Infrastructure for alternative fuel vehicles and their impact on large-scale vehicle deployment

Van den Bossche Peter
CITELEC
Pleinlaan 2
1050 Brussel
32-2-6292837
32-2-6293620
pvdbos@vub.ac.be
http://www.citelec.org/

Abstract

The use of "traditional", i.e. petroleum based fossil fuels in road vehicles is causing substantial concern, on one hand because of the noxious atmospheric emissions of such vehicles, on the other hand because of global energy issues and the need to move away from finite resources. Many alternative fuel solutions are being proposed; these will need however an adequate infrastructure to supply the vehicles. Safety and cost considerations will be contributing to the choice of a preferred solution, which will to some extent always be a compromise solution.
The proposed paper presents some characteristic alternative fuel solutions, and compares their infrastructure needs, both on local level (cost of infrastructure and local environmental impact) and on a global level (influence of large fleets of such vehicles).

Technological overview

In the framework of this article, "traditional" fuel vehicles are vehicles fuelled by liquid petroleum-based fuels (i.e. gasoline or diesel). All other energy sources are considered "alternative".

These alternatives can take different forms, and the internal structure of the vehicles and their drive trains goes beyond the scope of this paper; however: three main families can be distincted according to the refuelling options:

- Vehicles which are "fuelled" (i.e. charged) by electric energy only. This includes battery-electric vehicles.
- Vehicles which are fuelled with a chemical fuel only. This includes internal combustion vehicles, as well as non-battery depleting hybrids (including fuel cell hybrids).
- Vehicles which are fuelled both with electric energy and chemical fuel. This includes battery-depleting hybrids (including fuel cell hybrids).

The infrastructural impact will thus be based on the distribution of electricity on one hand and on the distribution of various chemical fuels on the other hand.

Infrastructure for electricity distribution to vehicles

Electric vehicles need access to the electric distribution network for recharging their batteries. The capacity of state-of-the-art traction batteries allows enough range to cover, in a majority of cases, the displacement needs of a single working day, leaving the night for battery charging (at reduced rates). However, opportunity charging during the day can offer interesting opportunities to enhance the flexibility of use of the vehicles.

The infrastructure necessary for electric vehicle conductive charging can be distincted according to the "mode" of charging, as described in the relevant standardisation documents[1]:

Mode 1 charging:

"Mode 1 charging" stands for *the connection of the EV to the a.c. supply network utilizing standardized socket-outlets at the supply side, single-phase or three-phase, and utilizing phase(s), neutral and protective earth conductors.*

This means that the electric vehicle is directly connected to a standard socket-outlet. This is currently the most frequent way of electric vehicle charging in Europe. It can be provided at low cost and is nearly universally applicable since standard socket-outlets are widely available.

The safe use of Mode 1 charging depends on the presence of a residual current device (RCD) on the supply side. Where the presence of an RCD on the supply side can not be ensured by national codes, mode 1 charging is not permissible. In some countries, mode 1 charging may be prohibited by national codes, or limited to private environments with controlled access.

The standard European socket-outlet provides up to 16A at 230V. This power level corresponds with normal charging for small and medium sized vehicles. An outlet of this power level can be installed at extremely low cost.

Mode 2 charging:

The safety concerns with Mode 1 charging in certain countries (particularly the USA) has lead to the definition of Mode 2: *the connection of the EV to the a.c. supply network utilizing standardized socket-outlets, single-phase or three-phase, and utilizing phase(s), neutral, and protective earth conductors together with a control pilot conductor between the EV and the plug or in-cable control box.*

Mode 2 allows additional protection of the cable and the vehicle, whilst using standard, non-dedicated socket outlets. In Europe, it is used very rarely.

---

[1] IEC 61851-1 Electric vehicle conductive charging system – Part 1: General requirements

Mode 3 charging:

Mode 3 charging refers to specific electric vehicle charging stations, with the *direct connection of the EV to the a.c. supply network utilizing dedicated EV supply equipment where the control pilot conductor extends to equipment permanently connected to the a.c. supply.*

The pilot conductor is a device which controls the integrity of the protective (earth) conductor, and which is able to perform additional safety functions, such as ensuring the socket outlet is dead when no vehicle is present. This is particularly interesting for charging stations located in public locations. Mode 3 charging stations come in different power levels:

- 16A, 230V: corresponding to standard socket-outlet but with enhanced safety features. The Mode 3 socket-outlet may be compatible with standard Mode 1 socket outlets, enabling vehicles both to charge at a private garage and at a public charging station.
- 32 A, 230V: this represents a higher power level (7kW) for semi-fast charging. This option is now widely developing, with special plugs and sockets compatible with Mode 1 socket-outlets (in Mode 1 however, the current is limited to 16A)
- High three-phase power: advanced three-phase inverters on electric vehicles may allow high power charging through direct connection to a three-phase network. This system allows fast charging without the heavy infrastructure of an off-board d.c. charger as in Mode 4.

Mode 4 charging:

In Mode 4 *(the indirect connection of the EV to the a.c. supply network utilizing an off-board charger where the control pilot conductor extends to equipment permanently connected to the a.c. supply),* the vehicle is charged with a d.c. current provided by an off-board charger. Vehicles in captive areas like industrial vehicles are mostly charged with off-board chargers; for road-going vehicles, this solution is most often used for fast charging stations which require a very heavy infrastructure. This infrastructure being very expensive, its usage has been largely limited to public charging stations for "emergency" charging.

Inductive charging

Charging systems with inductive energy transfer have been developed to overcome the need for a conductive connection and to enhance safety. The inductive systems can be divided in two main categories:

- **Paddle-type inductive charger**
  These devices consist of a primary inductor embedded in a paddle device to be inserted in a slot in the vehicle. Although inherently safe through the absence of galvanic contacts, they are still cable-based and need driver manipulation. They are very popular in the United States, and can accommodate various power levels.

- **Automatic inductive charger**
  These devices, several of which have been developed in Europe, encompass automatic docking eliminating the need for driver intervention. Due to the fact that they need a ground-based infrastructure and a mating device on the vehicle, they will be, in a first phase, primarily aimed to fleet applications.

Comparison between charging modes

The different charging modes can be compared in the following table, which takes into account:

- Performance (power level)
- Flexibility (ease of implementation everywhere, need for heavy infrastructure works)
- Safety (additional safety measures of the system which go beyond the basic safety requirements of the electrical connection)
- Cost of infrastructure (relative cost)

Type	Performance	Flexibility	Safety	Cost
Conductive Mode 1	•	••••	•	•
Conductive Mode 2	•	•••	••	••
Conductive Mode 3 16A	•	••	•••	••
Conductive Mode 3 32 A	••	••	•••	••
Conductive Mode 3 fast	••••	••	•••	•••
Conductive Mode 4	••••	•	•••	••••
Inductive paddle	•••	••	••••	•••
Inductive automatic	••	•	••••	••••

Evolutions

At least in Europe, it can be stated that Mode 1 charging will remain widely used for private and fleet applications, due to its simplicity and low cost. For public infrastructure Mode 3 will be enforced, offering the added advantage of semi-fast charging at a relatively low cost. Fast charging proper will be reserved for specialist or emergency use. Inductive systems are likely to be developed in niche applications (automatic rent-a-car systems, taxis, etc…) where the automatism of the system is of value.

Global infrastructure impact of electric vehicles

The electricity to charge the electric vehicles must be delivered by the mains network. One may ask if the current mains network can cope with the production and distribution of this electricity.

On production level, there are no significant problems, since electric vehicles are mostly charged overnight, when a considerable power reserve is available from base power stations and when electricity is sold at cheaper rates. Significant numbers of electric vehicles can be introduced without the need to build new power stations.

The demanded power must however be distributed at a local level. A study of this problem was performed by CITELEC[2] and related to downtown Brussels, taking into account real-life data of the electricity distribution company. With an electric vehicle share of 30% in Brussels, the following results were obtained:

---

[2] "Studie van het elektriciteitsnet te Brussel en evaluatie van de impakt van het invoeren van elektrische voertuigen", VUB-CITELEC, 1993

- On a global level (Brussels as a whole), the installed reserve power is sufficient;
- On a local level (individual distribution transformers), a number of transformers must be fitted with a higher power; in most cases, these are old transformers which are overloaded already today.

The study stated that the introduction of 30% electric vehicles in Brussels over a 10-year period would create no problems.

Infrastructure for chemical refuelling

Chemical refuelling of alternative vehicles can be done in many ways.

Electric vehicles with material refuelling

Some electric vehicle traction battery systems rely on mechanical replacement of the spent electrodes with fresh ones, for off-vehicle "recharging". The zinc-air battery is the best known example of this technology. These devices are in fact a kind of fuel cells rather than mere rechargeable batteries.
Practical tests with such systems have highlighted their major drawback, which is the need for a heavy infrastructure and complicated logistics to provide facilities for exchanging spent electrodes and for dispatching them to the recycling plant. The cost for infrastructure is high, as is the investment in material, as for every "active" electrode set (i.e. in service on board a vehicle, several others are needed, either in transit or in the recycling plant. This has been compared to beer casks: for every cask "active", i.e. being dispensed in a pub, a number of "inactive" casks are present (empties, in transit, in the brewery or maturing in the cellar). For this reason, these systems have known a limited success up to now.

Liquid alternative fuels

Liquid fuels for alternative-fuel vehicles include both alternative fuels for combustion engines (in straight internal-combustion vehicles or in hybrid electric vehicles), and fuels for fuel cell vehicles.
Dispensing of liquid fuels is straightforward; existing types infrastructure for petroleum products can be used. The infrastructure and logistics problems involved with liquid alternative fuels will not present insurmountable problems.
A number of fuels are being considered; their impact on infrastructure is described in the following paragraphs[3].

Rapeseed oil fuels
Rapeseed oil can be used as a fuel in diesel engines. In most cases, the methyl ester of the oil is used since this product has properties close to conventional diesel oil. It is thus known as "rapeseed methyl ester" (RME), "biodiesel" or "diester".
This fuel can be dispensed using the same infrastructure than for liquid fossil fuels[4]. It presents no particular safety hazards, and due to its vegetal origin it is less harmful then petroleum products when spilled in the environment.

---

[3] Information about the environmental impact of these fuels can be found in the MEET report (Methodology for calculation transport emission and energy consumption – EC Transport Research, 1999 – ISBN 92-828-6785-4)

The global impact of this fuel however will remain marginal since the areal of land available for rapeseed production can only cater for a small part of the vehicle market. The yield[5] of rapeseed is on average 2 tonnes per hectare, giving 0,8 tonnes of oil. This corresponds to the fuel consumption of an average urban light-duty vehicle covering circa 10000 km. Every RME-powered vehicle thus needs one hectare of land. The total areal of rapeseed in Canada (one of the world's major producers) is 5,5 million hectares, if this would completely be used as fuel (excluding current use which is mainly for food), it would not even be sufficient to fuel that country's automobile fleet.

Alcohol fuels: ethanol

Ethanol (ethyl alcohol) is usable as a fuel for gasoline engines. It can be mixed in low concentrations (10%) with gasoline in conventional engines, or used in higher concentrations (up to 85%) in specially tuned engines. The origin of the fuel is through fermentation and subsequent distillation of biomass; in Europe, it is now often procured from excess wine production.

This fuel can be dispensed using the same infrastructure than for liquid fossil fuels. It is less harmful than petroleum products when released in the environment; it presents however a particular hazard in case of fire, since it burns with a hardly visible blue flame which is less likely to be detected.

Ethanol for vehicles must be denatured to render it inpalatable in order to avoid abuse.

The development of large-scale ethanol-powered vehicle fleets is largely dependent on the availability of the fuel out of agricultural by-products.

Alcohol fuels: methanol

Methanol (methyl alcohol) has gained interest through its potential to be easily reformed, releasing hydrogen gas to be used in fuel cells. It can be used however in gasoline engines. Methanol can be prepared from organic sources (wood waste), but is increasingly made from natural gas. In the latter case, its origin is fossil of course.

This fuel can be dispensed using the same infrastructure than for liquid fossil fuels. It presents however a particular hazard in case of fire, since it burns with a hardly visible blue flame which is less likely to be detected. Its volatility and vapour density are lower than gasoline however, slightly reducing the fire hazard. The toxicity of methanol is well known, but is to be considered in relation to the toxicity of petroleum products.

Gaseous fuels

Gases can be used as fuels for both combustion engines and fuel cells. For infrastructure purposes, the distinction has to be made between gases which can be liquefied at ambient temperature and gases which can not.

Petroleum gas

This gas (LPG or liquid petroleum gas), mainly a mixture of propane and butane, is a by-product of the petroleum industry. Large amounts of petroleum are still flared at refineries

---

[4] It should be stated however that some parts of the infrastructure may have to be adapted to the specific properties of the alternative fuels. This includes joints and flexible tubing which must resist to the liquids used, which may be more corrosive than petroleum products. This applies to all alternative liquid fuels (rapeseed oil, methanol, ethanol,…)

[5] Figures obtained from the Canola Council of Canada

because no use is found to it; the use of LPG in vehicles should thus be promoted in order to eliminate this waste of a finite resource. The overall amount of LPG available is limited however, and the LPG alone will never be able to fuel a majority of current vehicle fleets.
LPG can be easily liquefied at ambient temperature and be stored in tanks under moderate pressures. The infrastructure technology of LP gas is well mastered and dispensing infrastructure has been deployed in most countries. The extra cost on a light-duty vehicle for a LPG installation is about 2000 Euros.

Natural gas
Natural gas has been acquiring much attention as a vehicle fuel, due to its very clean combustion properties. The storage of the gas on board the vehicle can be done on distinct ways:

- Compressed natural gas (CNG). The gas is stored in high-pressure tanks (made of steel, aluminium or composite material), under a pressure of typically 200 to 300 bar. The main issue concerning this solution is energetic: there is a considerable amount of energy needed to compress the gas to such high pressures. This energy can amount to about 20% of total energy consumption; this aspect is often overlooked when considering natural gas vehicles, and detracts from the primary energy efficiency.
  Furthermore, the recharging infrastructure, which consists of compressor groups connected with high-pressure buffer storage tanks, is very heavy and quite expensive. A small “home compressor” will cost about 5000 to 10000 Euros, however this equipment will only allow slow overnight refuelling for a single vehicle. Large refuelling stations which allow more rapid refill can easily cost 1000000 Euros.
  The extra cost on a light-duty vehicle for a CNG installation is about 4000 Euros.

- Liquefied natural gas (LNG) has been considered for some applications, since its energy density is higher than for compressed gas. However, natural gas only liquefies at very low temperatures (-164 °C), and a considerable amount of energy is needed to bring it to the liquid state. Hence, LNG fuelling of vehicles is only justifiable from an energetic point of view where there is a source of liquid natural gas present (e.g. in port terminals where LNG is being delivered).
  The storage of natural gas in a liquid state generates a permanent boil-off, which has to be consumed by the system, otherwise this gas is lost. Thus only fleet vehicles which are used intensively, and which are operated in designated areas, will benefit from LNG fuelling.
  The safe handling of cryogenic liquids has caused some concerns; special dispensing units have been developed to allow safe refuelling of LNG vehicles even by non-specialist users, with manipulations akin to a conventional gasoline pump.

Methane gas can also be obtained from biomass and waste. This fuel (“biogas”) is similar in characteristics to natural gas, but comes from renewable resources. As it is a by-product of waste processing, these resources are limited however, confining the use of the biogas to niche applications (like refuse collection vehicles powered by refuse-generated gas, as used in Stockholm, Sweden).

Furthermore, methane gas has been considered for fuel cell vehicles, providing it is reformed (cracked) to release its hydrogen content.

The global impact of natural gas vehicles will be dependent on the availability of this fossil fuel with finite resources.

Hydrogen
The base fuel for fuel cells is in most cases hydrogen gas. It can be obtained from fossil sources, or by electrolysis of water. The main issue concerned with the use of hydrogen is it storage on board the vehicle, which can be done as follows:

- Compressed hydrogen, in high-pressure tanks.
- Solid-state storage methods. They refer to the chemical or physical binding of hydrogen to a solid material. The most known of these systems is the use of metal hydrides. Special alloys (featuring, among other elements, magnesium, nickel, aluminium and titanium) are able to absorb hydrogen up to 6% of their weight.
  Other solid-state systems being investigated using adsorbtion on activated carbon fibres or glass microspheres.[6]
  The use of sodium hydride as a hydrogen carrier is also under investigation. Sodium hydride is packed in small plastic spheres (Powerballs™[7]) which are broken and put in contact with water, releasing hydrogen. The resulting sodium hydroxide solution is then recycled and re-processed. This system is also dependent on a two-way exchange logistics.
- Liquefied hydrogen, at cryogenic temperatures. Condensing hydrogen gas into the more dense liquid form enables a larger quantity of hydrogen to be stored and transported. However, converting hydrogen gas to liquid hydrogen is costly and requires a large input of energy.

Ammonia
The use of ammonia for fuel cell vehicles has been proposed and is being actively considered for a number of applications[8]. Ammonia can be liquefied under moderate pressures at ambient temperature, and, on board the vehicle, reformed in hydrogen (for the fuel cell) and nitrogen which can be released to the atmosphere. The use of ammonia as hydrogen carrier in stead of methanol eliminates the carbon dioxide emissions. Some concerns have however been expressed about the safe handling of the product, ammonia being a very irritant gas.
Ammonia is readily available as a chemical base product and is also a by-product of certain processes.

---

[6] "Advanced hydrogen transport and storage technologies" – DOE/GO-10095-066 – National Renewable Energy Laboratory – US Department of Energy
[7] PowerBall is a trademark of Powerball Technologies
[8] The ammonia technology however is still to be considered as experimental and under development.

Conclusions

The possible introduction of alternative fuel vehicles will be mainly based on two factors: environmental impact (mostly emissions) and primary energy availability. The infrastructure impact is generally regarded as a secondary motivation; however its influence should not be underestimated.

Electric vehicles need access to the electrical distribution network; for most applications this can be implemented easily and without excessive cost. For fast charging, the cost of both the infrastructure and the use of peak power should be considered. The flexibility of electricity as an energy vector will make this solution the preferred one wherever the chosen applications will justify its use.

For liquid fuels, handling logistics do not present excessive problems. Gases however require a more elaborate infrastructure; furthermore, the process energy needed for gas refuelling infrastructure (compression or liquefaction of the gas, either natural gas or hydrogen) shall be taken into account when considering overall energy efficiency.