



Original Research Article

Electricity versus hydrogen for passenger cars under stringent climate change control

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ABSTRACT

In this article we analyze how passenger car transportation in Europe may change this century under permanent high oil prices and stringent climate control policy. We focus on electricity and hydrogen as principal candidate energy carriers, because these two options are increasingly believed to become the long-term competitors in the transport sector. We complement a concise stylistic analysis with an in-depth investigation performed with the energy system optimization model TIAM-ECN, which we ran only for the European regions for this study. This bottom-up model, belonging to the TIMES family, has been adapted for the purpose of researching – amongst others – the transport sector. We particularly inspect the use of passenger cars and find that, if oil prices amount to 100–150 \$/bl during the remainder of the century, the transport sector could be little affected in the sense that it may continue to rely predominantly on (liquid or gaseous) fossil fuels: our model suggests that it could be optimal to start replacing gasoline and diesel by natural gas around the middle of the century if sufficient oil and gas reserves are available within this price range. If the European Commission achieves implementing its ambitious carbon mitigation plan, however, a massive restructuring of the transport sector away from fossil fuels could take place, which in three decades would transform it to broadly rely on hydrogen as main energy carrier according to our model runs. Under a broad set of sensitivity scenarios with varying assumptions regarding our most important modeling parameters, we find that if battery costs are reduced by at least 60% in comparison to our reference cost decline path, the passenger car sector could predominantly run on electricity from around 2050.

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Introduction

Mankind has recently entered an era of persisting high oil prices that will probably not fall much below 100 \$/bl anymore. In parallel there are ongoing efforts from the international community to implement a stringent global climate control policy. The purpose of this article is to investigate how the passenger car sector in Europe may transform under these fundamental changes that will have pervasive repercussions on energy services in all parts of our economy. Our research was initiated by the observation that today, after a wave of seemingly unlimited popularity during the nineties of last century and the first decade of this century for hydrogen fuelled vehicles, hydrogen no longer appears to be the

prime candidate energy carrier to fuel the car of the future. Instead, electricity-driven vehicles now are the most publicized option and seem the most promising forthcoming transportation technology. The hydrogen car hype of a decade ago has been replaced by the electric car hype of the late 2000s and early 2010s. This study provides a techno-economic perspective on these two major options, whereby we attempt to contribute to the discussion about which technology will or should ultimately prevail.

Since transportation plays a key role in solving problems of both energy security and climate change (see e.g., [15,29], the search for the dominant future technology in this sector is especially intense. It is not the first time that the promise of the hydrogen car – the deployment of which is seen more generally as one of the key drivers for the establishment of a hydrogen-based economy – has faded by the emergence of the electric car. Electric propulsion for the transport sector was considered several times during the 1970s–1990s after hypes for hydrogen, and today again appears to offer the best hope for change in the nearby future. We argue that the recent shift in perception can be traced back to at least

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four distinct factors: (1) the immediate usability of electric cars given extensive connection opportunities to current electricity networks, (2) the relative immaturity of hydrogen technology in conjunction with large infrastructure requirements and potential safety issues, (3) the economic impact from a fundamental rise of oil prices since 2008 that pushed up the cost of some of the main hydrogen production options more than it increased average electricity prices (especially in countries heavily relying on coal, nuclear or renewables-based power), and (4) the above mentioned “hype cycle”, which has punished hydrogen technology for being unable to meet earlier high expectations as fast as it was hoped for (see, for example, [4]).

The battle for the car of the future is shaped by ambitious intentions from industry, preferences from the public, societal hypes as well as uncertain economic conditions and environmental factors. Technical issues such as the driving range and recharging speeds for electric cars need to be improved, while for hydrogen cars the roll-out of a widespread fuel station network is an absolute necessity. Ultimately, however, the prospects for different car concepts are first and foremost a function of comparative techno-economic performance. Crucial factors for both electric and hydrogen vehicles are the cost developments of their key components, in particular the battery and fuel cell respectively. Upfront investment costs for both technologies need to decline, while simultaneously their lifetime needs to increase to reach substantial decreases in overall vehicle lifetime costs. The other most important economic factors are the development of world oil prices and the evolution of fiscal regimes for vehicles and fuels including carbon taxes. Non-economic aspects like personal tastes and the willingness of people to change their habits will significantly influence the introduction of new car technologies. These important facets are, however, not taken into account in our techno-economic analysis and we refer the reader to other studies, such as Lebutsch and Weeda [25], McKinsey [28], Schäfer et al. [35] and Yeh et al. [45], for complementary analyses on aspects such as infrastructural hurdles, political obstacles and social acceptance. Techno-economic analysis on passenger car choices in relation to emissions reduction impacts has been undertaken also by others, but, some of these studies focus on other low carbon options such as biofuels ([6,38,9]) or do not include hydrogen or electric vehicles ([43,44,39]), while yet other studies lack aspects of competition ([7,24,30]). Most similar to our work are studies by Anandarajah et al. [2], Grahm et al. [10] and Akashi and Hanaoka [1], but these have a global scope or more limited time horizon until 2050.

In the Stylic assessment below, we adopt a consumer perspective for which we carry out a stylistic assessment of the levelized costs per kilometer of four major car types. In Energy systems analysis: TIAM, we describe our bottom-up energy technologies approach in which decisions are taken in a setting of a social planner who optimizes the overall costs of the European energy system that includes a range of different vehicle types. In Energy system results, we report our main results and examine the robustness of our outcomes through multiple sensitivity tests with regard to our key assumptions. We conclude in Discussion and conclusion.

Stylistic assessment

We first develop a stylized evaluation of the competition between different future car technologies (see also [5]). This assessment captures quantitatively the essence of the competitive forces involved, and proffers a broad perspective of potential outcomes based on key assumptions regarding the combined effects of technological progress (reflected in vehicle costs), fuel price developments (of crude oil, electricity and hydrogen) and fiscal regimes (like tax rates on vehicles and fuels including carbon

prices). As main indicator for their relative economic fitness, both at present and in the future, we use the levelized costs per kilometer for owners of different vehicle concepts. From a consumer perspective several relatively straightforward observations can thus be made with regards to the diffusion potential of electric vis-à-vis hydrogen-based cars.

In our stylized context we consider four different types of passenger cars: internal combustion engine vehicles (ICEs) that use conventional fuels such as gasoline or diesel (that in practice may either be or not be mixed with biofuels); ICEs that are fuelled with natural gas; battery-based electric vehicles (BEVs); and fuel cell vehicles (FCVs) running on hydrogen. We include in this assessment natural gas as separate option to fuel cars, as no intrinsic economic reasons exist that would inhibit their widespread adoption. Possible additions of disperse unconventional resources to the current centralized reserve base may further strengthen the broad diffusion feasibility of natural gas as fuel for car transportation. The fact that to date natural gas cars are relatively uncommon in most of the world is probably induced by factors related to, for instance, distribution infrastructures, industrial choices and consumer preferences, which are mostly outside our capacity to investigate. To keep our analysis simple we assume henceforth that biofuels are not mixed with conventional fuels. We also exclude ICEs fuelled by only biofuels as a separate option in this assessment, because biofuels are in most cases mixed with traditional transportation fuels. Also hybrid versions between our four main vehicle options are not considered in our stylized inspection, as they do not proffer any additional insights. Multiple biofuel and hybrid options, however, are included in our more detailed energy systems analysis in the next section.

For comparing these main car categories we assume that all four types are used to drive 12 000 km annually. In Rösler et al. [33] and van der Zwaan et al. [41] we report our assumptions regarding vehicle performance and fuel efficiency improvements. In order to compute the levelized costs per kilometer for our four basic car types, assumptions need to be made regarding vehicle investment requirements and fuel (distribution) prices plus taxes. For the year 2020 our assumptions for the purchase costs of these car concepts, as well as for fuel prices, distribution costs and taxation levels are given in Table 1. The investment costs reported in Table 1 are mainly based on data available from IEA [18]. We assume that IEA's near-term estimates correspond to 2020.

For the following decades investment costs are assumed to reduce to the values described in Energy systems analysis: TIAM (Fig. 3). They decrease most markedly for BEVs and FCVs. The untaxed fuel price at the refinery is assumed to be 0.61 \$/liter – based on constant oil prices of 100 \$/bl, a refinery efficiency of 85%, and a refinery cost margin of 0.06 \$/liter – and we suppose a fuel distribution margin of 0.16 \$/liter (see e.g. [5]). We suppose that gas prices in Europe remain constant at 0.36 \$/m³, and that additional costs for transportation and distribution of gas amount to 0.22 \$/m³. Based on a representative composition of European electricity generation in 2020 (25% coal, 24% gas, 22% nuclear and 29% renewables including hydropower; see [19]), the electricity price is assumed to be 0.08 \$/kWh in 2020 and afterwards. We use a distribution cost margin of 0.04 \$/kWh, as was assumed by Bruggink and Rösler [5], but recognize that this figure could in reality be significantly higher e.g., due to additional recharger costs. Hydrogen is estimated to cost approximately 29 \$/GJ in 2020 and 27 \$/GJ in 2040, under the assumption that all hydrogen is produced through steam methane reforming (SMR) plants with an efficiency of 75% and a cost margin of 1.9 \$/GJ in 2020 and 1.7 \$/GJ in 2040. Additional transport and distribution costs for hydrogen are assumed to be 18 \$/GJ ([5]). Fuel taxation is supposed to stay as in the current fiscal regime of a typical (average) European country. This implies excise duties on gasoline of 0.72 \$/liter, on

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