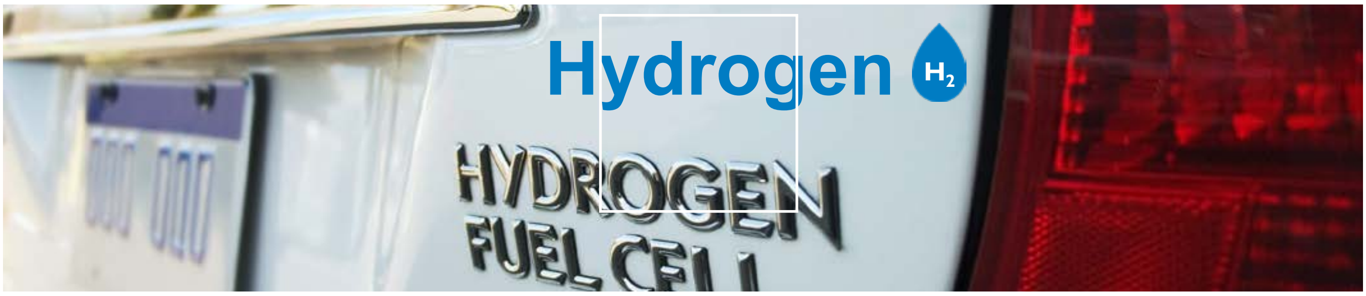
Arthur D Little

Viewpoint

What's in the future for fuel cell vehicles?

Will hydrogen fuel cell vehicles fully demonstrate their benefits with the uptake scenario still uncertain and OEMs already investing?

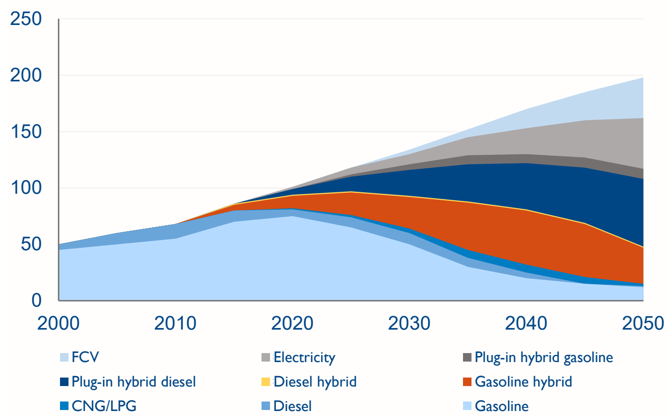


The development of new and diversified technologies is creating exciting opportunities within the automotive industry. Arthur D. Little has already analyzed and reported the evolution trends in traditional and innovative powertrain technologies. In this report Arthur D. Little provides its perspective on the present and future of fuel cell vehicles (FCVs), providing a synthetic comparison with other technologies, as well as an overview of FCV benefits and the main obstacles to their adoption.

Fuel cells are an expected market trend

FCV sales volumes are expected to be significant, but only in the long term, even with a favorable climate-policy scenario. Due to a recognized absence of CO_2 emissions during vehicle operation, expectations of the future FCV market are growing following the adoption of the Paris Agreement. The agreement for the first time brought all nations into a common cause to undertake ambitious efforts to combat climate change.

FCV sales volume predictions based on long-term powertrain mix scenario (Mln units)



Source: International Energy Agency 2012 (IEA)

Within a similar scenario, the international energy agency (IEA) estimates an FCV market share of about 17% by 2050 (35 million annual unit sales).

Yet will hydrogen fuel cells fully demonstrate their benefits when the uptake scenario is still uncertain?

The slow FCV uptake will mainly be due to:

- OEMs' need to achieve significant cost reductions.
- Market need of network infrastructures to build and local experiments that have proven successful.
- Time required to identify and standardize the most efficient solution for hydrogen production.

The role of public administration

To promote FCVs and break the initial impasse, various policy options could be evaluated:

- Government support through research, development, and deployment initiatives and grants (e.g. for building out the infrastructure for hydrogen distribution).
- Tax and/or subsidy policies to reduce the high initial cost of FCVs compared to conventional vehicles – directed at either consumers or manufacturers of FCVs and H_2 suppliers.
- GHG reduction policies. For example, setting targets for GHG intensity for the entire transportation fuel supply.

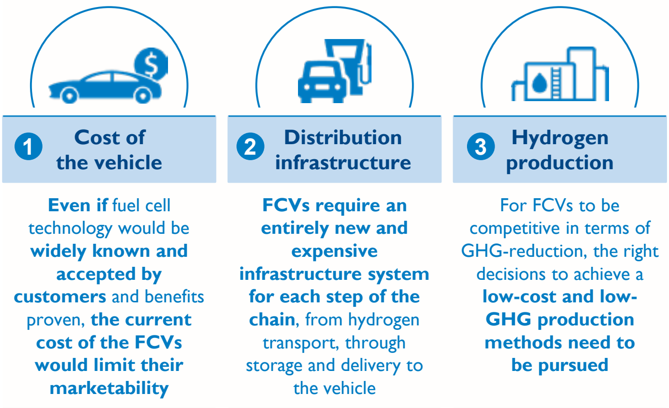
Main obstacles to FCV adoption

FCVs' potential adoption is suffering from three major problems: cost of vehicles, distribution infrastructure and hydrogen production.

a. **Cost of vehicles:** The high cost of FCVs mainly stems from the use of expensive catalysts and other materials used in the fuel cell "stack" (e.g. platinum). Today, based on a US DOE estimate, fuel cells can be manufactured for around

$280/kW at low volumes of 20k units/year. Yet their cost would drop down to $53/kW if they were manufactured at higher volumes (500k units). The US DOE also forecast a cost of around $40/kW in 2020 and $30/kW as an ultimate target. As a matter of fact, two more product iterations are likely to be needed to bring costs down and, given automotive product-cycle times, this suggests the 2020s, at the earliest, before costs can reach mass-market acceptance levels.

Main obstacles to FCV adoption



Source: Arthur D. Little analysis

b. **Distribution infrastructure:** The development of infrastructure requires important and expensive investment decisions, which need to be supported by sustained FCV market demand.

There is currently no national system similar to that for diesel or gasoline to deliver hydrogen from production facilities to filling stations. A completely new distribution infrastructure will be required to allow mass-market penetration of FCVs. Additionally, the total costs associated with replicating the gasoline fueling and storage infrastructure are huge. Today the cost of a commercial station is between $750k and $1.5Mln, with entry-level stations in the range of $350 to $500k. While cost reductions will be achieved as the technology matures, clearly the costs of replacing even a fraction of the national filling stations could total billions of dollars.

The hydrogen infrastructure problem is a classic "chicken-and-egg" issue: companies will not invest in infrastructure without a significant FCV market, and FCVs are not viable without an adequate level of infrastructure.

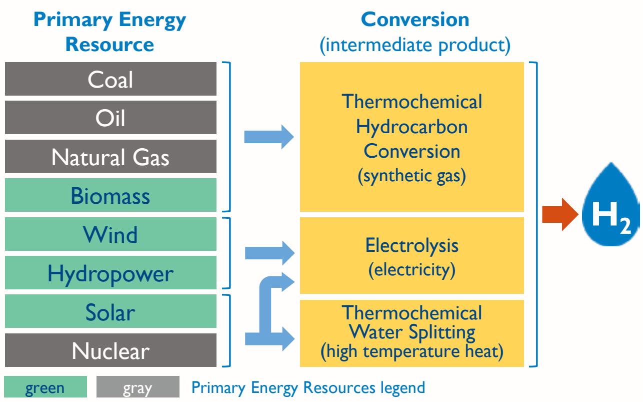
Today deployment is limited to a small number of countries. Government agencies in the US, Japan, Germany and the UK have funded the construction of hydrogen filling stations. In the United States, California is leading the way, developing the "Hydrogen Highway" (mainly in the Los Angeles and San Francisco areas). However, even here the number of installed stations falls below that required to make FCVs an attractive proposition for the majority of potential adopters.

Infrastructure issues are significantly mitigated for "fleet" applications such as buses, delivery services, post-office vehicles and so on, for which it is possible to return to a central location to refuel. Indeed, many of the early demonstrations of FCVs have focused on bus fleets, while fuel cells have found some success in the material-handling market niche.

c. **Hydrogen production:** Like electricity, the production of hydrogen can be derived from various primary energy resources, each having a different impact on the GHG footprint.

Depending on the primary energy resource from which the energy is produced, the hydrogen can be labeled "green" or "gray". In terms of GHG footprint, it is most favorable to produce hydrogen from renewable primary energy resources ("green"), rather than from "gray" resources.

Hydrogen production primary energy resources and intermediate products



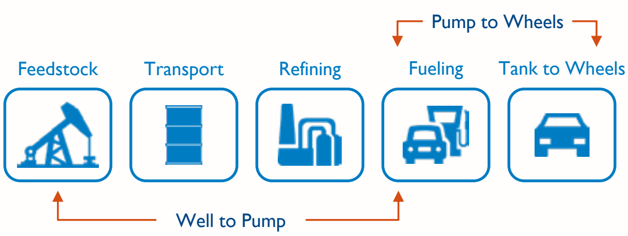
Source: Arthur D. Little analysis; The Hydrogen Transition, Joan Ogden, Christopher Yang, Michael Nicholas, and Lew Fulton (2014)

Nonetheless, the use of renewable energy to produce hydrogen will be subject to specific cost-benefit analyses. Indeed, the transformation of renewable energy in hydrogen involves significant process inefficiencies (and therefore cost inefficiencies), mainly due to losses from electrolyzing water.

Starting with renewable resources, FCVs are, as a matter of fact, less efficient in the *well-to-pump phase* compared to electric vehicles (EVs), which do not need to transform electricity into hydrogen.

Considering, instead, *the pump-to-wheels phase*, FCVs are about 50% less efficient than EVs, despite being up to twice as efficient as ICE vehicles.

Well-to-wheels value chain



Comparison of alternative and traditional fuel vehicles

Best Option   Worst Option

	Alternative			Traditional
	FCVs	BEVs	PHEVs	ICE
Refueling Time	Few minutes	>1 hour	Few minutes/ >1 hour for electric recharge	Few minutes
Drive Range	>450 km	400km (by 2018-2020)	Comparable to ICE	Up to more than 1000 km
Price of Car	Additional cost compared to BEV (BEV + FC system*)	Additional cost compared to ICE	Additional cost compared to ICE	Lower benchmark (consolidated technology)
Fuel Efficiency	Higher than ICE but lower than BEVs	Higher than ICE and FCVs	Higher than ICE but lower than BEVs	Lower benchmark
Fueling Infrastructure	H_2 stations similar to gas stations	Chargers (home and public)	Chargers / Gas stations	Gas stations

* But with a lower power battery

Source: Arthur D. Little analysis

Fuel cells: a mature technology that has to find its way towards widespread commercialization within the automotive market

The technology behind fuel cells sets its roots back in 1958, when a General Electric chemist devised a way of depositing platinum onto the ion-exchange membrane, creating the beginning of the proton exchange membrane (PEM) fuel cells used in vehicles today. One year later the first fuel cell vehicle (FCV), a farm tractor powered by an alkaline fuel cell with a 15kW output, was developed. Between 1966 and the end of the century several OEMs demonstrated viable fuel cell passenger-vehicle concepts, among them GM, Daimler, Toyota, Renault and Mazda. In 2008 Honda provided the first commercially available FCV, leasing its FCX Clarity to selected Californian customers for $600 per month. In 2013 and 2014, respectively, Hyundai and Toyota started the commercialization of their FCVs (Hyundai ix35 and Toyota Mirai). Concurrently the industry focus widened from cars to public transport and commercial vehicles.

How FCVs work

Fuel cell vehicles are between ICE- and battery-powered vehicles. Like internal-combustion engines, they make power by using fuel from a tank (pressurized hydrogen gas). However, in a process which resembles what happens in a battery, the hydrogen is fused chemically with oxygen from the air to release electricity, which is used to power the electric motor. The only waste product in the process is water – no CO_2 emissions are produced during vehicle operation.

FCVs' main benefits

Besides the absence of CO_2 emissions during vehicle operation, FCVs promise benefits among multiple dimensions:

- Refueling time – a few minutes (like for ICE engines) will be needed to refill the tank compared to the longer duration expected to recharge battery-electric vehicles (BEVs).
- Driving range – with more than 450km of driving allowance, FCVs are already commercially attractive and, on average, they support larger ranges than BEVs.
- Fuel efficiency – FCVs are more energy efficient than gasoline-powered vehicles: a fuel cell uses about 40 to 60 percent of the available energy in hydrogen, compared to about 20 percent in ICE vehicles. However, it is important to highlight that EVs are more efficient than FCVs, using about 75 percent of the energy available from the batteries.
- Weight and volume of energy storage – Compared to EV batteries, H_2 requires less weight and volume for energy storage to enable the same distance range: a lithium-ion battery system requires about six times more weight and twice the volume to allow comparable driving ranges (e.g. 500 km).
- Scalability – FCVs' power can be scaled up easily: to obtain enough electricity to power a vehicle, individual fuel cells are combined in series to make a fuel cell stack. This characteristic of the technology enables its use in heavyweight vehicles as well.
- Sustainability – besides emitting zero GHG while the vehicle is running, FCVs' drive batteries are smaller than those of BEVs, therefore with lower environmental impact related to the usage of heavy metals in the manufacture of Li-ion battery packs. However, when assessing FCVs vs. BEVs, pollution generated by power plants should be compared with pollution derived from the H2 generation process (which depends on the selected primary energy resource to produce it).

  In comparison with ICE vehicles, FCVs will produce lower levels of GHG, but may have higher environmental impact in manufacturing due to the utilization of battery packs.

This analysis highlights that:

- For FCVs to be competitive, more development of low-cost and low-GHG hydrogen production methods will be needed.
- In the absence of economical/technical benefits (e.g. longer range provided by FCVs, customers willing to pay higher prices), it could make sense to use this process only if there is a "surplus" of renewable energy that would otherwise be wasted. Yet if a surplus of renewable power was available, there could be more environmentally sustainable and profitable storage options. For example, it could be argued that using surplus electrical power to charge BEVs is simpler, safer and more efficient.

Another potentially attractive "green" option is the gasification of non-food and waste biomass, even if there are significant technology challenges in reliable production and purification of bio-hydrogen and processes are extremely costly.

Further obstacles to the development of FCVs to be taken into account are:

Key – FCV: fuel cell vehicle; BEV: Battery-electric vehicle; PHEV: Plug-in hybrid electric vehicle; ICE: Internal combustion engine

- **Durability and reliability:** FCV lifetimes will need to be comparable to those of conventional passenger vehicles (e.g. approximately 14 years).
- **Safety and public acceptance:** Concerns include the pressurized storage of hydrogen on-board vehicles. H_2 is odorless, colorless, and tasteless, and cannot be detected by human senses.
- **Onboard hydrogen storage:** Storing enough H_2 to obtain a long-range vehicle would require a very large tank or very high-pressurized tanks.

Conclusions

In an automotive industry characterized by increasing competition between alternative fuel and traditional ICE vehicles, fuel cell vehicles still have to fully demonstrate their attractiveness to the mass market.

Among FCVs' benefits, the most recognized by the market is the absence of CO_2 emissions during vehicle operation. Besides that, other advantages in comparison with BEVs are: shorter refueling time, longer driving range, lower weight, less volume needed for energy storage, scalability and sustainability. In comparison with ICE vehicles, FCV benefits are greater fuel efficiency and lower levels of GHG production. Despite these, FCVs' mass-market adoption is limited by three major problems: cost of the vehicle, distribution infrastructure and hydrogen production.

In the context of increasingly stringent automotive emissions regulations, in the future, expectations of the FCV market are growing, but the uptake is predicted to be significant only in the long term. This is due to significant constraints such as achievement of cost reductions by OEMs, development of infrastructures, and identification and standardization of the most efficient solution for hydrogen production. To promote and accelerate the adoption of FCVs, various policy options could be put into action, but this also depends on governments' and industry players' willingness to invest in hydrogen technology.

Arthur D. Little can leverage its extensive knowledge and experience in the automotive industry, helping governments and industry players to anticipate alternative fuel trends and understand the advantages and potential figures of FCVs by:

- Supporting the understanding of the technology and why it is key to driving infrastructural and industry investments.
- Identifying the key actors willing to invest in the new technologies and networking opportunities.
- Identifying the emerging/future market trends in order to be well prepared for the shift of demand.
- Analyzing how to better leverage potential investments in a national and global context.
- Prioritizing technology investment in an uncertain market and regulatory scenario.
- Supporting the sharing, incentivization and execution of a plan to modernize the national infrastructure.

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Arthur D. Little

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