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Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: Application to Occitania (France)

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ABSTRACT

A lot of recent studies have concluded that hydrogen could gradually become a much more significant component of the European energy mix for mobility and stationary fuel cell system applications. Yet, the challenge of developing a future commercial hydrogen economy still remains through the deployment of a viable hydrogen supply chain and an increasing fuel cell vehicle market share, which allows to narrow the existing cost difference regarding the conventional fossil fuel vehicle market. In this paper, the market penetration of hydrogen fuel cell vehicles, as substitutes for internal combustion engine vehicles has been evaluated from a social and a subsidy-policy perspective from 2020 to 2050. For this purpose, the best compromise hydrogen supply chain network configuration after the sequential application of an optimization strategy and a multi-criteria decision-making tool has been assessed through a Social Cost-Benefit Analysis (SCBA) to determine whether the hydrogen mobility deployment increases enough the social welfare. The scientific objective of this work is essentially based on the development of a methodological framework to quantify potential societal benefits of hydrogen fuel cell vehicles. The case study of the Occitania Region in France supports the analysis. The externality costs involve the abatement cost of CO_2, noise and local pollution as well as platinum depletion. A subsidy policy scenario has also been implemented. For the case study considered, the results obtained that are not intended to be general, show that CO_2 abatement dominates the externalities, platinum is the second largest externality, yet reducing the benefits obtained by the CO_2 abatement. The positive externalities from air pollution and noise abatement almost reach to compensate for the negative costs caused by platinum depletion. The externalities have a positive effect from 2025. Using a societal cost accounting framework with externalities and subsidies, hydrogen transition timing is reduced by four years for the example considered.

1. Introduction

Hydrogen, the simplest element on earth, consisting of only one proton and one electron, can store and deliver usable energy. Since hydrogen does not typically exist by itself in nature, it must be produced from compounds that contain it (IEA 2017).

Hydrogen production and distribution have been developed for many years mainly for several industrial applications, i.e., in chemical and metallurgical uses, food industry, and space program (IEA 2017). Hydrogen can also be used in fuel cells to generate power using a chemical reaction rather than combustion, producing only water and heat as by-products. These features make it attractive for the automotive sector, which requires a clean and feasible substitute for current internal combustion engine vehicles (ICEVs) that run with fossil fuels (IEA 2015). Transport is one of the main contributors to energy demand and, currently, the fastest-growing source of greenhouse gas (GHG) emissions: in 2015, the transport sector contributed 25.8% of total EU-28 greenhouse gas emissions. Hydrogen technologies, using hydrogen as a carrier of sustainably produced renewable energy, have been presented as solutions to rising levels of GHG emissions from transport, and at the same time, hydrogen fuel cell technologies promise very low levels of noise and particle pollution from cars (IEA 2017). A range of socio-cultural barriers to the implementation of hydrogen technologies in the transport sector needs yet to be overcome (Petersen and Andersen, 2009): awareness, familiarity, and general acceptance of the technologies.

Mobility attitudes of individuals cannot be considered as isolated choices of technically or environmentally efficient solutions

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Acronyms

APA	Pollution abatement
CBA	Cost-benefit analysis
CCS	Carbon Capture and Storage
CO	Carbon monoxides
FCV	Fuel Cell Vehicle
FCV_{number}	Number of FCVs
GA	Genetic algorithms
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	Hydrocarbon
HRS	Hydrogen refuelling station
HSC	Hydrogen supply chain
ICEV	Internal Combustion engine Vehicle
LCA	Life cycle assessment
NA	Noise abatement
NOx	Nitrogen oxides
NPV	Net present value
NSGA	Non-dominated sorting genetic algorithm
MC	Maintenance costs
MCDM	Multi-criteria decision-making
PD	Platinum depletion
PP	Purchase price
RC	Running cost
SMR	Steam methane reforming
SNPV	Social net present value
SCBA	Social cost-benefit analysis
TCO	Total cost of ownership
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VAT	Value added tax
vkm	Vehicle-kilometre

since the deployment of a hydrogen economy for mobility applications involves several stakeholders (consumers, automotive manufacturers, hydrogen producers, and distributors, filling station owners, and policymakers…). Although the risks associated with a fossil fuel-oriented transport system have been one of the driving forces behind the development of hydrogen technologies for transport, the hydrogen alternative is not considered without risk. For example, some concern has been expressed about the danger of explosion related to onboard storing of hydrogen for cars in high-pressure fuel tanks (Vieira et al., 2007).

In that context, the deployment of hydrogen supply chains (HSCs) for market penetration of FCVs has raised a lot of interest. A lot of studies have addressed several issues related to HSC design and deployment (Agnolucci et al., 2013; Almansoori and Betancourt-Torcat, 2016; Almansoori and Shah, 2012; Almaraz et al., 2014; Gondal and Sahir, 2013; Guillén-Gosálbez et al., 2010; Han et al., 2013; Hugo et al., 2005; Kamarudin et al., 2009; Kim et al., 2008; Kim and Moon, 2008; Sabio et al., 2010; Samsatli et al., 2016; Woo et al., 2016) to find the most efficient HSC network taking into account several criteria, that are mainly based on techno-economic consideration, such as the levelized hydrogen cost and environmental assessment with Global Warming Potential (GWP) impact as a key indicator and, in a more systemic way with Life Cycle Assessment (LCA) (Guillén-Gosálbez et al., 2010; Hugo et al., 2005) as well as a risk index (Almaraz et al., 2014; Han et al., 2013; Kim and Moon, 2008; Sabio et al., 2010).

Even if socio-cultural issues of technological development and energy transition are intertwined with the technological and economic aspects, socio-cultural criteria are often difficult to be quantified at early development so that they are scarcely integrated into design methodologies despite their importance.

The social aspects of hydrogen usage have so far been addressed mainly either from a qualitative sustainable perspective or at a macroscopic scale to evaluate the social relevance of global scenarios. Firstly, several papers have been focused on hydrogen, as the main actor to make the change to a more sustainable scenario regarding mobility and production of energy (Afgan et al., 2007; Chang et al., 2011; Ren et al., 2013; Ren et al., 2013; Hsu, 2013; Markert et al., 2016). Secondly, a few strategies have been assessed to narrow the gap towards a hydrogen economy (Qadrdan et al., 2008; Moliner et al., 2016; Keles et al., 2008). The potential of a hydrogen economy and its acceptance in the future have also been investigated compared to other sustainable alternatives (Ball and Weeda, 2015; Ricci et al., 2008; Sgobbi et al., 2016).

For policy-making and large-scale studies on emission reduction, cost-benefit analysis (CBA) and, in particular, social cost-benefit analysis (SCBA) referring to cases where the project has a broad impact across society has received much attention over the last 20 years, requiring that the benefits are expressed in monetary units. Social cost-benefit analysis is a systematic method to survey all the impacts caused by a project encompassing the financial effects (investment costs, profits …), and the societal effects, like pollution, environment, safety, health, labor market impacts, legal aspects …. This is particularly useful for projects, that have both socio-economic and environmental components. Social CBA is scientifically established and widely used in policy impact assessments as highlighted in (van der Kamp, 2019).

To our knowledge, the societal lifetime cost of hydrogen fuel cell vehicles has been first addressed in (Sun et al., 2010). This work evaluates societal lifetime cost as an important measure for evaluating hydrogen fuel cell vehicles (FCVs) from a societal welfare perspective as compared to conventional gasoline vehicles. In this paper, special attention is focused on the comparison of both types of vehicles.

More recently, a social cost-benefit analysis (CBA) for hydrogen market penetration has been investigated in some significant works: the progressive replacement of gasoline ICEV by hydrogen FCV in the European market over the period 2015-2055 has been assessed in (Sun et al., 2010; Creti et al., 2015). This study provides a comprehensive support scheme that bridges the gap between three main dimensions: (1) market requirements with the reduced cost of cars and hydrogen fuelling stations, (2) sustainability and climate requirements, and (3) hydrogen technology development (Cantuarias-Villessuzanne et al., 2016) targeting to lower or replace the use of noble materials like platinum in fuel cells and electrolyzers.

On a smaller scale, a techno-economic-financial evaluation of a PV production plant to produce hydrogen to be sold as a feedstock for industries and research centers has been recently proposed in (Nicita et al., 2020).

Despite the benefits behind green hydrogen, policy initiatives that help reduce its cost and remove market barriers need to be set up, as highlighted in (Creti et al., 2015).

Given the challenges of the hydrogen market for mobility, this work presents an SCBA framework to assess the progressive replacement of ICEVs by hydrogen FCVs in the French market of the Occitania region (part corresponding to the former Midi-Pyrénées region) over the period from 2020 to 2050, supported by the multi-objective optimization framework for HSC design and deployment proposed in (Cantuarias-Villessuzanne et al., 2016).

In the studies about hydrogen mobility CBA studies (Creti et al., 2015; Cantuarias-Villessuzanne et al., 2016) that are reported in the literature, the hydrogen supply chain encompasses processes with a “coarse-grained” approach for each technology including techno-economic and environmental assessment (average values for cost and carbon emissions for instance). They are more prospective-oriented investigations while this study is more design-oriented for the identification of the components of a supply chain adapted to a specific region. The approach proposed by (Cantuarias-Villessuzanne et al., 2016) thus considers a hydrogen production mix of five technologies: steam methane reforming (SMR) from natural gas; SMR with carbon capture and storage (CCS); water electrolysis; SMR with biogas and SMR on-site type station.

The contribution of this work is the development of a comprehensive framework based on a “fine-grained” approach that connects the results that have been obtained from multi-objective optimization and a subsequent multi-criteria decision making for hydrogen supply chain design with the SCBA evaluation criteria so that a more precise description of the mix of technologies of the different echelons of the supply chain is involved. The scientific objective of this work is thus essentially based on the development of a methodological framework to quantify the potential societal benefits of hydrogen fuel cell vehicles. The main interest is to show how, from a methodological point of view, the information from the optimization and decision support approach can be used to feed the SCBA analysis and how the different approaches can interact.

The case study that will be proposed is a part of Occitania’s region, the former Midi-Pyrénées: Occitania’s ambition is to become the first Positive Energy Region in Europe and is committed to dividing by two its energy demand per capita, that is the equivalent of a 40% reduction of the energy demand of the Region, and to multiplying by three its renewable energy production, both by 2050. The costs and benefits of the penetration of FCV will be studied here as one solution to achieve this ambition, even some of the data used are not the most accurate that are available.

This paper attempts to answer the following research questions: how can the HSC design strategy integrate an SCBA methodology? What is the magnitude of externalities and other social costs for FCVs as compared to ICEVs? Will the societal benefits of hydrogen and FCVs make these vehicles more competitive with ICEVs? How does this affect transition timing for hydrogen FCVs?

This paper is divided into four sections following this introduction. Section 2 presents the methods and tools used in the global framework involving multi-objective optimization framework for HSC design, Multi-Criteria Decision Making (MCDM), and Social Cost-Benefit analysis. Section 3 is devoted to the application of the methodological framework with the main assumptions used. The results obtained are discussed in Section 4. The conclusions are highlighted in Section 5.

2. Methods and tools

Fig. 1 presents the global framework including the multi-objective optimization formulation for HSC design and deployment model, the Multi-Criteria Decision Making technique used for the selection of a compromise solution, and the SCBA methodology.

2.1. Multi-objective optimization framework for HSC design

The first step of the methodology for the determination of the optimal HSC network is based on a multi-objective multi-period demand-oriented model (Ochoa Robles et al., 2016) using a genetic algorithm to generate the Pareto front.

A general Supply Chain Network (SCN) model for hydrogen is considered (production plants, storage units, distribution grids and demand for each grid) (see Fig. 2) The model formulation involves the territory division into districts in which the number, size, and type of production and storage units (integer variables) have to be determined with the considered objective functions and constraints as well as the flow rate (continuous variables) of hydrogen transported into the network. An average distance between the main cities is considered to calculate the delivery distances over the road network. The technical, financial, and environmental data as well as the hydrogen demand are embedded in the model as input parameters.

The assumptions for this study are:

- A grid is defined as a territorial division,
- The number of grids is known;
- The capacity of the production plants and the storage plants is known;
- The demand for each one of the grids is fixed and known;
- It is possible to either import or export hydrogen from/to each grid;
- Liquid hydrogen transport is achieved by tanker trucks. Even if distribution costs will drop significantly with higher utilization of distribution system infrastructure, and in particular with the usage of existing pipeline networks, this option has not been explored for the case study due to the relatively low hydrogen demand at the regional scale;
- In the model, hydrogen can be produced by either steam methane reforming (SMR) or electrolysis: (1) at or near the site of use in distributed production (DisElectrolysis), or (2) at large facilities and then delivered to the point of use in central production (Electrolysis).
- The model also computes the number of hydrogen refueling stations (HRS) to be installed.

The modeling approach used one economic objective based on hydrogen total daily cost (TDC) derived from Total Cost of Ownership (TCO) and one environmental objective based on GHG (greenhouse gas) emissions based on Global Warming potential indicator. These two criteria were identified as target criteria in a previous study from which the comparison may be possible among the scenarios that have been studied (see (De-León Almaraz et al., 2014)). The involved constraints are related to demand satisfaction, the availability of energy sources, production facilities, storage units, transportation modes, and flow rates.

The issue addressed in the paper is formulated as a multi-objective (here bi-objective) problem as most of the practical engineering optimization problems. It is well recognized in the dedicated literature that typical challenges in solving optimization problems include a large number of decision variables as well as a large number of constraints. In addition, in multi-objective optimization, a high number of objective functions provides additional challenges for algorithms (Greco et al., 2017).

Among these methods, existing evolutionary multi-objective optimization methods, which turned out to be very attractive due to their ability to lead to a well-representative set of Pareto-optimal solutions in a single simulation run, are generally applied only to problems with two to three objective functions. The major impediments in handling a large number of objectives are related to the stagnation of search process, increased dimensionality of Pareto-optimal front, and large computational cost. Furthermore, several objectives may be redundant so that a multi-objective strategy is not, strictly speaking, necessary.

Multi-objective optimization is part and parcel of the global HSC design framework. The interest of performing the optimization with Total Cost of Ownership and Global Warming Potential as objective functions is that their evaluation requires fewer parameters than for the evaluation of the criterion involved in SCBA, thus reducing uncertainty at the main optimization step of the methodology. The monetized version (to optimize based on a single parameter) that could be used including all the externalities and not

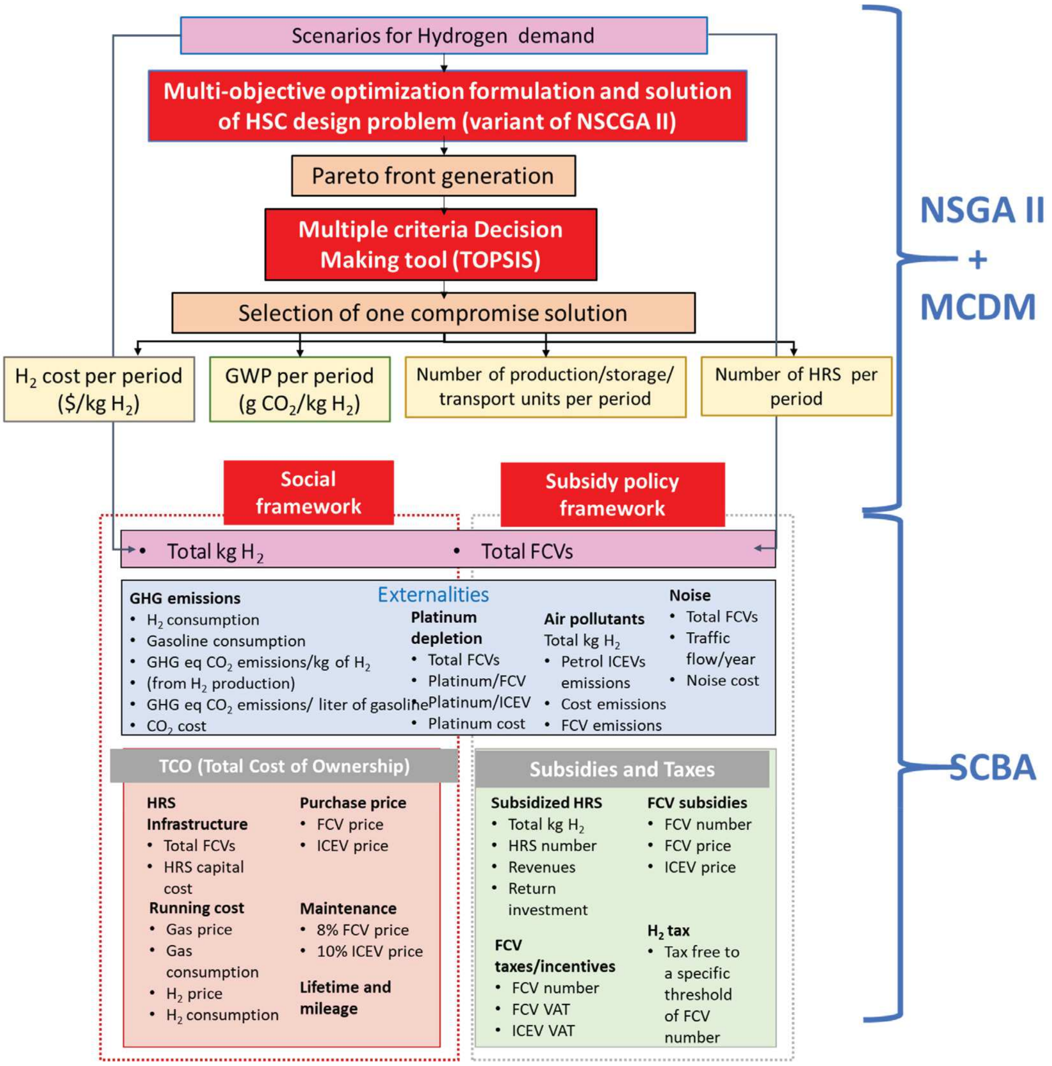


Fig. 1. General methodology - FCV: Fuel Cell Vehicle; ICEV: Internal Combustion engine Vehicle; NSGA II: Nondominated Sorting Genetic Algorithm II; MCDM: Multi-criteria decision-making; SCBA: social cost-benefit analysis.

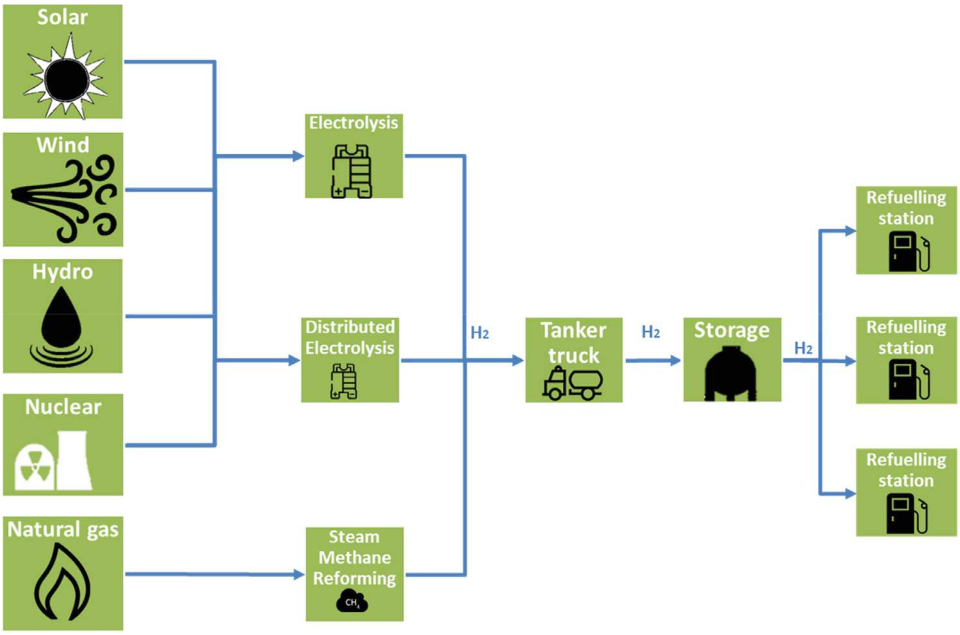


Fig. 2. Supply chain network model.

only Global Warming Potential has thus not been considered at this level.

All these elements are in favor of the methodology proposed here and justify why the externalities have been added neither to the set of objective functions nor as additional constraints related to SCBA in the optimization phase.

This model has been embedded in an external optimization loop based on a variant of the non-dominated sorting genetic algorithm (NSGA-II) to manage multi-objective formulation so that compromise solutions can be produced automatically (Ochoa Robles et al., 2020).

2.2. Multi-criteria decision making (MCDM) with TOPSIS

The choice of the HSC configuration that will be selected and proposed to SCBA is performed through a multi-criteria decision-making process. MCDM approaches are major parts of decision theory. The objective is to help decision-makers to learn about the problems they face, and to identify a preferred course of action for a given problem. A large variety of approaches have been proposed in the dedicated literature (Mardani et al., 2015). Among them, TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is a common method used in engineering problems. Its main advantage over other methods is the reduced number of parameters involved in its implementation thus limiting subjectivity. A modified TOPSIS (M-TOPSIS) evaluation is based on the original concept of TOPSIS and proposed by (Ren et al., 2007) is used. It chooses an alternative that has simultaneously the closest distance from the positive ideal solution and the farthest distance from the negative ideal solution, solving the rank reversal and the evaluation failure problem presented in the original TOPSIS technique.

2.3. Social cost-benefit analysis (SCBA)

2.3.1. Social framework

The methodological framework is based on the SCBA proposed by (Cantuarias-Villessuzanne et al., 2016) that also extends the CBA approach conducted by (Creti et al., 2015). The interest of using SCBA is to include external costs in order to consider the costs and benefits to society as a whole (Cantuarias-Villessuzanne et al., 2016): costs and benefits will be considered from a broad, societal perspective as opposed to the « narrow » perspective of individual investors in greenhouse gas reduction activities. The study presented by (Creti et al., 2015) was applied to the German market considering the abatement cost of carbon through FCV and various hydrogen production processes while the external costs related to platinum depletion were also included (Cantuarias-Villessuzanne et al., 2016).

The societal perspective can be applied to a country, a region, e.g. the European Union, or the world. This work sets out to consider the perspective of the former region « Midi-Pyrénées » for which the HSC deployment has already been studied before the new region segmentation in France in 2016.

A baseline scenario considering that petrol ICEVs would be the dominant form of vehicles in the future has been implemented for comparison purposes.

Besides, for performing a social cost-benefit analysis of a long-lasting project, several crucial aspects should be addressed:

(I) First, benefits and costs at different dates should be aggregated. For this purpose, a specific discount rate is used to find the present values of future benefits and costs generated. A social discount rate - i.e. a rate of discount appropriate for social cost-benefit analysis of a project - needs to be applied instead of any financial discount rate that is only relevant to the project promoters;

(II) Second, external effects need to be identified: based on a literature review (Sun et al., 2010; Creti et al., 2015; Cantuarias-Villessuzanne et al., 2016; Nicita et al., 2020), the following externalities GHG emissions, platinum depletion, air pollutant, and noise have been considered and their social value is assessed: a price per period must be assigned to each externality.

(III) Financial (market) prices may be corrected for project acceptance: indirect subsidies need to be added and indirect taxation subtracted (Egenhofer et al., 2006).

(IV) At last, the net present value (NPV) which is the sum of the discounted differences between benefits and costs is referred to as the indicator of the viability of the project. The project should be accepted if the NPV is positive (Creti et al., 2015) and rejected otherwise. The NPV is calculated as follows:

$$NPV = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+i)^t} \quad (1)$$

where n is the project duration, i is the discount rate. In this expression, C_t and B_t represent the future cost or benefit in monetary terms at year t.

NPV will be indexed NPV_{CBA} and NPV_{SCBA} when respectively a cost-benefit (or a social cost-benefit) assessment is implemented. NV will refer to the differences between benefits and costs (without discounting).

2.3.2. Subsidy policy framework

The abovementioned discussion has emphasized that the market penetration of fuel cell vehicles (FCVs) involves different stakeholders. According to the dedicated literature, most economic models describing the introduction of hydrogen-powered vehicles have only focused on one segment of the car market. One significant contribution (Keles et al., 2008) models the market penetration of fuel cell vehicles, taking the various stakeholders involved into account: this study highlights that the combination of tax-free hydrogen fuel, subsidies on FCVs, and sufficient hydrogen infrastructure supply could lead to quick market penetration of FCVs. Although the study proposed in (Keles et al., 2008) can be viewed as relatively old, the analysis has been conducted through scenarios seeking to represent the key processes driving a transition to a hydrogen-fueled transportation system. So even if the scenario can be considrered as optimistic (McDowall, 2016) it has been used in this study for the sake of illustration of the proposed methodology that is generic enough to be replicated with updated data. The definition of energy scenarios, and particularly, the role that hydrogen should play in the future energy mix. is identified by several authors as a challenging task (Quarton et al., 2019).

The analysis proposed by (Keles et al., 2008) is particularly meaningful in the sense that it takes into account the actions of the whole market (consumers, automotive manufacturers, filling station owners, and policymakers) and their interactions as well as the corresponding data set. According to our knowledge, no such comprehensive study has been published most recently.

Following the guidelines proposed by (Keles et al., 2008), the impact of subsidy policies is considered in the social CBA addressed here based on the work reported in (Cantuarias-Villessuzanne et al., 2016).

2.3.3. SCBA criteria assessment

The economic comparison for the social framework is evaluated by the Total Cost of Ownership (TCO) method (Creti et al., 2015). The TCO of replacing petrol ICEVs by FCVs considers the costs over the lifetime of a vehicle, including purchase price (the sum of all costs to deliver the assembled vehicle to the customer), maintenance cost, running cost and HRS infrastructure cost. This economic comparison is based on the difference between buying

Table 1
HSC configuration.

Year	2020	2030	2040	2050
Demand (t per day)	7.90	59.43	138.79	198.17
Number of total production facilities	*25*	*62*	*92*	*110*
Number of total storage facilities	*12*	*66*	*150*	*214*
Capital cost				
Plants and storage facilities (10^6 €)	304.47	401.53	263.71	43.44
Operating cost				
Plants and storage facilities (10^3 € per day)	43.44	307.15	708.68	1013.16
Total daily cost (10^3 € per day)	80.12	489.34	1036.96	1446.56
Cost per kg H_2 (€)	*10.14*	*8.23*	*7.47*	*7.30*
Production facilities (t CO_2-eq per day)	8.27	61.35	142.51	201.91
Storage facilities (t CO_2-eq per day)	5.56	41.84	97.71	139.51
Total GWP (t CO_2-eq per day)	13.73	103.18	240.22	341.42
kg CO_2-eq per kg H_2	*1.74*	*1.74*	*1.73*	*1.72*

an FCV, including the infrastructure needed, and the conventional case of buying a petrol ICEV (Cantuarias-Villessuzanne et al., 2016).

The ΔTCO is given by the variation of cost of ownership of the vehicle (FCV vs. petrol ICEV) for the purchase price (PP), maintenance cost (MC) and running cost (RC), plus the investment on HRS infrastructure (HRSI) per car unit in the market, as shown in Eq. 2.

$$\begin{aligned}\Delta TCO_t &= \Delta PP_t[ICEV - FCV] + \Delta MC_t[ICEV - FCV] \\ &\quad + \Delta RC_t[ICEV - FCV] + HRSI_t \\ &\qquad \forall\; t \in 2020\ldots2050\end{aligned} \tag{2}$$

The purchase price (PP) has been distributed among the different years included in the lifetime of the vehicles. The running cost (RC) depends on fuel consumption, using the results obtained in Table 1.

The NPV_{TCO} is obtained by the product of ΔTCO_t and the number of FCVs in each period, as shown in Eq. 3.

$$NPV_{TCO} = \sum_{t=0}^{n} \frac{1}{(1+i)^t} (\Delta TCO_t \times FCV_{number}) \tag{3}$$

Eq. 4 expresses SNPV for the social-economic framework.

$$SNPV = \sum_{t=0}^{n} \frac{1}{(1+i)^t} \begin{bmatrix} -(\Delta TCO_t \times FCV_{number}) + NV_{CO_2\ abatement} \\ -NV_{platinum\ depletion} + NV_{air\ pollution\ abatement} \\ +NV_{noise\ abatement} \end{bmatrix} \tag{4}$$

A similar expression can be proposed for the subsidy-policy framework, in Eq. (5)

$$\begin{aligned} NPV_{subsidies} = \sum_{t=0}^{n} \tfrac{1}{(1+i)^t} \big[&-NV_{Subsidies\ HRS} - NV_{Subsidies\ FCVs} + NV_{Taxes\ FCVs} \\ &- NV_{Taxes\ H_2} + NV_{CO_2\ abatement} - NV_{platinum\ depletion} \\ &+ NV_{air\ pollution\ abatement} + NV_{noise\ abatement} \big] \end{aligned} \tag{5}$$

where:

$$NV_{Subsidized\ HRS} = \frac{II}{AI} + (II \times M) - (Q_{2020} \times MG) \tag{6}$$

$$NV_{Subsidies\ FCVs_t} = FCV_{price_t} - FCV_{paid_t} \tag{7}$$

$$NV_{Taxes\ FCVs} = FCV_{number_t} \times (VAT_{ICV_t} - VAT_{FCV_t}) \tag{8}$$

$$NV_{Taxes\ H_2} = \left(\frac{FCV_{2020} - FCV_{untaxed}}{FCV_{2020}} \times Q_{2020} \times C_{2020} \right) \tag{9}$$

In these expressions:

II is the initial investment for the HRS
AI is the depreciation period for HRS
M is the maintenance cost in percentage of the II
Q_{2020} is the quantity of hydrogen consumed by the FCVs in 2020
MG is the profit margin per kg of H_2
FCV_{price} is the price of each FCV with VAT
FCV_{paid} is is the price of each FCV with VAT
FCV_{number} is the number of FCVs
VAT_{ICEV} is the VAT of the ICEV
VAT_{FCV} is the VAT of the FCV
$FCV_{untaxed}$ is the number of untaxed FCVs
FCV_{2020} is the number of FCVs in 2020
C_{2020} is the H_2 cost per kg in 2020 i is the discount rate

3. Applications of the methodological framework

3.1. Hydrogen demand and FCV market

To identify the demand of vehicles for each grid, a study of their evolution in the last 20 years was conducted, and then a weight factor depending on population density was assigned. Finally, following the observed trend, a 30 year-prediction has been implemented for demand estimate. The categories considered are particular vehicles. The hydrogen demand is a function of the average distance covered in km/year and of the standard fuel economy for each category.

The introduction of FCVs is compared to a business-as-usual scenario considering the existing petrol ICEVs. This work only considers passenger vehicles, accounting for almost 90% of the existing vehicles in Europe, and over 60% of the CO_2 emissions from transport mobility (International Council on Clean Transportation 2016). The number of FCVs (market size) and the hydrogen demand are based on market penetration assessment from (De-León Almaraz et al., 2014):

$$FCV_{number} = Market\ penetration \times Total\ number\ of\ vehicles \tag{10}$$

3.2. Main features of HSC configuration for post-optimal SCBA

The HSC configuration corresponds to the compromise solution obtained from the sequential implementation of the multi-objective optimization procedure and the MCDM technique (see Table 1), i.e., TOPSIS (Ren et al., 2007) with equal value for cost and environmental criteria.

Even if hydro-electric and wind power are among the top clean energy technologies, their environmental impact can be analyzed, assessed, and compared via a life-cycle assessment approach (including the manufacturing, construction, operation, and decommissioning stage). Due to the importance of Global Warming Potential

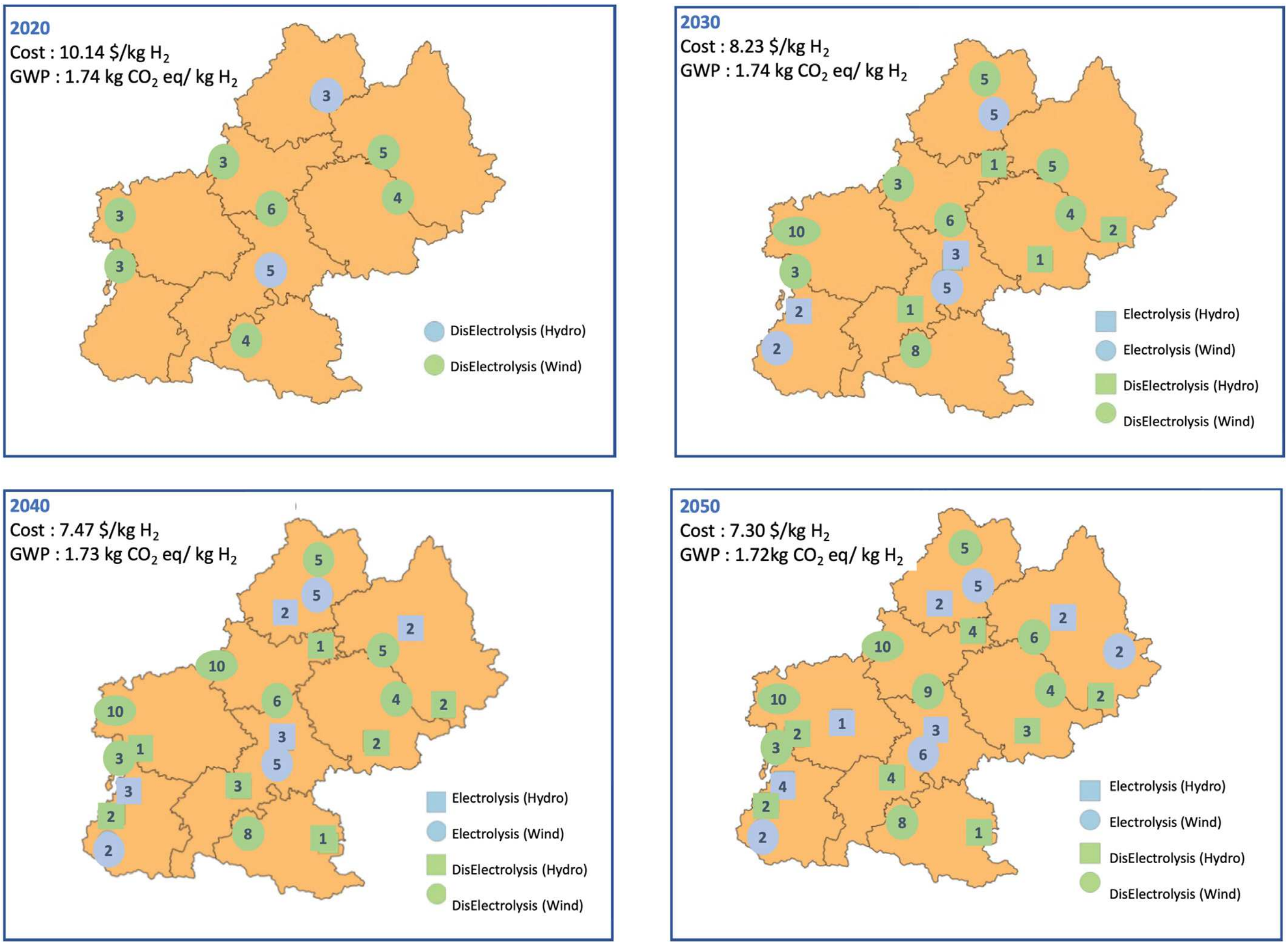


Fig. 3. Maps of the HSC configuration (the number of installed plant is indicated between brackets).

Table 2
Use ratio of energy sources for hydrogen production.

Energy sources	2020	2030	2040	2050
Hydro	22%	30%	22%	33%
Wind	78%	70%	78%	67%

in climate change metrics, this indicator has been adopted and its value covers the activities of the entire supply chain.

In the first period (see Fig. 3), the distributed plants are the main source of production, while in the other periods the electrolysis plants started to be installed in the grids. There is also no transport between grids (this is also recurrent for the other periods and the HSC is fully decentraliszed) and the CO_2 emissions for the plants installed remain very low (Table 1) and quite constant. For all the periods, most of the energy sources used stem from wind, with almost the 70% of the electricity produced (Table 2): hydrogen produced via electrolysis from solar energy (see Appendix) is eliminated in the optimization process since it is the most expensive process and exhibits a higher carbon footprint compared to wind and hydro.

Hydrogen produced with electrolysis from a hydro source is the less expensive one (see Appendix for the cost model). It must be emphasized that in Occitania (in particular in former Midi Pyrénées region), hydropower is one main energy source in some departments, (i.e. 950 MWp installed in 130 hydraulic plants in Hautes Pyrénées). Only the run-of-river power plants were considered, as the production of impoundment facilities is essentially used as a water reservoir, and the pumped storage systems are used for electricity generation during high demand peaks.

3.3. Assumptions for SCBA

The SCBA analysis that has been conducted is based on the following assumptions:

- the average distance per vehicle is 14,000 km/year (ACEA 2009),
- the lifetime of a vehicle is set at 10 years (Creti et al., 2015),
- FCV vehicles enter the market in 2020,
- four sizes of HRS are considered: 80, 200, 400 and 1000kg/day (Creti et al., 2015),
- the lifetime of an HRS is fixed at 15 years (Creti et al., 2015),
- a discount rate of 5% is considered as in (Cantuarias-Villessuzanne et al., 2016). A low value for the discount rate is generally adopted in order to promote renewable energies as highlighted in the scenarios presented in (ADEME 2016) and in (Ferrero et al., 2016).
- the hydrogen demand, the production mix, the CO_2 emissions (production step), and the production costs are obtained from (Ochoa Robles et al., 2016),
- the maintenance costs (MC) considered represent 8% and 10% of the capital costs, for FCVs and petrol ICEVs respectively and are constant over the time period (Creti et al., 2015),
- a total of 2.3 million car journeys per day in Toulouse, each one of 7 km was considered (Thomas, 2017). The total vehicle distance per year is 5,876,500 (1000 vkm (vehicle-kilometre)).

Table 3
Noise abatement cost.

Mode	Time of the day	Urban (€ per 1.000 vkm)	Suburban (€ per 1.000 vkm)	Toulouse Metropolitan (€ per 1.000 vkm)
Car	Day	15.10	0.95	12.27
	Night	27.50	1.70	22.34
				13.78
			Noise abatement cost	1.70

Table 4
Air pollutant assumptions.

	ICEV emissions (g/km)	Unitary Cost (€/t)
Nox	0.06	8,419.85
CO	1.00	2,185.93
HC	0.10	3,322.31

- according to ('Toulouse Population 2018' 2017), 80% of Toulouse population is 80% urban and 20% suburban. In the same way, as the distance traveled during the day is longer than during the night, a 0.85-0.15 ratio has been adopted,
- a marginal noise cost of 8.8 and 21.4 € per 1000 vkm, for dense and light traffic respectively, is considered during the day. During the night, a cost of 38.9 and 17.7 € per 1000 vkm, for a dense and light traffic respectively, is considered (Ricardo-AEA 2014). A ratio of 0.5-0.5 for the type of traffic has been adopted,
- the noise reduction for using an EV instead an ICEV is 12.30% (Iversen, 2015). The noise abatement cost is 1.70 € per 1000 vkm (Table 3),
- the NOx (nitrogen oxides), CO (carbon monoxides), and HC (hydrocarbon) emissions for ICEV, and their associated cost are

Table 5
General main assumptions (the running cost is given by multiplying the gasoline price with ICEV efficiency (Cantuarias-Villessuzanne et al., 2016 in Table 5) (with VAT).

		Units	2020	2030	2040	2050
	FCV efficiency (Cantuarias-Villessuzanne et al., 2016)	kg/100km	0.870	0.800	0.7529	0.700
	Market penetration (De León Almaraz, 2014)		1%	8%	18%	25%
	Number of vehicles		31,565	236,744	552,403	789,148
	ICEV efficiency (Cantuarias-Villessuzanne et al., 2016)	l/100km	6.20	4.88	4.83	4.80
	Average carbon price (Cantuarias-Villessuzanne et al., 2016)	€/ton CO_2	40	90	130	155
HRS types (Capital cost) (Creti et al., 2015)	80 kg/d	k€	1,000	872	822	783
	200 kg/d		1,000	872	822	783
	400 kg/d		1,732	1,418	1,312	1,235
	1,000 kg/d		3,000	2,301	2,121	1,984
HRS types (Units)	80 kg/d		0	0	0	0
	200 kg/d		9	58	31	0
	400 kg/d		7	44	107	75
	1,000 kg/d		6	44	111	182
	FCV purchasing cost (20% VAT not included) (Cantuarias-Villessuzanne et al., 2016)	k€	37.90	28.90	25.41	23.10
	ICEV purchasing cost (20% VAT not included) (Cantuarias-Villessuzanne et al., 2016)	k€	21.40	21.10	20.80	20.50
	Gasoline price (wo VAT) (Cantuarias-Villessuzanne et al., 2016)	€/l	1.35	1.46	1.58	1.71
	ICEV running cost (Cantuarias-Villessuzanne et al., 2016)	€/km	0.100	0.085	0.092	0.098
	ICEV CO_2 emissions (Cantuarias-Villessuzanne et al., 2016)	Kg CO_2/100 km	17.4	13.7	13.6	13.5
	FCV Platinum (Cantuarias-Villessuzanne et al., 2016)	g/vehicle	35.00	18.70	12.96	10.00
	ICEV Platinum (Cantuarias-Villessuzanne et al., 2016)	g/vehicle	5.60	5.60	5.60	5.60
	Platinum Cost (Cantuarias-Villessuzanne et al., 2016)	€/g	19.44	19.44	19.44	19.44
	FCV Distance traveled	km	4,419,100	33,144,160	77,336,420	110,924,417
	Total FCV distance per year	1000 vkm	117,527	881,474	2,056,773	2,938,250

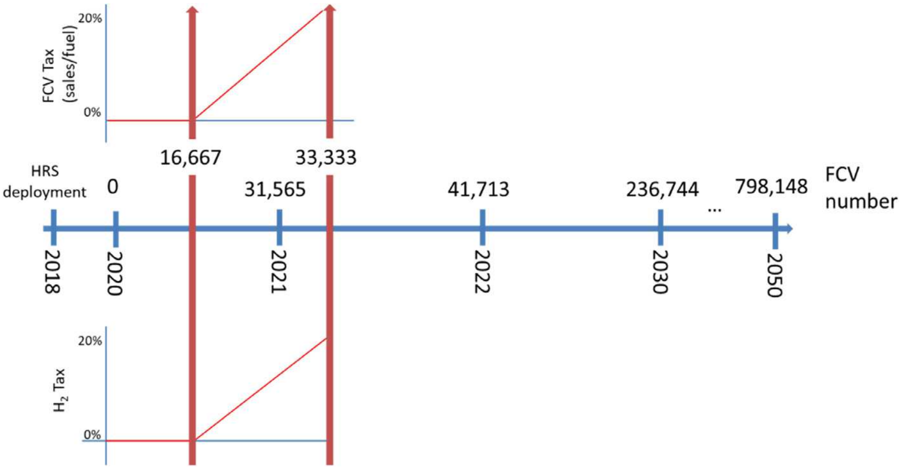


Fig. 4. Consideration of taxes for FCVs and hydrogen fuel.

Table 6
Initial HRS investment.

HRS type	Number of HRS	Initial Investment (M€)
80 kg/d	0	0.0
200 kg/d	9	13.5
400 kg/d	6	12.0
1000 kg/d	2	6.0
Total		31.5

based on (Song, 2016) (Table 4). The FCVs are considered as zero-emission vehicles.

- FCVs and ICEVs are analyzed within the same scope. For both vehicles, the manufacturing step is not included in the lifecycle assessment.
- Some assumptions concerning the number of FCVs, the cost and number of HRS, the FCV and ICEV purchasing costs, and additional information are presented in Table 5.

The dataset adopted is mainly from (Cantuarias-Villessuzanne et al., 2016). It must be yet highlighted that more updated values could have been adopted (see for instance (IEA, 2017) for ICEV efficiencies).

In the case of the subsidy-policy framework, the main assumptions have been based on the estimatesperformed in (Keles et al., 2008) for the German market (44.4M passenger cars (Bekker, 2016), adjusting the parameters to Midi-Pyrénées (1.58M passenger cars (De León Almaraz, 2014)):

- 17 subsidized HRSs are implemented before FCV market penetration in 2017 with cumulated hydrogen supplying capacity of 2,133 tonnes/year (Q_{2020}). The initial investment (II) for the deployment of the HRS is 31.5M€, in order to satisfy the required supply capacity (Table 6). A 8-year depreciation period (AI) is considered for HRS (depreciation of 3.94 M€/year).
- the HRS operational and maintenance costs (M) represent 10% (of the capital cost) in 2020 and decrease until 9% in 2025,
- a margin of gain (MG) of 2€ is considered for the initial HRS, to the hydrogen price that allows generating some profits,
- subsidies for FCVs equal the cost difference between FCVs and petrol ICEVs, minus 2,000€. Consumers are willing to pay 2,000€ more for the "clean" technology (Keles et al., 2008) (FCV_{paid} is the price of each FCV with VAT plus 2000),
- hydrogen fuel is completely tax-free until the FCV market represents 16,667 cars ($FCV_{untaxed}$). Subsequently, the vehicle tax level is raised, following a linear growth curve, to reach 20% VAT until 33,333 FCVs are sold (Fig. 4),

4. Results and discussion

4.1. Economic framework

Following the abovementioned guidelines, TCO is evaluated and the results are presented in Table 6. The social framework will be compared to this baseline scenario in what follows. From the results of Table 7, FCVs become cost-competitive with petrol ICEVs in 2046.

4.2. Subsidy-policy framework

Incentives to subsidize both HRS and FCV that help stimulate the adoption of fuel cell and hydrogen technologies have been considered (Table 8), including subsidies for HRS, FCV, tax alleviation of hydrogen tax, and of FCV purchase (see the aforementioned assumptions). The equations used to obtain the subsidy-policy framework are those presented in Section 2.3.3. From an economic viewpoint, the implementation of the subsidy-policy framework is less favourable.

4.3. Externalities

The externalities are third-party effects caused by hydrogen mobility usage, which are not accounted directly for as a monetary cost or benefit.

4.3.1. Greenhouse gas emissions

A comparison of GHG emission level between FCVs and petrol ICEVs is performed from the optimization results. Regarding FCVs, GHG emissions are involved for production, storage, and transportation of hydrogen (yet no transportation has been observed for the optimal HSC under study). Regarding ICEVs, only the emissions generated during the combustion process have been considered.

Besides, the future carbon prices in EU-28 will be used to calculate CO_2 abatement value. The CO_2 abatement is given by the difference of the emissions between FCV and ICEV and the price of CO_2 (in €/ton CO_2). For the case of the FCV emissions, the values from Table 1 are used (Eq. 10).

$$CO_2abatement_t = (\Delta Emissions_t)(CO_2cost_t) \tag{10}$$

To calculate CO_2 abatement, an average value of carbon prices in EU-28 has been used. The results show the cumulated CO_2 abatement benefits through the different periods (Table 9). The presence of FCVs contributes to a reduction of 21 × 10^9 $kgCO_2$ from 2020 to 2050. Moreover, this reduction represents an external social benefit of 42.22 M€ (2017) in 2050.

Table 7
Economic comparison.

		2020	2030	2040	2050
Δ HRSI infrastructure	€ per year year/vehicle € per year	-1239.47	-183.42	-116.09	-100.64
Δ Purchase price		-1980.00	-936.00	-552.00	-312.00
Δ Maintenance cost		-892.00	-202.00	48.00	202.00
Δ Running cost		-64,96	-260,18	-340,49	-617,83
Δ TCO	€ year/vehicle	4046,51	1061,24	279,60	-407,20
NV_{TCO}	M€ per year	-127,73	-317,95	-238,58	254,16
NPV_{TCO}	M€ per year	-110,34	-168,61	-77,67	50,80

Table 8
Net present economic values for the subsidy-policy framework.

		2020	2030	2040	2050
NPV Subsidized HRS	M€	-10.80	0	0	0
NPV Subsidies for FCVs		-474.44	-222.13	-92.77	-15.26
NPV Taxes on FCV purchase		-59.04	12.76	11.89	8.48
NPV Taxes on hydrogen		-10.14	0	0	0
Total NPV		-554.43	-209.37	-80.88	-6.78

Table 9
CO_2 abatement results.

		2020	2030	2040	2050
Total FCVs Emissions	10^3 ton CO_2	6.68	46.08	101.19	134.41
Total ICEVs Emissions	10^3 ton CO_2	77.33	451.81	1,051.77	1,497.47
Δ Emissions	10^3 ton CO_2	70.65	405.73	950.57	1363.06
Average CO_2 price	€/ton CO_2	40	90	130	155
NV CO_2 abatement	M€ in year	2.82	36.51	123.57	211.27
NPV CO_2 abatement	M€	2.44	19.36	40.23	42.22

Table 10
Platinum depletion results.

		2020	2030	2040	2050
Δ Platinum depletion	M€ in year	-18.04	-15.33	-13.07	-9.07
NPV platinum depletion	M€	-15.58	-8.13	-4.25	-1.81

4.3.2. *Platinum depletion*

Expensive and insufficient platinum supply could be expected to be a barrier to widespread commercialization of hydrogen FCVs. According to (Cantuarias-Villessuzanne et al., 2016), the required platinum amount at a European level could reach nearly 600 metric tons by 2050, which is three times the current platinum supply. Thus, its scarcity will be calculated by measuring platinum depletion.

The mineral depletion is the change in stock value of the mineral resources and is commonly evaluated by the net price method (the market price minus the marginal extraction cost).

According to (Cantuarias-Villessuzanne et al., 2016), each gram of platinum extracted is depleting at 19.44 € (2015). This value is considered as constant over the studied period.

Currently, on the one hand, an FCV contains approximately from 30 to 40 g of platinum and a progressive reduction of platinum use down to 10-15 g in 2050 is expected to occur (Calle-Vallejo et al., 2015). As the fuel cell technology applied to vehicles is quite new, the required amount of platinum is expected to decrease due to technology improvement over the first years and stabilize progressively afterwards.

On the other hand, each petrol ICEV consumes 5.6 g of platinum and, given the maturity of the technology involved, this quantity is expected to remain stable during the analysed period.

The platinum depletion (PD) can be expressed as follows:

$$PD_t = FCV_t\,(\Delta platinum_t)\left(cost_{platinum_t}\right) \tag{11}$$

where (FCV_t) is the number of FCVs each year, ($\Delta platinum$) is the discrepancy between the platinum amount used in FCVs and ICEVs and ($cost_{platinum}$) is the cost per gram of platinum.

Table 10 presents the results regarding the platinum depletion cost and the cumulative present value of the platinum depletion costs over time. The presence of FCVs generates an external social cost, due to platinum scarcity, of 1.81 M€ (2017) from 2020 to 2050.

4.3.3. *Air pollutant abatement*

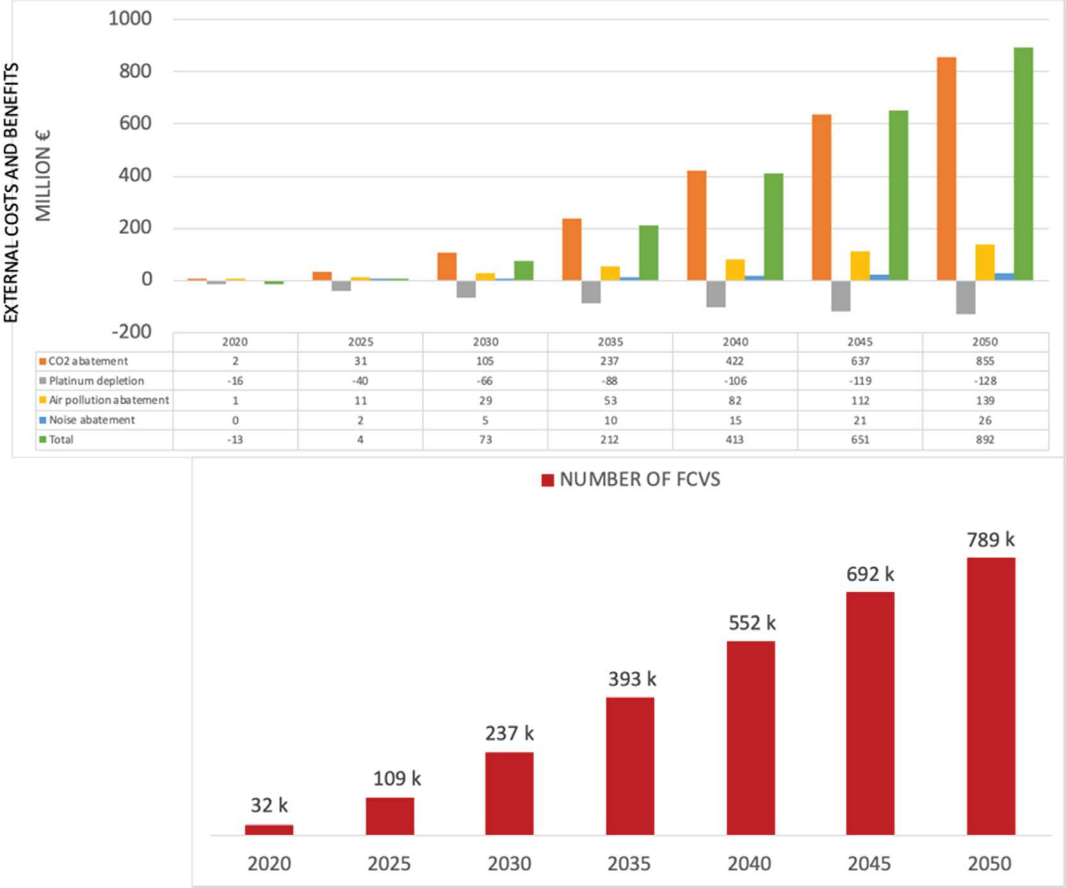
Air pollution has important impacts on human health, as well as on the natural and built environments. Through the damage cost methodology, it is possible to predict the impacts of changes in air pollution. These damage costs measure the marginal external costs or benefits caused by each additional tonne of pollutants emitted or avoided and can be used to value the benefits of air quality impacts of certain policies or projects when the only information available is the amount (in tonnes) of a pollutant that is reduced.

The air pollution abatement caused by the deployment of hydrogen takes into account the emissions of petrol vehicles and FCVs (zero-emission).

The air pollution abatement (APA) is based in (Song, 2016), and is given by the sum of the abatements of NO_x, CO and HC, multi-

Table 11
Air pollution abatement results.

		2020	2030	2040	2050
Δ NOx emissions	t NOx	26.51	156.53	361.64	515.79
NOx abatement	M€	0.22	1.31	3.04	4.34
Δ CO emissions	t CO	441.91	2608.87	6027.25	8596.46
CO abatement	M€	0.96	5.70	13.17	18.79
Δ HC emissions	t HC	44.19	260.89	602.73	859.65
HC abatement	M€ in year	0.14	0.86	2.00	2.85
NV Air pollution abatement	M€ in year	1.33	7.88	18.22	25.99
NPV air pollution abatement	M€	1.15	4.18	5.93	5.19



	2020	2025	2030	2035	2040	2045	2050
🟧 CO2 abatement	2	31	105	237	422	637	855
■ Platinum depletion	-16	-40	-66	-88	-106	-119	-128
🟨 Air pollution abatement	1	11	29	53	82	112	139
🟦 Noise abatement	0	2	5	10	15	21	26
🟩 Total	-13	4	73	212	413	651	892

Fig. 5. Temporal evolution of monetary cost of externalities (cumulated value) and FCV market deployment.

Table 12
Noise abatement results.

		2020	2030	2040	2050
NV Noise abatement cost	M€ in year	0.19	1.49	3.48	4.98
NPV noise abatement cost	M€	0.17	0.79	1.13	0.99

plied by distance traveled by the FCVs (Eq. 12).

$$APA_t = (FCV distance)[(\Delta NOx_t)(cost NOx_t) + (\Delta CO_t)(cost CO_t) + (\Delta HC_t)(cost HC_t)] \quad (12)$$

Table 11 presents the temporal evolution of pollution abatement benefits. The introduction of FCVs involves a significant reduction of air pollution from 2020 to 2050. This reduction represents an external social benefit of 5.19 M€ (2017) in 2050.

4.3.4. Noise abatement

The noise emissions generated by road traffic have not been very widely tackled in the CBA literature despite their environmental concern. Noise exposure is not only a disutility in the sense that it disturbs people, but can also result in health impairments and a loss of productivity and leisure. The reason the problem is growing is a combined effect from greater urbanization and an increase in traffic volume. Whereas the increase in traffic volume means higher noise levels, the urbanisation has led to more individuals being exposed to traffic noise (Ricardo-AEA 2014). According to this report, several studies have treated this problem by analyzing and quantifying the exposure to high noise levels and its consequences.

The external cost of road mobility considering the different modes of transport, the time of the day, the traffic type, and the region (urban, suburban and rural) has been quantified in (Ricardo-AEA 2014). Annoyance (reflecting the disturbance which individuals experience when exposed to traffic noise) and health impacts (related to the long-term exposure to noise, mainly stress-related health effects like hypertension and myocardial infarction) are the two major impacts usually considered when assessing noise impacts.

Table 13
Social NPV results.

			2020	2030	2040	2050
NPV economic comparison	TCO	M€ in year	-110,34	-168,61	-63,81	50,80
NPV with externalities	CO_2	M€ in year	2,44	19,36	40,23	42,22
	Platinum depletion		-16,78	-10,16	-6,17	-3,05
	Air pollution		0,96	3,39	4,86	4,32
	Noise		0,17	0,79	1,13	0,99
	SNPV	M€ in year	-123,55	-155,23	-23,76	95,28

In the case of fuel cells, as they use no combustion or moving parts, they are quieter than internal combustion engines. FCVs almost entirely eliminate engine noise, and the relatively high-pitched noise electric motors do emit does not propagate that far. Moreover, car horns and sirens could also be made quieter, because they would not have noisy engines. Nonetheless, basic traffic noise is a combination of engine, tire, wind passage and road-noise (different surfaces have different noise characteristics).

The noise abatement (NA) is given by the FCV market share ($\%market$), the distance traveled by the FCVs ($FCVdistance$) and the noise cost (Iversen, 2015) in € per 1.000 vkm (Eq. 13).

$$NA_t = (\%market_t)(FCVdistance_t)(Cost_{noise}) \qquad (13)$$

The benefits obtained from the noise abatement due to the introduction of hydrogen FCVs are shown in Table 12. These results are the cumulative noise abatement benefits over the different periods studied, considering the annual FCV market share.

These results show that the noise abatement has a relevant impact on the overall social analysis, being of a similar order of magnitude as the platinum depletion and air pollution. Its external social benefits are of 0.99 M€ (2017) in 2050.

4.3.5. Summary of externality costs/benefits

A summary of the external costs and benefits and their temporal evolution is shown in Fig. 5. The CO_2 abatement showed by far the biggest share. From 2030 to 2050 (with a step of 5 years), it accounts for 154%, 112%, 102%, 98%, and 96% of the externality benefits. The evolution is strongly correlated with the increase in FCV launched in the market for the scenario considered. Platinum is the second-largest externality, yet reducing the benefits obtained by the CO_2 abatement. From 2035, the positive externalities from air pollution and noise abatement are almost of the same order of magnitude in absolute value of platinum depletion and compensate for its negative cost.

The global benefits obtained from the externalities will have to be compared to the economic costs and the subsidy policies.

4.4. SCBA results without and with subsidy-tax strategy

The social net-present value is computed, where all the costs and benefits are updated to the base year (2017) (see Table 13).

The analysis of SNPV shows that the expenses from the economic comparison and the platinum depletion are compensated by the benefits of the other externalities in 2050 (50.42 M€ (2017)).

Fig. 6 shows the evolution of the NPV_{SCBA} over time for the different strategies studied.

Without accounting for externalities and subsidies, the cumulative net present value needed to bring hydrogen FCVs to lifetime cost parity with gasoline vehicles reaches a breakeven point in 2046. Using a societal cost accounting framework with externalities and without subsidies, hydrogen transition timing is reduced by 3 years.

The results of the subsidy policies NPV are shown in Table 14.

The expenses related to subsidies and the platinum depletion are balanced by the other externalities. A benefit of 39.82 M€ (2017) is generated over the period from 2020 to 2050.

With this framework, the evolution of the benefits vs. cost difference per year starts from a very negative deficit in 2020 (under -550 M€) due to the purchase of FCV supported by the subsidies. Also, as a 10-year average lifetime for FCVs is considered, a neg-

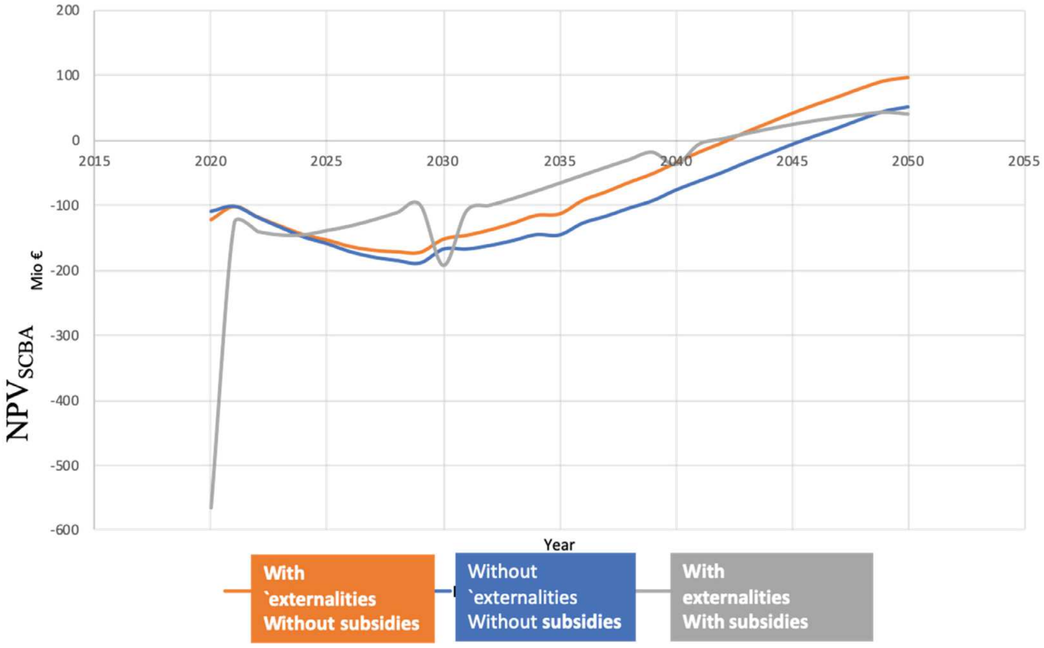


Fig. 6. Evolution of NPV vs. year for the different strategies: without externalities, with externalities and without subsidies, with externalities and with subsidies.

Table 14
NPV_{SCBA} with subsidy policies.

			2020	2030	2040	2050
NPV subsidy policies	Subsidy for HRS	M€ in year	-2.43	0.00	0.00	0.00
	Subsidy for FCVs		-474.45	-222.13	-92.77	-15.26
	Taxes on FCV purchase		-59.05	12.77	11.89	8.48
	Taxes on hydrogen		-10.14	0.00	0.00	0.00
NPV externalities	CO_2 abatement	M€ in year	2.44	19.36	40.23	42.22
	Platinum depletion		-15.58	-8.30	-4.25	-1.81
	Air pollution abatement		0.96	1.15	4.18	5.93
	Noise abatement		0.17	0.79	1.13	0.99
NPV_{SCBA} with subsidy policies		M€	-566.24	-193.15	-37.83	39.82

ative peak due to FCV fleet renewal occurs from 2030. The year of conversion is 2042 (Fig. 6). The earlier breakeven of the subsidy scenario is due to the higher tax income but the discrepancy is not very significant with the other scenarios.

This study suggests that the payback time is 2043 (socio-economic scenario), 2042 (subsidy-policy scenario), or 2046 (economic scenario). Our results are broadly consistent with those obtained for France in (Cantuarias-Villessuzanne et al., 2016) in which the value obtained is 2049 (optimistic scenario), 2052 (moderate scenario), or 2054 (conservative scenario).

The subsidies do not make a big difference in the breakeven year (only 3 years).

With a 20% increase in gasoline price conducted in an additional computation, the economic comparison converges in 2044 (economic scenario), or in 2041 (social-economic scenario). The small difference between the original and the increased-price cases can be explained by the scale at which the analysis has been performed.

Other externalities as hydrogen risks, supply stability/reliability, energy independence, employment effects, could also be quantified and added to the SCBA framework. The geographical scope could also be widened to the whole country of France to have a national point of view, and other types of vehicles could be incorporated to evaluate the impact of hydrogen mobility.

5. Conclusions

The scientific objectives set out in this study had manifold levels that were achieved and presented in this paper.

From a methodological viewpoint, a generic framework has been proposed to quantify the potential societal benefits of hydrogen fuel cell vehicles (FCVs). For this purpose, the methodology that was developed in our previous work (Ochoa Robles et al., 2016) to tackle the Hydrogen Supply Chain (HSC) design problem has been associated with an SCBA as a post-optimal assessment. The global HSC design has been formulated by a multi-objective optimization method. The interest of performing the optimization with Total Cost of Ownership and Global Warming Potential as objective functions is that their evaluation requires far fewer parameters than for the evaluation of the criterion involved in SCBA, thus reducing uncertainty at the main optimization step of the methodology. A post-Pareto approach is then proposed by the application of an MCDM method (TOPSIS) to prune the non-dominated set of solutions obtained by multiple objective optimization so that a compromise solution is then proposed to SCBA.

The cost-benefit analysis of FCEV versus gasoline ICE vehicles was tackled from a methodological viewpoint:

- it starts from a scenario characterized by an exogenously given market size for the deployment of FCEV over the period 2020-2050, (using the Occitania market as an illustration);
- the various cost components associated with this scenario (manufacturing, distribution, fuel, infrastructure…) have been obtained from multi-objective optimization and multicriteria decision making;
- the relevant externalities have been determined;
- a subsidy policy framework has been introduced;
- SCBA criteria have been defined.

From the viewpoint of externalities for FCVs as compared to ICEVs, we have considered greenhouse gas emissions due to their contribution in the transport sector with respect to climate change, local air emissions, responsible for particulate matter, ozone and acid rain, noise as well as the use of platinum metal groups in the fuel cell stack, that could lead to platinum depletion. The SCBA approach is then based on the computation of the Total Cost of Ownership considering these externalities. A subsidy/tax policy framework has also been integrated.

CO_2 abatement dominates the externalities and for the case study considered, platinum is the second-largest externality, yet reducing the benefits obtained by CO_2 abatement. Nevertheless, the positive externalities from air pollution and noise abatement almost reach to compensate for the negative costs caused by platinum depletion. The externalities have a positive effect from 2025.

From a socio-economic viewpoint, for the case study considered, the societal benefits of hydrogen and FCVs that make these vehicles more competitive with ICEs are only observed from 2043 (socio-economic scenario), 2042 (subsidy-policy scenario) or 2046 (economic scenario). The subsidies do not make a big difference for transition timing for hydrogen FCVs and are not very efficient.

It must be yet emphasized that the trends observed are dependent on the scenario of the case study and the outcomes of the numerical example may not be generalized and could be updated for further study. The analysis has been conducted through scenarios seeking to represent the key processes driving a transition to a hydrogen-fueled transportation system. The proposed methodology is generic enough to be replicated with updated data.

Authorship conformation form

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

Declaration of Competing Interest

None

Table A1
Prices of natural gas and costs of electricity from different sources (2013)

Energy source (Price/unit)	2020	2030	2040	2050	Reference
European price of natural gas ($2010/kg)	0.587	1.300	1.750*	2.200	For 2030 and 2050 (IEA 2011)
Cost of electricity (nuclear) in France ($2013/kWh)	0.0439	0.0665	0.089*	0.112*	For 2020: (EDF 2013) For 2030: (Percebois et and Mandil, 2013)
Cost of electricity (PV) France ($2013/kWh)	0.328	0.101	0.060*	0.053	For 2020: (EDF 2013) For 2030 and 2050: (ADEME 2015)
Cost of electricity (Wind) France ($2013/kWh)	0.073	0.068*	0.063*	0.058	For 2020[59] For 2050: (ADEME 2015)
Cost of electricity (Hydro) France ($2013/kWh)	0.018	0.044*	0.071*	0.098	

*Calculated by interpolation

Table A2
Original UPC values (De León Almaraz, 2014)

Production technology	UPC ($ per kg)
SMR	3.36
Electrolysis	4.69
DisElectrolysis	6.24

Appendix

In addition to hydrogen demand, one of the most significant parameters is feedstock cost (Ochoa Robles et al., 2020). In the original model (De León Almaraz, 2014), the unit production cost (UPC) of electricity remains fixed for all the time periods whatever the technology, which was a severe simplification. In what follows, an evaluation of UPC is considered taking into account the fixed facility costs (maintenance, labor cost) as well as electricity and feedstock costs.

Table A1 presents the price of electricity produced from different energy sources and the price of natural gas for conditions in France (2013).

In the original model, UPC is a fixed parameter (Table A2) which is only dependent on the size of the production unit ($ per kg H_2). A better vision of UPC is to consider the fixed costs as well as theelectricity and feedstock costs. The fixed cost is related to labor and maintenance.

All the contributions are reflected in Eq. (A1), where the UPC calculation ($ per kg H_2) is given by the addition of the fixed cost of a production plant type p size j in period t (FCP_{ept}, $ per kg H_2), the electricity cost for general usage in a production plant type *p* projected for the time period *t* (EC_{ept}, $ per kg H_2) and the feedstock *e* cost for production plant *p* type (FSC_{ept}). The FSC_{ept} is obtained by multiplying the feedstock *e* efficiency in the process *p* in time *t* ($kWh_{elec}/kg\ H_2$) by the feedstock *e* price ($\$/kWh_{elec}$), for electrolysis process, the feedstock considered is electricity and the energy source cost will vary depending on the type, e.g. fossil vs. renewable (Eq. A1).

$$UPC_{e,p,t} = FCP_{e,p,t} + EC_{e,p,t} + FSC_{e,p,t} \tag{A1}$$

The feedstock cost is likely to gain importance because it depends on the energy transition scenario and will induce a cost change of renewable energy impacting the hydrogen cost in the long-time horizon from 2020 to 2050.

The new UPC calculated for the model is presented in Table A3 where hydrogen produced via electrolysis with solar energy is the most expensive, while hydrogen produced with electrolysis from a hydraulic source is the less expensive one.

Table A3
UPC calculated with the new costs

Production technology	Fixed cost of production ($ per kg H_2)	Feedstock cost for production plant ($ per kg H_2)	Electrical need to produce a kg of H_2 $kWh_{elec}/kg\ H_2$	Cost of energy source ($ per kg H_2)*				UPC ($ per kg H_2)				
					2020	2030	2040	2050	2020	2030	2040	2050
SMR	0.16	0.02♦	4.02■	3.71	2.61	3.46	4.62	3.89	2.79	3.64	4.80	
Electrolysis	PV	0.39	0.06	55	18.04	5.56	3.30	2.93	18.49	6.01	3.75	3.38
	Wind	0.39	0.06	55	4.00	3.72	3.45	3.17	4.45	4.17	3.90	3.62
	Hydro	0.39	0.06	55	0.98	2.44	3.90	5.36	1.43	2.89	4.35	5.81
	Nuclear	0.39	0.06	55	2.41	3.66	4.90	6.14	2.86	4.11	5.35	6.59
Dis Electrolysis	PV	0.75	0.11	55	18.04	5.56	3.30	2.93	18.90	6.42	4.16	3.79
	Wind	0.75	0.11	55	4.00	3.72	3.45	3.17	4.86	4.58	4.31	4.03
	Hydro	0.75	0.11	55	0.98	2.44	3.90	5.36	1.84	3.30	4.76	6.22
	Nuclear	0.75	0.11	55	2.41	3.66	4.90	6.14	3.27	4.52	5.76	7.00

*[Energy source cost ($/KWh)x Electrical need to produce a kg of H_2 ($kWh_{elec}/kg\ H_2$)].
■ kg/kg H_2.
♦Electricity usage of production plant ($ per kg H_2).

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