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Abstract

The deployment of hydrogen technologies in the energy mix and the use of hydrogen fuel cell vehicles (FCV) are expected to significantly reduce European greenhouse emissions. We carry out a social cost-benefit analysis to estimate the period of socio-economic conversion, period for which the replacement of gasoline internal combustion engine vehicles (ICEV) by FCV becomes socio-economically profitable. In this study, we considered a hydrogen production mix of five technologies: natural gas reforming processes with or without carbon capture and storage, electrolysis, biogas processes and on-site production.

We estimate two external costs: the abatement cost of CO_2 through FCV and the use of non-renewable resources in the manufacture of fuel cells by measuring platinum depletion. We forecast that carbon market could finance approximately 10 % of the deployment cost of hydrogen-based transport and that an early economic conversion could be targeted for FCV. Almost ten years could be saved by considering externalities.[1]

Keywords: Hydrogen economy, hydrogen fuel cell vehicles, social cost-benefit analysis, external costs, carbon abatement cost, platinum depletion.

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[1] Abbreviations used: CBA, cost-benefit analysis; CCS, carbon capture and storage; ETP, Energy Technology Perspectives; FCV, fuel cell vehicles; HRS, hydrogen refueling stations; ICEV, internal combustion engine vehicles; LCA, life cycle assessment; NPV, net present value; SMR, steam methane reforming; SNPV, social net present value; TCO, total cost of ownership.

1. Introduction

Several studies have explored the potential technological innovations, the associated economic conditions and prospective scenarios for the deployment of new power-trains in Europe [1, 2, 3, 4, 5].

Hydrogen requires a comprehensive support scheme that bridges the gap between three main dimensions: *(i)* market requirements, *(ii)* sustainability and climate requirements, and *(iii)* hydrogen technology development [6].

(i) Market requirements for hydrogen as energy carrier is tackled by the following points: competitive price compared to other environmentally friendly energy carrier like batteries; refuelling infrastructure permitting the autonomy range requierd by users; fast and easy storage process enabling a great autonomy for mobility; and safety levels equal to or better than carbonized energy sources. Acceptance of this new use of hydrogen is also related to its safety. Though the different accidental risks of hydrogen are well known, the risks related to the industrial use and the private use of hydrogen cannot be compared, because the private users do not have the same restrictions as professional users.

(ii) Sustainability and climate requirements for hydrogen energy have to fit the political objectives initiated by the European Commission and the different Member States; eg. the 2020 package is a set of binding legislation to ensure the EU meets its climate and energy targets for the year 2020. The use of hydrogen energy should enable to reduce greenhouse gas emissions by 20 % (from 1990 levels), also enable 20 % of EU energy to be renewable, and finally increase the energy efficiency by 20 %. Furthermore hydrogen cars have also to be conform to existing legal requirements like measures to prevent and limit waste from end-of-life vehicles (ELVs) and their components and ensure that where possible these are reused, recycled or recovered.

(iii) Concerning the hydrogen technology development, mass-market in hydrogen mobility requires reduced cost of cars and hydrogen fuelling stations. To fulfill this requirement the technology development targets to lower or replace the use of noble materials like platinum in fuel cells and electrolysers. Furthermore the technology development is drawn by the need of higher storage density (meaning higher autonomy range) and simultaneously to obtain lower storage pressures. Today the standardized storage pressure is 35 MPa and 70 MPa, the tendency is almost 70 MPa for passenger cars while it is only 35 MPa for buses as reflected by the European directive on the deployment of alternative fuels infrastructure making reference to the technical specification ISO/TS 20100 Gaseous hydrogen—Fuelling stations. While high pressure is important for high energy density it implies high costs related to the compression and high cost regarding the safety requirements

for high pressure equipment. New storage materials like hydrides or storage vessels working with cryo-compressed hydrogen could lower these costs by maintaining high energy autonomy.

Given the challenges of the hydrogen market for mobility, this article presents a social cost-benefit analysis (CBA) framework to assess the progressive replacement of gasoline ICEV by hydrogen FCV in the European market over the period 2015–2055.

First, we present the social CBA framework in section 2.1. The following sections deal with the assumptions, for hydrogen demand in section 2.2 and supply in 2.3. The economic comparison by the total cost of ownership (TCO) is computed in section 3.1. The section 3.2 presents the external costs such as carbon abatement cost and platinum depletion. The social CBA is performed in section 3.3 providing final results and discussions. Lastly, conclusions are drawn in section 4.

2. Materials and Methods

2.1. Methodological framework

The methodological framework is based on the CBA of German market conducted by Creti et al. [7]. They analyze the abatement cost of carbon through FCV and various hydrogen production process and their cost. We extend their analysis to include external costs in Europe, in order to consider the costs and benefits to society as a whole. For this reason, we refer to CBA as social cost-benefit analysis [8]. A social CBA highlights environmental-social benefits and costs, and computes in monetary units the impacts on a project, both positives and negatives; these impacts should be appropriately priced.

The social benefits are estimated in terms of carbon prices for three scenarios. We included the carbon abatement cost on the deployment net present values, in order to estimate the share of the transtition costs to hydrogen as an alternative transport fuel that carbon market could finance. Regarding social costs, we consider external costs related to the consumption of non-renewable resources [9] to manufacture fuel cells. Even if platinum loading per FCV has significantly been reduced and platinum recycling rate increases, the demand for this mineral will continue rising [10].

The Figure 1 presents the social CBA framework in terms of underlying assumptions, intermediate values and final results. It is composed of three steps: *(i)* the economic comparison via the TCO, *(ii)* the external cost estimation, and *(iii)* the social-economic comparison (social CBA). The final results consist of two indicators that take into account external costs of carbon abatement and platinum depletion: the social net present value (SNPV) and the year of social conversion.

2.2. Hydrogen demand of FCV in Europe

To achieve the economic and social comparison of ICEV and FCV during the period 2015–2055, we assume a complete replacement until 2055 in buying a FCV instead of an ICEV. New acquisitions of passenger light cars (ICEV) in Europe[2] will be replaced by the FCV following the trends of Energy Technology Perspectives (ETP) 2014 estimated by the International Energy Agency [12][3].

The ETP 2014 forecasts the percentage of hydrogen used as alternative transport fuel in Europe, allowing us to estimate the number of FCV during the analyzed period. The demand of FCVs is estimated according the next points: year 2015 is taken as the start time when FCV enters automobile market [13, 14, 15]. The trend is a slow introduction of FCV for the period 2015–2030, followed by an important market share starting around 2035 [16], as predicted by the European projects HyWays [1], POLES model and PROTEC H2 project [17, 18]. The forecasted hydrogen demand is plotted in Figure 2.

We consider three scenarios[4] according to the average daily driven distances in different European countries [19]: 80 km in the "optimistic" scenario; 60 km in the "moderate" scenario; and 40 km in the "conservative" scenario.

Other important assumptions are the FCV specifications based on commercial information: *(i)* a vehicle efficiency of 0.95 kg H_2 per 100 km in 2015 and of 0.7 kg H_2 per 100 km in 2050 [7], *(ii)* a driving range of approximately 600 km per fill-up [20] and *(iii)* a vehicle lifetime of 10 years.

2.3. Hydrogen supply and production mix in Europe

The supply scenario is constructed by two main assumptions. First, the current dominance of steam methane reforming (SMR) process from natural gas will be progresively replaced by cleaner alternatives [21]. The SMR is considered as a transition technology. Secondly, we assume that long-term solutions for hydrogen supply will foster carbon-neutral processes with significant hydrogen production by electrolysis of water using renewable energy sources. The French law [22] is the main driver of this energy transition and

[2]There were 11.8 millions of vehicles in 2013 in EU–28 [11].

[3]We work with data that assumes actions to limit global warming to 2 °C.

[4]Poland and Spain are in the first group; Italy, Germany and France in the second; the United Kingdom is in the third.

we assume there will be similar drivers at the European scale. This electrolysis development would be supported by the surplus of European electricity. The optimization of intermittent energy flow generated by renewable sources could be used to reduce electrolysis cost. This production mix was developed during exchanges with experts and industrial leaders during the European project DEMCAMER, see Figure 3.

Five hydrogen production technologies are considered in the present study. The production mix includes: SMR process from natural gas; SMR with carbon capture and storage (CCS); water electrolysis; SMR with biogas and SMR on-site type station. The associated costs are shown in Figure 4.

However, the deployment of hydrogen-based transport raises new challenges for production infrastructures that need to evolve towards flexible small scale on-site production facilities. It is considered that on-site production at the hydrogen refueling stations (HRS) are designed to $50\,\mathrm{Nm^3/h}$ of H_2, which corresponds to the refilling of 25 vehicles per day [21] and a daily storage capacity of 100 kg of H_2.

The capital cost per HRS with on-site production is expected to decrease from k€ 1500 in 2015 to k€ 700 in 2050. Moreover, annual operating and maintenance cost should decrease from 10 % to 8 % of the capital cost [7]. Lastly, the number of HRS is a linear estimation from the hydrogen demand determined for each of the three scenarios. The capital cost includes HRS infrastructure cost and HRS operating and maintenance cost for the period analysed. The capital cost per vehicle is reduced as the fleet of FCV increases.

3. Results and discussion

3.1. Economic comparison of FCV and ICEV

The economic comparison is evaluated by the TCO method [3]. For the present study, the TCO of the replacement ICEV by FCV considers the costs over the lifetime of a vehicle, including purchase price Car_t (the sum of all costs to deliver the assembled vehicle to the customer) and running cost Run_t (fuel cost and maintenance cost per vehicle) and infrastructure on HRS. This economic comparison is the difference between buying a FCV including the infrastructure needed and the conventional case of buying an ICEV. We compute the variation of TCO and the investment Inves_t on infrastructure for HRS per unit of car in the market, see equation 1.

$$\Delta\mathrm{TCO}_t = \Delta\mathrm{Car}_t\Big[\mathrm{FCV} - \mathrm{ICEV}\Big] + \Delta\mathrm{Run}_t\Big[\mathrm{FCV} - \mathrm{ICEV}\Big] + \mathrm{Inves}_t \qquad (1)$$

The total deployment cost of hydrogen-based transport DC_t is the variation of TCO multiplied by the number of cars.

Hereafter, the economic comparison is performed by considering the moderate scenario. Firstly, we evaluate the variation of TCO. The delta cost of TCO per vehicle starts at a very high level, around k€ 49 in 2015, and progressively drops from k€ 14 in 2025 to k€ 8 in 2035 and converges in 2052. The infrastructure cost on HRS declines rapidly from k€ 9 in 2015 to about k€ 2 in 2021. The relative high cost of hydrogen production (in 2015: € 8 per kg H_2 by electrolysis and € 2.9 per kg H_2 by SMR from natural gas, see Figure 4) is compensated by the efficiency of FCV. This is an advantage for FCV, considering that gasoline price growth rate decrease from 5.4 % in 2020, to 3 % in 2040 and 1.5 % in 2050 [23]. Secondly, the main expenses on infrastructure will follow from 2020 to 2035 and then the period 2030 to 2050 will be characterized by significant surplus as the FCV fleet increases. Lastly, the year of economic conversion is the moment at which the total cost of FCV is equal to the total cost of ICEV for the period analyzed. The total cost include infrastructure cost and vehicule lifetime cost and hydrogen production mix. Under the moderate scenario, the cash flow is compensated approximately by 2052. Results of the conservative and optimistic scenarios are detailed in Appendix A.

3.2. External costs

3.2.1. FCV fleet as a carbon abatement option

The climate change impacts avoided by hydrogen-based transport are evaluated via the abatement cost of carbon. This includes the whole deployment as an investment, spread from 2015 to 2055, in a fleet of hydrogen vehicles that abate emissions. Our aim is to estimate the lowest carbon price needed to make hydrogen FCV profitable.

To evaluate carbon emissions, we use life cycle assessment (LCA) studies [24, 25, 26] for the emissions of the hydrogen production mix (see Table 1) and emissions of the ICEV [5]. The variation of CO_2 avoided per vehicle is estimated. The abatement cost of CO_2 for the substitution of all cars is computed by equation 2

$$\mathrm{AC}_t = \frac{\mathrm{DC}_t}{\Delta \mathrm{CO}_2} \tag{2}$$

where the abatement cost AC_t is the minimum avoided carbon price for the year t and DC_t is the total deployment cost of hydrogen-based transport.

The carbon price at the end of the period is actualized to 2015 at the social discount rate of 5 % [27].

[5]These LCA values are not the most appropriate ones in this specific analysis but they are used as preliminary values because of the lack of European studies. These are values from different literature sources and relevant to the USA context.

Table 1: Carbon emissions of different hydrogen technologies

H_2 technology and transport	Carbon emissions ($kg\ CO_2$ per $kg\ H_2$)
SMR + natural gas	9.23
SMR on-site	9.42
SMR + biogas	2.93
SMR + CCS	2.54
Electrolysis from renewable energy	0.00
Pipeline or road transport to market	1.09

Source: [24, 25, 26].

Based on the moderate scenario, carbon abatement cost by using FCV is estimated to be approximately € 18 per ton eq. CO_2 in 2015 and avoided greenhouse emissions are estimated at 2 millions tons CO_2 in 2015. The net present value (NPV) of deployment cost is € 382 millions in 2015. The results show that a carbon market could finance approximately 10 % of the hydrogen deployment cost. See carbon price estimates for the other scenarios on the supplementary data in the Appendix A.

3.2.2. Platinum depletion

We assessed that the required platinum amount could reach nearly 600 metric tons by 2050, which is three times the current platinum supply. It is also expected that insufficient platinum supply and expensive platinum would be a barrier to widespread commercialization of hydrogen FCV [10].

We take into account the scarcity of minerals by measuring platinum depletion. The mineral depletion is the change in stock value of the mineral resources. In the theoretical economic model of increasing scarcity, the mineral depletion is the total rent generated by the natural resource [9]. Mineral depletion is commonly evaluated by the net price method [28]. Moreover, fast growth in demand of minerals results in high estimated scarcity rents to encourage higher primary extraction rates.

Sun et al. [10] analyze the cost of platinum in future FCV considering platinum prices, demand and supply. Each FCV contains approximately from 30 to 40 g of platinum in 2015. Based on the works of Calle-Vallejo et al. [29], we assume a progressive reduction of platinum use for FCV down to 10–15 g of platinum in 2050.

As of today, ICEV consumes 5.6 g of platinum per vehicle; moreover given the maturity of the technology involved, we expect this quantity to remain stable during the analyzed period.

Platinum has a very high recycling rate for different uses in the jewelry, automobile, electronics, chemical industry, petroleum, glass and other industries. The recycling supply creates a counter balance of the depletion effect.

Platinum depletion estimated by net price method is computed as the market price minus the marginal extraction cost of platinum. Alonso [30] analyzed scarcity and recycling rates of platinum over a 50-year period. The net price (platinum depletion) is valued to approximately 2010 € 18 per gram of platinum extracted, using Alonso [30]'s average estimates: USD 55.6 (2010 € 41.94) as the market price and USD 31.7 (2010 € 23.91) as the marginal cost of extraction of one gram of platinum. Hence, each gram of platinum extracted is depleting at 2015 € 19.44.

Platinum depletion is considered constant over the studied period, and represents about 8 % of the deployment cost in 2015.

Overall, taking into account the carbon abatement cost and the platinum depletion we found that while the former usually gets much more attention than the latter, these two external costs are quantitatively close.

3.3. Social-economic comparison

The present social cost-benefit analysis of FCV vs. ICEV provides two main results.

3.3.1. The year of social conversion

The economic comparison by TCO converges in 2049 (optimistic scenario) or in 2052 (moderate scenario) or in 2054 (conservative scenario). At this point in time the FCV and ICEV will have the same lifetime cost. This is the first step in the total deployment evaluation.

Next, in each scenario the benefits of carbon abatement by hydrogen vehicles and costs by platinum depletion are integrated for each year.

In conclusion, including external costs enable to save about 10 years in the time needed to reach the conversion time for the full deployment of hydrogen-based transport (see Table 2).

3.3.2. Social net present value (SNPV)

Under more ambitious carbon prices estimated by ETP 2015 [31] from 2020 to 2050 (see Table 3), we estimate a social cash flow of introducing FCV to replace ICEV. It includes low and high global marginal abatement costs for CO_2 as well as the platinum depletion estimated before.

The social net present values are computed for each scenario over the social discount rate s of 5 % [27]. They represent net savings resulting from

Table 2: Years of conversion in social cost-benefit analysis of FCV vs. ICEV

Scenario	Economic conversion (year)	Social conversion (year)
Conservative	2054	2046
Moderate	2052	2040
Optimistic	2049	2038

Source: authors.

Table 3: Future CO_2 prices in EU-28 (€ per ton eq. CO_2)

	2020	2030	2040	2050
Low carbon price	30	80	120	140
High carbon price	50	100	140	170

Source: [31].

the replacement of ICEV by FCV during the period analyzed. The equation (3) defines SNPV and table 4 summaries the estimates.

$$\mathrm{SNPV} = \sum_{t=0}^{n} \frac{1}{(1+s)^t} \Big[(\mathrm{DC})_t + \mathrm{AC}_t \times (\Delta \mathrm{CO}_2)_t - \mathrm{PD}_t \times (\Delta \mathrm{Pt})_t \Big] \tag{3}$$

Table 4: Social net present value (SNPV) (Millions €)

Scenarios	Low carbon price	High carbon price
Conservative	3	8
Moderate	20	30
Optimistic	45	62

Source: authors.

All external costs are measured under the assumptions of the hydrogen production mix (Section 2.3 and Figure 2).

3.4. Discussion

Our work extends [7] in the case of Europe, and includes another external cost (platinum depletion). Creti et al. [7] have shown the impact of carbon abatement on the FCV deployment in the case of Germany, they underline that carbon market could partially finance the infrastructure for FCV. We find that the social balance is positive including also platinum depletion, generating net savings for Europe. The Figure 5 plots the carbon abatement cost for two different prices and the platinum depletion vs. the market size of FCV of the moderate scenario.

To extend the present social CBA of hydrogen-based transport, it would also be important to consider other aspects. Air quality in Europe and related health impacts demand ambitious climate policies [32, 33], and air pollution avoided by hydrogen FCV should be included in further social cost-benefit analysis. To reach this objective, it is necessary to make full fuel cycle assessments of different hydrogen production considering the European energy production mix, as performed in the USA routes. The California Energy Commission [34] supported a significant life cycle assessment determined on a "well-to-wheels" basis, which includes fuel production and distribution, fuel cycle emissions and vehicle emissions.

Related to risks, further standardization is also necessary in order to facilitate the introduction of different hydrogen technologies to markets and enable interoperability with the existing infrastructure and appliance providing an enhanced protection of users. This is in the scope of European directive 2014/94/EU on the deployment of alternative fuels infrastructure making technical specifications for hydrogen refueling points for vehicles. Therefore the directive takes reference to several standards actually developed by the CEN 268 WG 5 hydrogen refueling station in order to take into account safety aspects.

This social CBA includes key assumptions that require further attention. Our results are quite sensitive to the hydrogen production mix; extended analysis of other hydrogen production configuration would improve robustness of our model. In addition, other external costs could be evaluated such as noise benefits and social acceptance of hydrogen risks.

4. Conclusions

The present study integrates societal benefits for the reduction of greenhouse gas emissions and social costs for the increase of platinum consumption in the manufacture of fuel cells. By including external costs, economic benefits of the replacement of ICEV by FCV were highlighted as well as the generation of positive social net present values

This study suggests that the year of future economic conversion—the profitability horizon—could be shortened by about 10 years. Today, under the moderate scenario assumptions, internalizing carbon price could finance approximately 10 % of the hydrogen-based transport from 2015 to 2055.

European countries have started to internalize externalities for moblity using regulations. Finland and the Netherlands among others reformed existing *ad valorem* taxes on new cars to affect relative prices of cars by emissions level and to constitute a leverage effect to promote low-emission vehicles [35]. Another initiative is the recent release of the French law on the Energy Transition for Green Growth and the related decree (under preparation) defining the criteria of low-emission vehicles. This decree includes electric battery and hydrogen vehicles.

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Appendix A. Supplementary data

Supplementary data related to this article can be found in the enclosed Excel file. It includes full estimates of the social cost-benefit analysis in the conservative, moderate and optimistic scenarios, as well as platinum depletion estimates.

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Figure 1: Social cost-benefit analysis framework FCV vs. ICEV

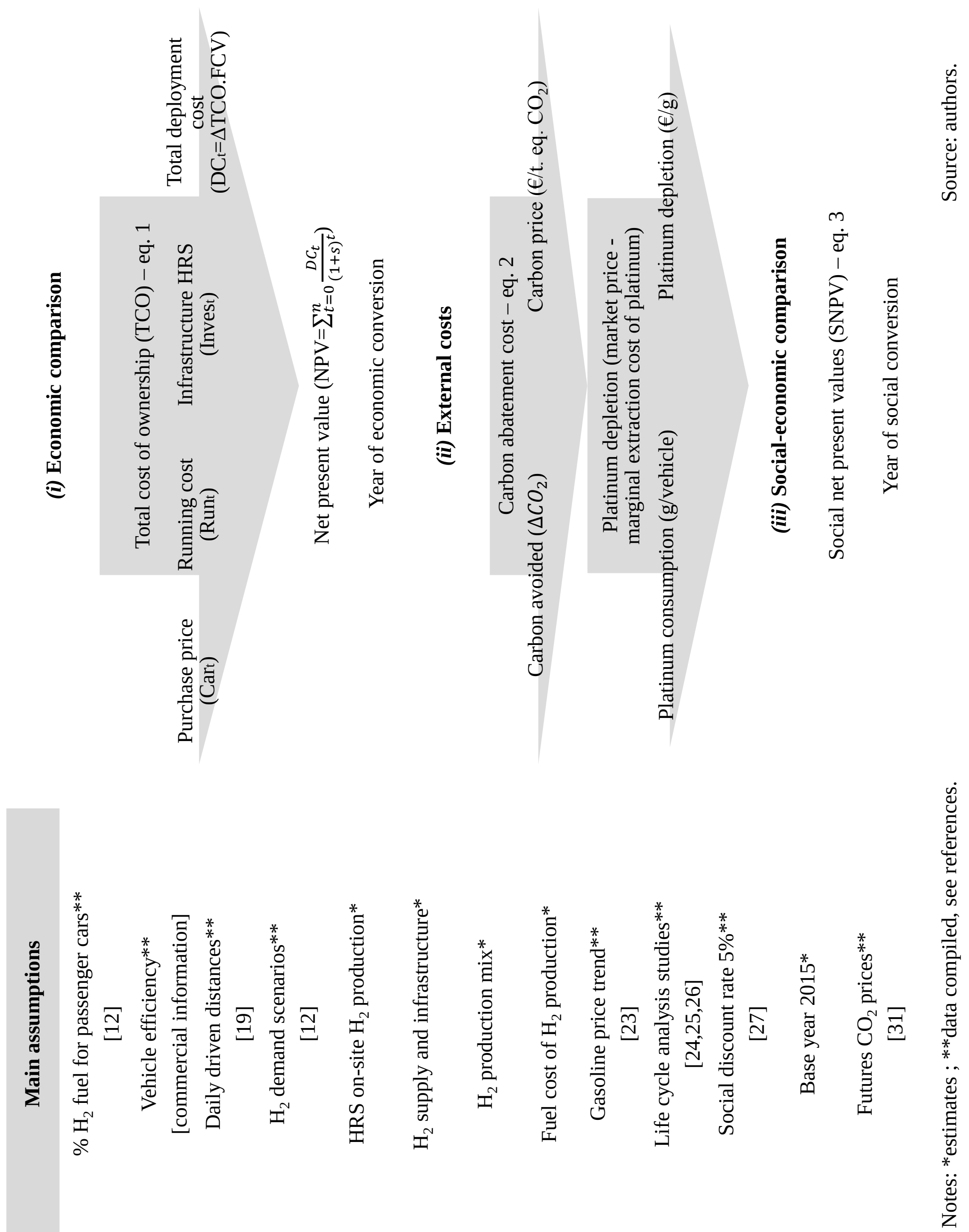
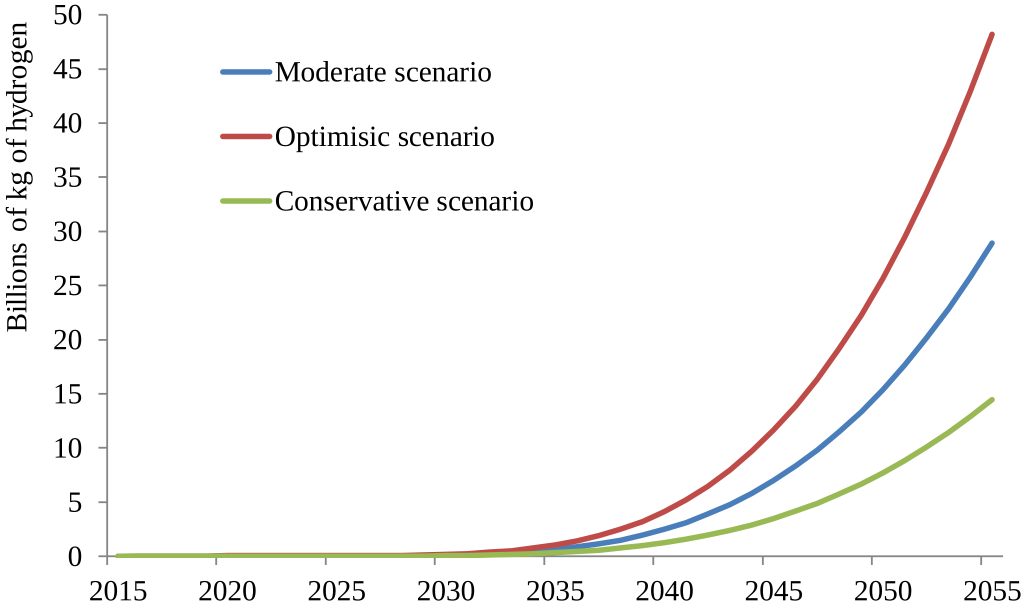
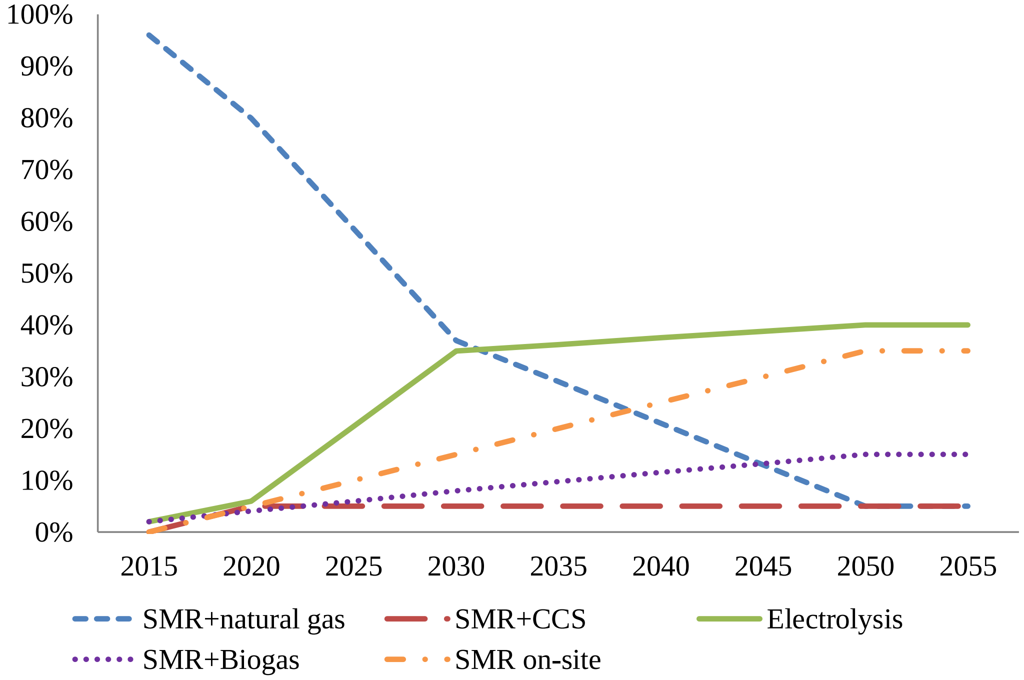


Figure 2: Hydrogen demand to FCV in EU–28



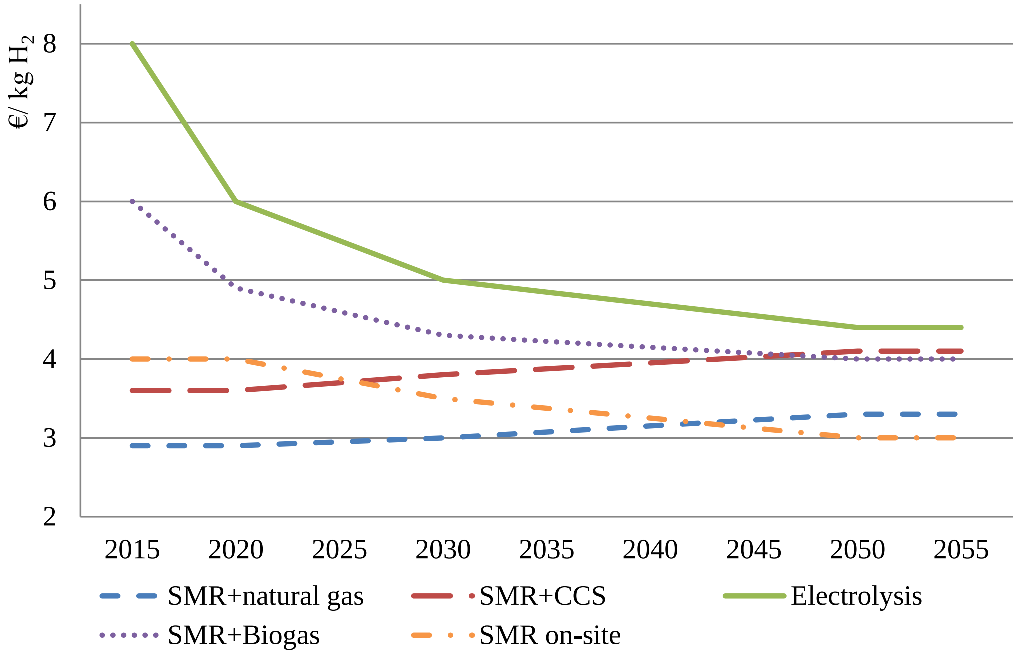
Source: [17, 18].

Figure 3: Hydrogen production mix 2015–2055 in EU–28



Source: authors.

Figure 4: Fuel cost by type of hydrogen production 2015–2055 in EU–28



Source: authors.

Figure 5: External costs in the moderate scenario (millions 2015 €)