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Full fuel cycles and market potentials of future passenger car propulsion systems

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Abstract

The focus of the paper covers the current discussion on the contribution of fuel cell vehicles to so-called "sustainable mobility". It evaluates whether advantages for the environmental situation and energy carrier supply can be expected from the already visible future characteristics of fuel cell propulsion systems in the transport sector. This contribution therefore determines full fuel cycle data for the energy demand and emissions as well as economic data.

The different paths of a hydrocarbon-based fuel supply are evaluated with respect to primary energy use and CO_2 emissions from the fuel cycle. The technical systems analysis of fuel cell propulsion systems was realised with dynamic simulation models for driving cycles. The energy consumption and emission reduction potentials in the German passenger car transport sector were estimated for the introduction of fuel cell propulsion systems. Therefore scenario calculations were carried out to indicate how the results of the single analysis of technology and fuel supply concepts affect the German transport sector.

The application of fuel cell electric vehicles in comparison to advanced internal combustion engine vehicles identifies a small CO_2 emission reduction potential for the German transport sector depending on the assumed full fuel cycles. The reduction of limited emissions can be expected to be much greater, which can help to reduce local smog problems.

1. Introduction

Fuel cell propulsion systems are still at the developing and testing stage. They have to compete with propulsion systems like drive trains with advanced internal combustion engines (ICE), hybrid propulsion systems with high weights and costs, as well as electric vehicles with the same disadvantages of weight and cost due to the battery system.

With the application of hydrogen from non-fossil sources fuel cells show advantages like low specific energy demand and low or no specific emissions in comparison to conventional internal combustion engines.

In contrast to niche products, other energy carriers than hydrogen will have priority for the medium-term energy market (next 10–20 years):

- for stationary applications: natural gas
- for mobile applications: natural gas, alcohols, liquid synthetic hydrocarbons (in combination with on-board hydrogen generation for fuel cell propulsion systems)

The trend of fuel cell development for mobile applications is affected by the discussion about the "right" fuel, functional performance of the technology, cost reductions as well as considerations about new added values. Different requirements at the fuel cell stack, system, fuel, onboard hydrogen generation and the entire vehicle have to be considered for fuel cell vehicles (see Table 1).

Currently requirements at the cell, stack and system lead to the use of low-temperature fuel cells with a polymer electrolyte membrane in vehicle propulsion systems. Therefore only PEFC (polymer electrolyte fuel cell) propulsion systems are analysed for the evaluation of the full fuel cycles in the study. The calculations of emission and energy consumption for different full fuel cycles were subdivided into vehicle and fuel supply considerations.

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Table 1
Requirements at fuel cell vehicles

Fuel cell	solid electrolyte high power density
Stack	heat dissipation (liquid cooling system) high power density
System	fast operational standby good dynamic behaviour (velocity of load change) high degree of efficiency for net electric power generation provision of electric power in vehicle standby mode small standby losses high vibration insensitivity and shock resistance minimum risk potential low-cost solutions for the periphery
Fuel	high energy density (high radius of operation) long-term availability future target: non-fossil fuel
On-board hydrogen generation	high fuel variability high dynamic behaviour little impairment of efficiency for net electric power generation
Vehicle	high acceleration (power storage facility) sufficient radius of operation recovery of brake energy and storage facility (stop and go)

2. Vehicle analysis

The technical analysis of fuel cell propulsion systems was carried out with the dynamic simulation model SIMBA [1]. With this model it is possible to determine the energy demand and emission data for the entire vehicle system in different driving cycles. The consideration of the energy and power management and the allocation of the fuel cell vehicles to different vehicle classes were the subject of further investigations (see Figs. 1 and 2).

Fig. 1 compares the results of the vehicle simulation in the study for the methanol fuel cell vehicle with results from other studies [1,2]. Besides the methanol-fuelled vehicle a variant with compressed hydrogen is also simulated. The parameters of the simulated vehicles reflect those of compact passenger cars. The results are therefore not representative of the whole passenger car population. The calculations show a possible reduction of energy demand by the introduction of electric storage facilities for the methanol fuel cell vehicle with PEFC.

The simulation results of the assumed vehicle class spread in Fig. 2 show a very wide range of fuel consumption for typical vehicle classes. These classes are characterised by typical vehicle parameters like weight, maximum power, maximum top speed, minimum acceleration and so on. The high customer demands concerning acceleration and top speed in the different classes, especially in the large vehicle size, lead to a high weight of the FC vehicle. The reason for this is the current high power specific weight of the fuel cell propulsion system. The assumptions of the average customer requirements concerning basic weight, acceleration, top speed and so on were made with the aid of registration statistics for the current vehicle population in Germany. Table 2 indicates some assumed characteristic vehicle parameters.

The characteristic vehicle and fuel cell data of the small methanol fuel cell vehicle in Fig. 2 are not identical with those of the vehicle in Fig. 1 (different approach for required driving power of the propulsion system). As mentioned before the currently high weight of fuel cell propulsion systems in comparison to ICE drive trains leads to greatly increased fuel consumption by large vehicles. Presently small vehicle classes therefore seem to be the only meaningful market.

Besides the application of fuel cells in combination with electric motors for vehicle propulsion systems, the efficiency advantages of fuel cells may lead to increasing acceptance of an electrical energy supply for vehicles. These auxiliary power units (APU) generate electric power in an efficient way (e.g. premium-class vehicles with high electrical power requirements) even in periods of vehicle standby.

In order to complete the full fuel cycle analysis the results of the vehicle analysis have to be combined with different fuel supply paths.

3. Fuel supply

The introduction of new fuels should achieve the goals of fuel availability, generation, transportation, infrastructure, cost, safety and homologation requirements. The primary energy use and the CO_2 emissions of different hydrocarbon-based fuel supply paths were determined with the emission-balancing model KRAKE [3]. The starting point for different fuel supply paths is the primary energy carriers crude oil and natural gas. The results for the different fuel supply cycles show a widespread dependence on the selected final energy carrier and the assumed production and transportation paths (see Fig. 3). The supply of new fuels like methanol and compressed or liquefied hydrogen may leads to significantly higher CO_2 emissions except for CNG in comparison to the refinery path of gasoline and diesel.

As part of a study by Research Centre Juelich [4] cost estimations for new fuel infrastructures were compared with the aid of data currently available on investment costs for oil tankers, pipelines (remote and local) and filling stations. The supplementary expenditure for the new fuel infrastructure and thus the costs show a large range from a negligible

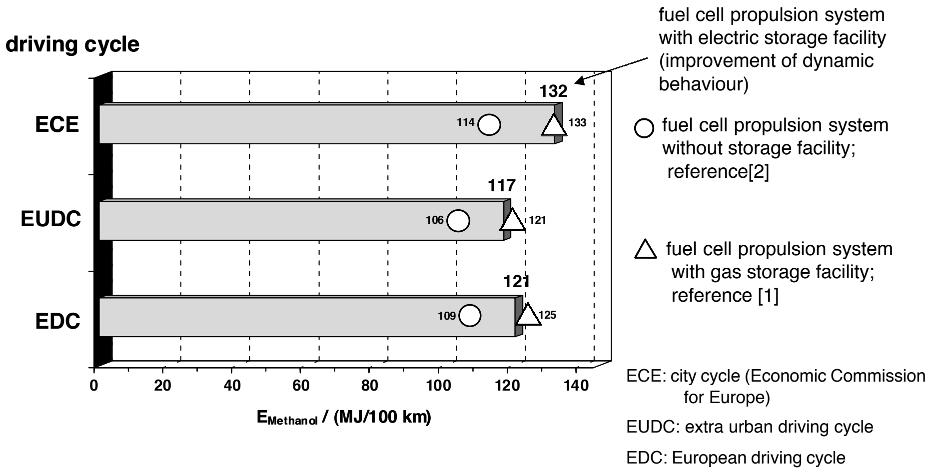

Fig. 1. Dynamic simulation of a methanol fuel cell propulsion system (compact class vehicle): results and comparison with literature sources.

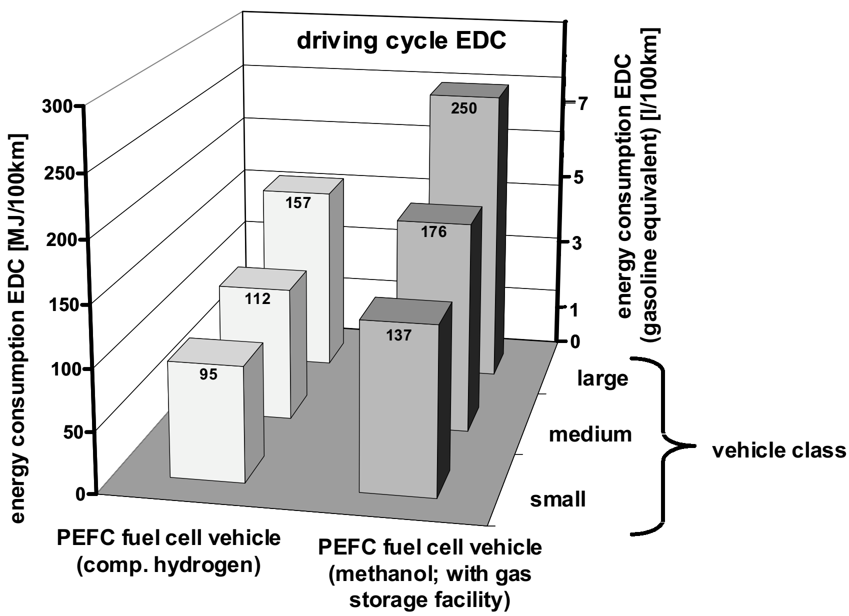

Fig. 2. Dynamic simulation of energy consumption in different vehicle classes.

increase for methanol up to one decimal power more for liquefied and compressed hydrogen.

In the study [4] different safety instructions were compared for gasoline, methanol and hydrogen fuels, including considerations about health hazards like toxicity and environmental hazards like water contamination. The considerations resulted in the assessment that the risk potential of new fuels should not to be regarded as greater but different, thus complicating their homologation.

Table 2
Assumed typical vehicle parameters in different vehicle classes

Vehicle class	Small	Medium	Large
Basis weight vehicle w/o propulsion system (kg)	860	950	1270
Top speed (km/h)	150	180	220
max acceleration (time from 0 to 100 km/h) (s)	15	11	9

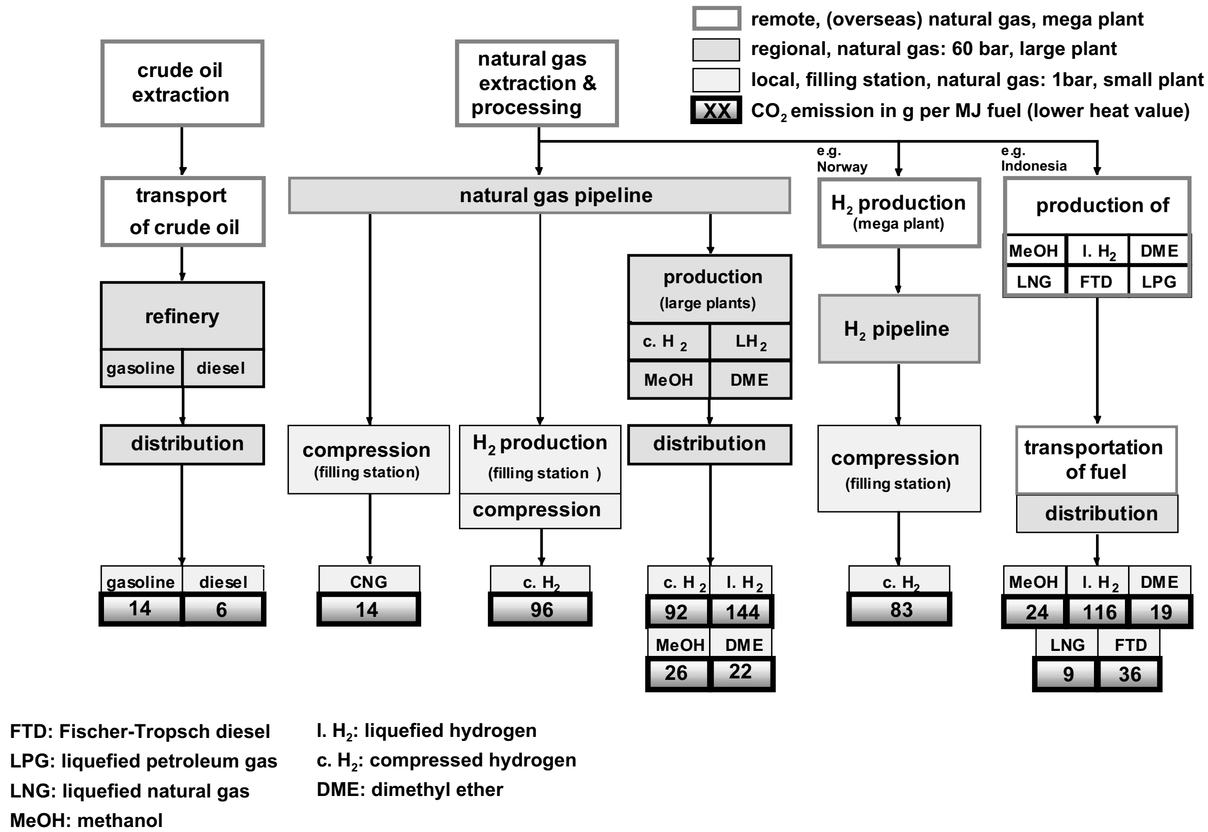

Fig. 3. Hydrocarbon-based fuel supply paths.

Even if the technical and logistic problems of fuel cell vehicles are solved the introduction of the product into a consumer market may not necessarily be successful. A potential purchaser expects at least the same performance and economic handling of new products in comparison to competitive ones. Taking this into consideration thus completes the analysis of the market potential.

4. Cost analysis

At the moment it is certain that a fuel cell vehicle will not be cheaper in comparison to a conventional car. The market indicates that comparable vehicles fuelled by diesel can be sold although they have higher selling prices. The reason for this is that their total economy, taking into consideration not only capital costs but also the operating costs, can be comparable to gasoline-fuelled vehicles or better. The same economic considerations could be conceivable for fuel cell passenger cars, too. Therefore possible extra charges for fuel cell electric vehicles were weighed up against the move towards competitive costs. The basic idea was that a customer and driver will accept a higher price for a fuel cell vehicle if

(A) the performance is comparable to a conventional car. A critical factor is the acceleration capability. Present fuel cell propulsion systems are heavier than conventional systems so that a higher total vehicle mass has to be accelerated. As a consequence, a more powerful fuel cell system has to be carried on board. The difference in power increases significantly from small to upper class vehicles,

and/or

(B) the higher selling price of the car is compensated by lower operating costs. This means that the fuel efficiency has to be higher than that of comparable conventional vehicles. Additionally the price of the fuel per energy content at the filling station should not exceed the price of gasoline.

On the basis of these assumptions and assumed modifications of the mineral oil tax legislation a comparison of the operating costs for different vehicle classes was carried out. The competitive vehicle price level starts above that of diesel cars in the small class and declines relatively to about the same price as a gasoline passenger car in the medium class. The higher performance requirements for upper class passenger cars reduce the extra costs for fuel cell passenger cars in comparison to conventional gasoline cars. The increased engine power required by the customer means that the difference in weight between the fuel cell car and conventional car also increases. This results in a higher power demand of the fuel cell propulsion system, which also becomes heavier in order to deliver the expected acceleration values. The consequence is higher consumption of fuel, which cancels out the higher energy efficiency of the fuel cell vehicle. Therefore the premium class cannot currently compete with conventional passenger cars. In the large vehicle class fuel cells could only be of interest in replacing the electric generator supplying the high energy requirements of additional energy-consuming luxury aggregates (auxiliary power unit).

For example, in Germany the same selling prices for new fuels in comparison to gasoline can only be reached by the reduction of fuel taxes (for methanol approximately to the same level as the diesel fuel tax—43 €-cents instead of 61 €-cents—and for compressed hydrogen at least tax-free).

In order to achieve the competitive vehicle price level for passenger cars mentioned above the fuel cell propulsion system should cost less than 60 €/kW of engine power. This cost target is more than 10 times lower than the accepted cost target of about 900€/kW electrical power for stationary applications. For an existing stationary application the cost structure and cost reduction potential of a fuel cell stack was analysed. As a result the cost reduction potentials were identified, in particular during the stack production process. Costs of mass production can be reduced by learning effects and by improved production processes.

5. Full fuel cycle and balance of transport sector

In order to illustrate how the results of the single analysis of technologies and fuel supply concepts affect the total context of the transport and energy supply sector, full fuel cycles were analysed in an integrated way. Scenario calculations with the IKARUS transport model [5] indicate possible potential for the reduction of CO_2 emissions in the German transport sector. The calculations were performed for the introduction of fuel cell technology in the German passenger car sector (see Fig. 4).

The energy consumption and emission factors of internal combustion engine (ICE) vehicles for the assumed traffic patterns were extracted from the technology data record of the IKARUS model. The required allocation to different vehicle classes and data records for the fuel cell vehicles was generated by means of simulation computations (see Chapter 2).

In order to estimate the maximum CO_2 emission reduction potential in the passenger car sector a complete replacement of all propulsion systems was assumed. The ranges of CO_2 emissions for the expected improvement potentials of future propulsion technologies are shown in the chart in

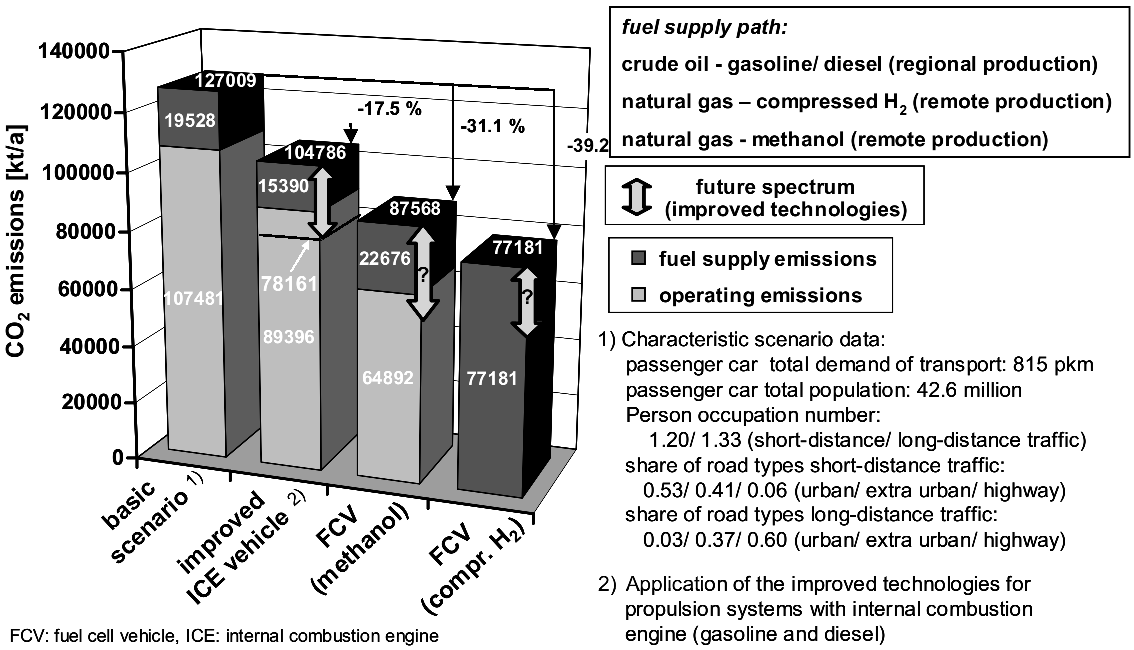

Fig. 4. Maximum CO_2 emission reduction potential for the German passenger car sector.

order to represent uncertainties concerning the assessment of future technologies. These uncertainties were set for the expected improvement potentials between a normal ongoing development and the introduction of new technologies such as more efficient engines, reduced road resistances or high-efficiency auxiliary equipment. A corresponding range for advanced fuel cell propulsion systems could not be specified because of the lack of reliable trends.

For the carbon dioxide emissions of the fuel supply chain the specific emission factors in Fig. 3 were assumed. The vehicle tank represents the interface of emission balancing between the fuel supply chain and the vehicle operation phase.

The scenario calculations indicate that the introduction of fuel cells (methanol and compressed hydrogen) in passenger car propulsion systems could have a small CO_2 reduction potential (according to vehicle class and fuel supply path) in comparison to conventional internal combustion engine vehicles. Advanced ICE vehicles (e.g. direct injection technology, improved drive lines, reduction of road resistance) have a similar CO_2 reduction potential but disadvantages with respect to the limited emissions (carbon monoxide, nitrogen oxide, hydrocarbons, soot particles).

The results for different fuel supply paths strongly depend on the final energy carrier and the assumed production and transportation paths. Clear CO_2 reductions could only be expected with renewable fuels (depending on the propulsion system). With an expected limited offer of renewable fuels efficient use of these renewable fuels should be achieved by consumption-optimised vehicles. This is possible with fuel cell vehicles apart from the premium class.

6. Conclusions

Hydrogen as well as methanol or synthetic liquid hydrocarbons will be generated in medium term (next 10–20 years) from natural gas for internal combustion engines and fuel cell vehicle propulsion systems. Within this time scale, fuel cell vehicles will have a small CO_2 reduction potential in comparison to conventional internal combustion engine vehicles or a similar CO_2 reduction potential in comparison to advanced ICE vehicles. Their real advantage is the mitigation of local smog problems.

In addition, there is little incentive for individual customers to purchase fuel cell vehicles because of the small additional profit. Since fuel cell vehicles are a substitution product they are exposed to high pressure of costs.

With the exception of fuel cell vehicles fuelled with gasoline or diesel in combination with onboard hydrogen generation, new fuel production capacities and new fuel supply infrastructures require a great deal of capital investment. On the other hand, propulsion systems with fuel cells are the most efficient.

Clear CO_2 reductions cannot be expected before a renewable- (or nuclear-) based production of the required fuel (irrespective of the propulsion system) is introduced. Consequently a sustainable use of fuel cells in passenger car propulsion systems is linked to the long-term aim of producing renewable-based energy carriers without the burden of producing additional CO_2 emissions.

Although these energy carriers could be used in vehicles with internal combustion engines in a sustainable way the fuel cell has an advantage since the expected production capacities of renewable fuels at an acceptable cost level are limited. Because of the higher efficiency of fuel cells in comparison to internal combustion engines and therefore of the lower fuel consumption more vehicle kilometres could be driven with the same amount of fuel. In conclusion, Table 3 points out different goals for bringing fuel cell vehicles onto the market.

Table 3
Challenges for bringing fuel cell vehicles onto the market

Vehicle	Cost reduction of the propulsion system (stack and periphery) Reduction of mass and volume
Fuel supply	Establishing an infrastructure for fuel supply Development and production capacities for fuels based on non-fossil energy carriers (renewable or nuclear—fission or fusion)
Accompanying measures	Political support for developing fuel cell systems and renewable fuel production lines Selling incentives for fuel cell vehicles such as lower fuel and vehicle operating taxes Investment support for establishing the production and supply infrastructure

References

[1] Grube Th, Hoehlein B, Menzer R, Stolten D. Neue Herausforderungen im Straßenverkehr: Brennstoffzellen-Antriebe für Pkw; EUROFORUM Technical Conference; 20–21 January 2000.
[2] Gossen F. Brennstoffzellenfahrzeuge im Vergleich zu weiterentwickelten konventionell angetriebenen Fahrzeugen, PhD thesis RWTH Aachen in Schriftenreihe Automobiltechnik; ika RWTH Aachen; Germany; 2001.
[3] Hoehlein B, Grube Th, Stolten D. Energieketten – Wege der Kraftstoffbereitstellung; lecture script, VDA Technical Congress, Bad Homburg, Germany, 26–27 March 2001.
[4] Biedermann P et al. Brennstoffzellensysteme für mobile Anwendungen; Schriften des Forschungszentrums Jülich. Reihe Energietechnik/Energy Technology, vol. 19, ISBN 3-89336-310-6; Jülich; 2002.
[5] Walbeck M, Linßen J. Scenario study: Development of non-CO_2 greenhouse gas emissions in the land transport sector; 3rd non-CO_2 greenhouse gases symposium; Lecture Script, Maastricht; Netherlands; 21–23 January 2002.

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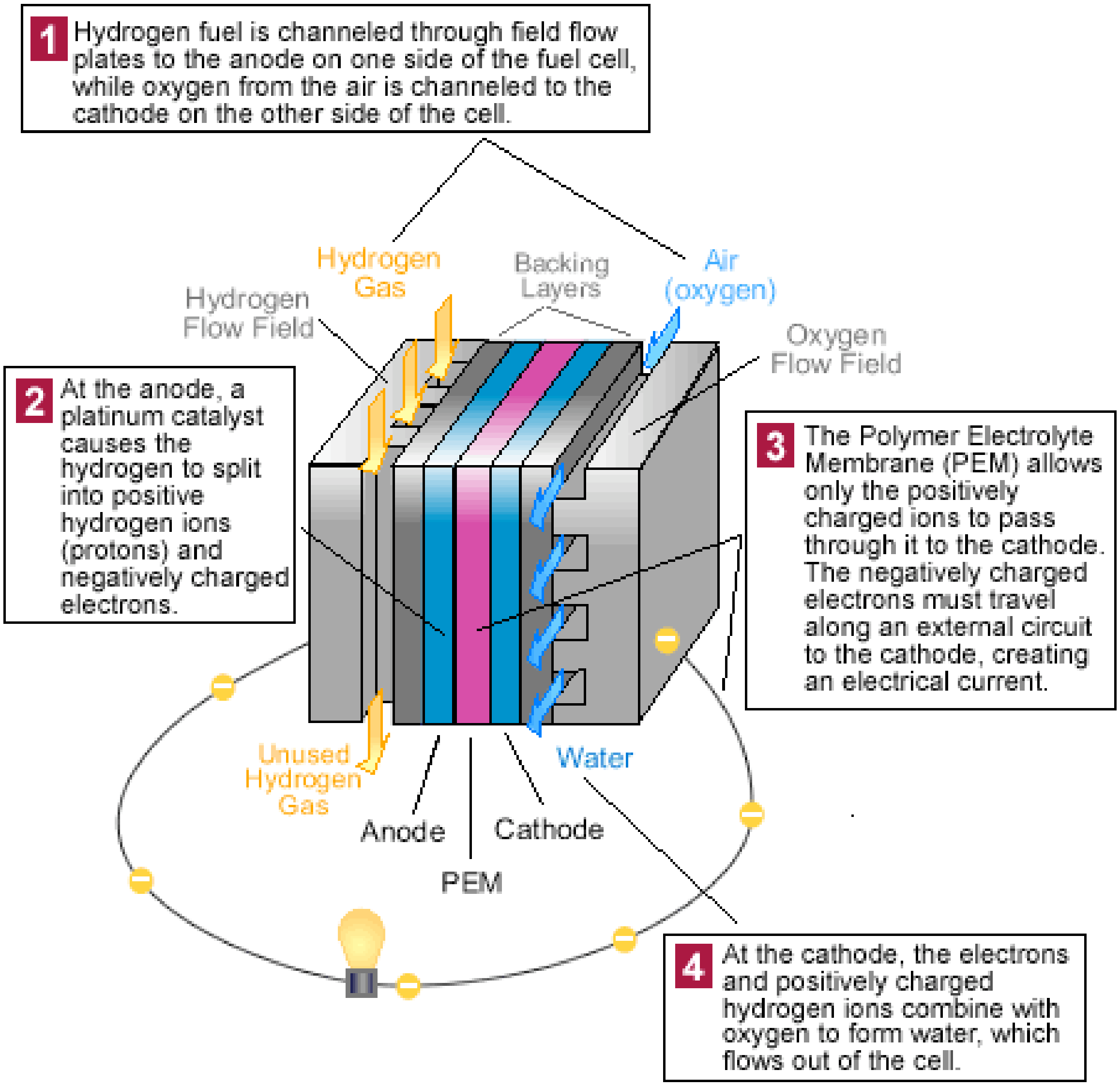

There are several kinds of fuel cells, but Polymer Electrolyte Membrane (PEM) fuel cells—also called Proton Exchange Membrane fuel cells—are the type typically used in automobiles. A PEM fuel cell uses hydrogen fuel and oxygen from the air to produce electricity.