deployment trajectory and gives a relevant proxy for policy analysis. The dynamic approach consists in computing the abatement cost of the whole deployment. This approach considers the whole deployment as an investment spread over 35 years, from 2015 to 2050, in a fleet of vehicles that starts functioning and abating emissions from 2050 and implies a yearly cost to operate and renew the fleet. Within base case scenario the dynamic abatement cost for FCEV is equal to 53 €/t.

For industrial actors this means that they may start investing in mass deployment of hydrogen mobility within context of H2 Mobility project in Germany, when State guarantees carbon prices in the range between 50 and 60 €/t.

This study allowed me to deeply understand technological and economic challenges of hydrogen mobility, to get familiar with problems related to its long-term deployment financing (notably, investment death valley issue) and to develop a complex spreadsheet financial model for H2 Mobility project in Germany. This model constituted a base for further works on an innovative financing mechanism for hydrogen infrastructure deployment (Laffitte, Leguet, Lemer, Quint, 2015).

The cost benefit analysis served as a starting point for the paper *'Defining the Abatement Cost in Presence of Learning-by-doing: Application to the Fuel Cell Electric Vehicle'* (Ecole Polytechnique and Energy and Prosperity Chair affiliation).

The deployment of BEV and FCEV in 2015: California, Germany, France, Japan, Denmark, done in collaboration with Julien Brunet and Jean-Pierre Ponssard (available at https://hal-polytechnique.archives-ouvertes.fr/hal-01212353)

This study aims to provide a complete panorama of BEV and FCEV deployment in a set of countries. First, global targets in terms of current share of GHG emissions for road transportation, its evolution relative to 1990, total car park in 2015, and its average annual growth trend are defined. Moreover, specific roadmaps for BEV and FCEV are detailed with respect to specific targets, institutional framework (public, public private partnership), financing (global budget dedicated to the roadmap), milestones, and public procurement. Second, this study overviews main policy instruments addressing car manufacturers (technical norms and the way they are applied, mandates i.e. minimum requirements for portfolio within the market); infrastructure deployment (subsidies for different types of infrastructures); and customers (CO2 tax, rebates on purchase price, perks such as free parking, driving lanes, private subsidies; etc.) Third, this study assesses deployment as in 2015 for car manufacturers, infrastructure and customers. For manufacturers, it describes how manufacturers have complied or intend to comply with the norms and the minimum requirements. It also provides illustrations of some global strategies of car market players: Tesla (California, USA), Daimler (Germany), Symbio Fuel Cell (France), Toyota (Japan), Better Place (Denmark). For infrastructure deployment it presents number of deployed stations, its type, location and operation entity. For vehicle deployment this study details number of vehicles by segment (light duty vehicles, utility vehicles, of which through public procurement including auto lib, buses).

This case study reveals important differences for the deployment of BEV versus FCEV. BEV is leading the game with a cheaper infrastructure investment cost and a lower cost for vehicle. The relatively low autonomy makes BEV mostly suited for urban use, which is a large segment of the road market. The current level of BEV vehicles on roads starts to be significant in California (70,000), Germany (25,000), France (31,000), Japan (608,000) Denmark (3,000), but they remain very low relative to the targets for 2020: California (1.5 million), Germany (1 million), France (2 million), Japan (0.8-1.1 million for ZEV new registrations), Denmark (0.25 million). The developments and efficiency gains in battery technology along with subsidies for battery charging public stations are expected to facilitate the achievement of the growth. The relative rates of equipment (number of publicly available stations / number of BEV) provide indirect evidence on the effort made in the different countries: California (3%), Germany (12%), France (28%), Japan (11%), and Denmark (61%). In some countries public procurement plays a significant role. In France Autolib (publicly available cars in towns) represents a large share of the overall BEV deployment (12%), and the government recently announced a 50% target for low emissions in all public vehicles new equipment.

FCEV is still in an early deployment stage due to a higher infrastructure investment cost and a higher cost for vehicle. The relatively high autonomy combined with speed refuelling make FCEV mostly suited for long distance and interurban usage. At present there are only a very limited numbers of HRS deployed: California (28), Germany (15), France (6), Japan (31), Japan (7), Denmark (12), and only a few units of hydrogen vehicles on roads: California (125), Germany (125), France (60), Japan (7), Denmark (21). However, a detailed analysis of the current road maps suggests that FCEV has a large potential. Targets for the 2025-2030 horizons are significant in particular in Germany (4% in 2030), Denmark (4.5% in 2025) and Japan (15-20% for ZEV new registrations). The California ARB has recently redefined its program (subsidies and mandates) to provide higher incentives for FCEV. France appears to focus on specialized regional submarkets to promote FCEV (such as the use of hydrogen range extending light utility vehicles). The financing of the hydrogen infrastructure appears as a bottleneck for FCEV deployment. Roadmaps address this issue through progressive geographical expansion (clusters) and a high level of public subsidies HRS in particular in all countries except France.

This study concludes that at this stage of deployment BEV and FCEV do not appear as direct competitors but rather as complementary goods: currently they address different car segments. Unexpected delays in the development of infrastructure in FCEV, possible breakthroughs in battery technology, and the promotion of national champions may change the nature of this competition, making it more intense in the future.

This overview attracted industrial interest and was communicated to internal services of Air Liquide (notably, to the teams of Advanced Businesses and Technologies and Strategic department). It was also presented by myself at workshop *Déclinaison sectorielle des scénarios de transition : Application au secteur de la mobilité* organised by Energy and Prosperity Chair, by Julien Brunet and myself at talk show *Regards Croisés : Mobilité Durable* organised by Orange Labs, and by Jean-Pierre Ponssard at *R&D Day* oragnised by EDF.

This case study partly constituted a data basis for the paper 'Transition Towards a Hydrogen-Based Passenger Car Transport: Comparative Policy Analysis' (Ecole Polytechnique affiliation). The results were presented, by Caroline Le Mer at the conference of *International Partnership for Hydrogen Energy*, by Pierre-Etienne Franc at the Air Liquide board meeting, and by myself at 3d International Conference on *Electromobility Challenging Issues* organised by Armand Peugeot Chair in Singapore.

Industrial Conclusion

The theoretical findings of this research provide an academic base for several industry recommendations:

1. FCEV manufacturers and hydrogen gas producers are encouraged to increase their hydrogen mobility deployment effort in Denmark, Japan, California and Germany, where they can benefit from strong State support.

In Denmark and Japan local authorities provide strong price-based incentives (such as subsidies and tax exemptions) and make FCEV more financially attractive than its gasoline substitute; they also coordinate hydrogen infrastructure ramp-up on the national territory. Germany solely focuses on the infrastructure supply (notably through H2 Mobility project) and does not provide important incentives to support vehicle demand. California implements a mixed scheme to encourage both vehicle supply (ZEV regulation) and vehicle demand (important subsidies for ZEV purchase). Currently Denmark and Japan provide the most favourable conditions for hydrogen mobility (FCEV) deployment; while in California and Germany, results are expected in the longer term.

2. Industry needs to start investing in hydrogen mobility deployment, when State guarantees carbon prices in the range between 50 and 60 €/t. Before that, Industry needs to put in place necessary early stage market development initiatives to indicate its engagement to public authorities and show that the Hydrogen path is worth and will become affordable.

FCEV could be a socially beneficial alternative for decarbonizing part of the projected German car park in the 2050 time frame. The corresponding abatement cost falls in the range of 50 €/t CO_2 to 60 €/t CO_2 in 2015 for the deployment trajectory to start. This range is higher but not very far from the current estimate for the normative cost of carbon as expressed in Quinet (2009 and 2013), which is around 30€/t in 2015. This gap can be shortened by a feasible set of market and cost conditions.

3. Industry is encouraged to accelerate the FCEV deployment trajectory within H2 Mobility project in Germany.

The trajectory based on industrial forecast is shown to be suboptimal and there is an economic interest to accelerate it, notably, due to a lower transition cost and a shorter corresponding duration of negative cash flow (also know as Investment Death Valley). Both learning-by-doing (LBD) and convexity in investment costs have an impact on the optimal deployment characteristics. The convexity related to the cost of infrastructure deployment should be treated with attention: in the case of linear LBD a high LBD induces an earlier switch towards green cars for low convexity and a later switch for high convexity.

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université PARIS-SACLAY | ÉCOLE DOCTORALE Sciences de l'homme et de la société (SHS)

Titre : Choix de politiques sectorielles pour la décarbonisation de l'économie. Application au cas de l'hydrogène pour le secteur du transport

Mots clés : Décarbonisation du Transport, Voiture Pile à Combustible (FCEV), Politiques Sectorielles, Prix du Carbone Dynamique, Effet d'Apprentissage

Résumé : La mobilité hydrogène (FCEV) contribue à la décarbonisation du secteur européen des transports à long terme (2030-50). Quel cadre économique et réglementaire pourrait soutenir son déploiement ? Une comparaison des politiques de soutien montre que le Japon et le Danemark en fournissent les meilleures conditions. Les autorités locales introduisent de solides instruments prix (tels que des subventions et des exemptions fiscales) pour rendre le FCEV plus attractif par rapport à son analogue à essence et coordonnent le déploiement de l'infrastructure hydrogène sur le territoire. Le coût de production du FCEV est sujet aux effets d'apprentissage fort et convexité. Un coût d'abattement 'ajusté' doit en tenir compte et représente un outil politique pratique pour identifier la date de lancement optimale d'une technologie verte. Une modélisation empirique du marché automobile allemand montre que les FCEV deviendront une option économiquement viable dès que le prix du carbone atteindra 50-60€/t. Un effet d'apprentissage plus fort et une accélération du déploiement aboutissent à une transition moins coûteuse et une période de cash flow négatif plus courte.

Title: Analysis of a hydrogen-based transport system and the role of public policy in the transition to a decarbonized economy

Keywords: Transport Decarbonisation, Fuel Cell Electric Vehicle (FCEV), State Technology Policy, Dynamic CO_2 price, Learning-by-Doing

Abstract: Hydrogen mobility (FCEV) will contribute to the decarbonisation of the transport sector in Europe in the long term (2030-50). What economic and policy framework could foster its wide deployment? A cross-country policy analysis reveals that Denmark and Japan currently provide the most favourable conditions for FCEV deployment. Local authorities put in place price-based incentives (such as subsidies and tax exemptions) making FCEV more financially attractive than its gasoline substitute, and coordinate ramping-up of their hydrogen infrastructure nationally. FCEV is subject to both learning-by-doing and convexity in production costs. An 'adjusted' abatement cost, which accounts for these two effects, represents a convenient policy tool to set an optimal launching date for a new green technology. Empirical modelling of the decarbonised German car market shows that FCEV would be an economically viable alternative as soon as the CO_2 market price reaches 50-60 €/t. A higher FCEV learning and a deployment acceleration would result in a lower corresponding deployment cost and a shorter time period for project's negative cash flow (aka Investment Death Valley).

Université Paris-Saclay
Espace Technologique / Immeuble Discovery
Route de l'Orme aux Merisiers RD 128 / 91190 Saint-Aubin, France