# Is the Hydrogen Fuel Cell truck a better option to ride? A decision support with a real options approach

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**Overview:** The transformation of current production and consumption patterns and energy supply to reduce greenhouse gas (GHG) emissions are priority sectors. In particular, the production of electricity can be decarbonized by using energy sources with low or no GHG emissions. Cleaner mobility by 2050 based on hydrogen technology takes on its full strategic value when political decision-makers and consumers anticipate a reversal in the evolution of the various parameters, upsetting the pre-established order in terms of economic performance. To describe this phenomenon, it will therefore be necessary to obtain information on the evolution of the prices of electricity, hydrogen, fuels used and long-term demand. For instance, factors that influence the rate of adoption of hydrogen fuel cell truck technology include the benefits it brings, the presence or absence of substitute or complementary products (diesel, electric trucks), the ease of use (presence of hydrogen refuel stations), the regulatory framework that increase the benefits of adoption (financial incentives, subsidies), the costs of adopting the technology (relative price of hydrogen fuel cell trucks) and uncertainty about the usefulness of the technology (reducing carbon emissions, NetZero 2050). Therefore, a more comprehensive analytical framework should simultaneously incorporate the short-term uncertainties associated with the operation of hydrogen and fuel cell technology, storage and the necessary infrastructure, and the associated long-term uncertainties such as market developments, investment in low-carbon assets and financing costs. In our paper, we use a real options approach and we assess the regulatory uncertainty in terms of subsidy and the speed of adoption of fuel cell trucks in France. With a continuous-time model and dynamic programming method we determine the optimal timing and scale of investments in hydrogen infrastructure, influenced by dynamic subsidy policies and adoption rates of fuel cell hydrogen trucks.

**Methods:** The literature on the hydrogen as a vector for energy transition is significant and encompasses a variety of disciplinary fields. In economics there is a noted increase in the literature studying the economics of green hydrogen projects, as illustrated by the reviews of Vandewalle et al. (2015), El-Emam and Ozcan (2019), Lynch et al. (2019), as well as those by Glenk and Reichelstein (2019) and Jiang, Deng, and You (2019). Nonetheless, some of these works are already obsolete due to the rapid evolution of cost reductions. It is therefore necessary to understand how these reductions impact past and current studies. More recently, using short-term (2020-2040) and long-term (2030-2050) scenarios, Khan et al. (2021) present a detailed framework of discounted costs to determine the costs of hydrogen produced by renewable energies, as well as the sensitivity to various techno-economic parameters. One of the main limitations of these studies is that they do not account for the dynamic nature of uncertainties regarding hydrogen pricing, electrolyzer’s costs, and other parameters, such as life cycles or load variation capacity. Furthermore, Li and Mulder (2021) and Hesel et al. (2022) analyze the evolution of hydrogen markets within a perfect competition framework. Michalski et al. (2017) explore the German energy transition, evaluating hydrogen production technologies and storage solutions, indicating hydrogen's significant role in mobility and its potential to mitigate wind curtailments and peak energy loads. Wu et al. (2021) identify and analyze obstacles to HFCV growth in China using a novel method, providing targeted recommendations to overcome these challenges. Gandhi et al. (2022) investigate the construction of a green hydrogen economy, assessing the project's feasibility against variable cost and market conditions while Moon et al. (2022) identify consumer trust as a significant barrier to HFCV adoption in South Korea, advising policy enhancements to promote these vehicles. Chen et al. (2023) and Wang et al. (2023) focus on optimizing hydrogen energy infrastructure and vehicle adoption, emphasizing economic benefits and the potential to reduce carbon emissions. These studies leverage models like NPV and LCC to assess the viability of hydrogen projects, especially in combating wind curtailment and enhancing the economic and environmental potential of fuel cell electric vehicles (FCEVs) by 2030. Similarly, Abadie and Chamorro (2023) analyze the economic viability of wind-based green hydrogen production in Spain, using Monte Carlo simulations to highlight its competitiveness, despite some overlooked factors. Choi and Kang (2023) present an economic and environmental analysis of hydrogen use in the steel industry, providing insights for GHG reduction and cost estimation. Harichandan and Kar (2023) explore Indian consumers' attitudes towards HFCVs, highlighting the need for comprehensive government policies that address both demand and supply-side incentives. We contribute to the previous literature by considering two strands of literature. More precisely, we use a real options approach combined with literature from the field of diffusion of an innovation, by introducing uncertainty in a standard Bass model (1969). The Bass model provides a framework to understand how new products or technologies are adopted over time within a market. The model considers two main types of adopters: innovators, who are influenced by the product's attributes and their own knowledge, and imitators, who are influenced by the adoption choices of others. On the other hand, Real Options Theory, offers a method to evaluate and manage the uncertainty and flexibility inherent in investment decisions. It treats investment opportunities as options, giving the investor the right, but not the obligation, to undertake certain business decisions, like deferring, abandoning, expanding, or staging investments. The real options theory and the innovation diffusion model in the energy sector have been explored in several studies. Rout (2009) addresses the uncertainty in learning rates of energy technologies, underscoring the need for policy support to mitigate this uncertainty and facilitate technology diffusion. Recently, Li et al. (2020) study with real options the investment in hydrogen-fuel infrastructure in the Netherlands under uncertainty on in the existence of the infrastructure. We adapt the Bass model, tailoring it to better represent the spread of adoption of hydrogen fuel cell trucks in France. Using a dynamic programming approach in continuous time and considering gradually two types of uncertainty (on the regulatory framework and on the infrastructure) our study provides stakeholders with a set of options for constructing flexible strategies to deal with uncertainty in the field of mobility, including hydrogen-based technologies.

**Results**: The Bass model of diffusion of innovation and real options theory can be linked when analyzing the uncertainty surrounding the regulatory framework and the availability of infrastructure, particularly in the context of fuel cell hydrogen trucks or energy systems like hydrogen fuel stations. We model the subsidy policy as a stochastic process to reflect its uncertainty over time. This parameter affects both the cost structure of adopting hydrogen trucks for fleet owners and the investment in hydrogen fueling infrastructure. Furthermore, we use the Bass model to determine the adoption rate of hydrogen trucks, incorporating the effect of subsidy uncertainty. The subsidy level modifies the parameters in the Bass model, reflecting how financial incentives influence early adopters and followers. Through dynamic programming methods, we develop decision rules based on real options valuation for when to invest in infrastructure, considering the current state of subsidy policy, observed adoption rates, and market feedback. We conduct sensitivity analysis, and we show that the regulatory changes can significantly impact both innovators and imitators' willingness to adopt fuel cell hydrogen trucks. For instance, favorable regulations might accelerate adoption by reducing perceived risks or improving the technology's perceived benefits. On the contrary, the uncertainty in the regulatory environment introduces volatility, which increases the value of waiting to invest. Firms may delay investments in new infrastructure or in the production or the use of hydrogen trucks until regulatory outcomes become clearer. Moreover, we show that the availability of the infrastructure, seen in our model as a series of sequential investments, influence the use and the adoption curve for hydrogen trucks. The value of waiting to invest (defer option) is influenced by the volatility of the subsidy, while the potential market size (determined by the Bass model) affects the value of expansion options.

**Conclusions:** Our paper provides insights into how subsidy uncertainty impacts the strategic deployment of hydrogen fueling infrastructure and the adoption of hydrogen trucks. Furthermore, it helps stakeholders identify optimal investment strategies under different subsidy scenarios and market responses, ultimately guiding policy and investment decisions in the hydrogen truck ecosystem. For the French case, according to our Bass model including variables such as the coverage of refueling stations and the relative price of hydrogen trucks based on subsidy, it is very likely that trucks will account for 20% of the government in 2050, even with low innovation and imitation coefficients. However, if a higher share of the market is to be achieved, the innovation and imitation coefficients will have to be manipulated, and a significant subsidy policy will have to be put in place to sell hydrogen trucks and ensure that they are adopted by both innovators and imitators.

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