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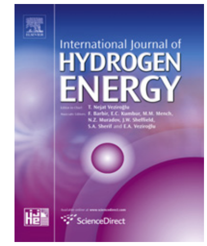

Review

Fuel cell vehicles: State of the art with economic and environmental concerns

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ABSTRACT

Hydrogen fueled fuel cell vehicles (FCVs) will play a major role as a part of the change toward the hydrogen based energy system. When combined with the right source of energy, fuel cells have the highest potential efficiencies and lowest potential emissions of any vehicular power source. As a result, extensive work into the development of hydrogen fueled FCVs is taking place. The aim of this paper is to highlight some of the research and development work which has occurred in the past five years on fuel cell vehicle technology, with a focus on economic and environmental concerns. It is observed that the current efforts are divided up into several parts. The performance, durability, and cost of fuel cell technology continue to be improved, and some fuel cells are currently ready to be mounted on vehicles and tested. Environmental and economic assessments of the entire hydrogen supply chain, including fuel cell end-use, are being carried out by groups of researchers around the world. It is currently believed that fuel cells need at least five more years of testing and improvement before large scale commercialization can begin. Economic and environmental analyses show that FCVs will likely be both economically competitive and environmentally benign. Indeed, the transition of the transportation sector to the use of hydrogen FCVs will represent one of the biggest steps toward the hydrogen economy.

1. Introduction

Concerns about the finite nature of fossil fuel resources and global climate change due to the combustion of those fossil fuels have sparked the people of the world to seek a clean, sustainable energy source for our ever increasing demands [1,2]. Hydrogen has been called the optimal replacement for fossil fuels, particularly in the transportation sector which represents the majority of petroleum consumption world-wide. The properties of hydrogen (H_2) make it a unique fuel and give it certain advantages and disadvantages over conventional fuels.

Hydrogen can be used for automotive applications via a blended mix of hydrogen and hydrocarbons used in a hydrogen internal combustion engine (ICE), or used in a fuel cell stack onboard light duty vehicles. The latter option, vehicular applications of fuel cells, is the focus of this paper.

There has been much research into fuel cell electric vehicles (FCVs or FCEVs) in the recent past. Within the last five years, research has been published in regards to a variety of fuel cell aspects. It should be noted that on a macro scale, FCVs are still in the research and development phase. As such, the existing literature on fuel cells (FCs) covers areas such as specific FC mechanisms and phenomena, comparative analyses between fuel cells and other power sources, the environmental impacts of FCVs, economics which justify or discredit FCVs, and even papers concerning their effect on human health.

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Nomenclature

APU	auxiliary power unit
BEV	battery electric vehicle
CFD	computational fluid dynamics
DH-FCV	Sim direct hydrogen add on to fuel cell vehicle simulator
EV	electric vehicle
FC	fuel cell
FCHEV	fuel cell plug-in hybrid electric vehicle
FCV	fuel cell vehicle
FCVSim	fuel cell vehicle simulator
FFOV	fossil fuel on-road vehicle
GHG	greenhouse gas
HEV	hybrid electric vehicle
HV	hydrogen vehicle
ICE	internal combustion engine
PEM	proton exchange membrane
PEFC	polymer electrolyte fuel cell
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
ME	mobile energy
VOC	volatile organic compound
WTW	well-to-wheels

For vehicular applications, the polymer electrolyte fuel cell (PEFC), also known as the proton exchange membrane (PEM) fuel cell (FC), seems best suited [1,3]. There continues to be research into optimal purification methods of fuel cell grade hydrogen [4], optimal operating points and automatic control [5], fuel cell cold start ability in low temperature conditions [6], and many other operating characteristics. Recently published simulation tools will assist researchers in the future as they continue to bring FC technology to maturity [7,8]. Component degradation and durability is anticipated to be a critical issue for the practical use of fuel cells [9].

The United States Department of Energy has specified long-term targets for vehicular PEFC development. By the year 2015, fuel cells for these applications are expected to be 60% efficient, and cost 30 US$/kW. Furthermore, vehicular fuel cell stacks are expected to have a nominal lifetime of at least 5000 h, which is equivalent to 150,000 mile at 30 mile per hour. The targets are echoed within the international community and represent concrete milestones for vehicular PEFC development [10].

Some researchers are taking existing data on available FC stacks and comparing them to each other to determine which configurations are optimal. This work acts as feedback for fundamental research efforts, and steers future studies in the most promising direction [3,10–12].

There is enough fundamental information about FCs that larger analyses can be carried out. An environmental analysis of the impact of FCVs is a popular topic for research and has appeared frequently in recent literature. A common interest of many of these studies is comparing emissions from the entire hydrogen supply chain infrastructure to those of an analogous fossil fuel infrastructure [2,13–16]. Other environmental research has begun to look more deeply into changes in both total and urban emissions [17]. In the US, some research is focused on the possibility of using coal for transportation fuel in response to the growing desire for energy security [18].

An environmental analysis can be coupled with an economic analysis to obtain a realistic indication of the viability of an FCV market. Fuel cell technology is currently being considered by marketing experts to determine the best strategies for marketing and growing an FCV economy [19–21]. Some think that niche roles such as PEFC auxiliary power units could provide short- and medium-term growth [22], while others are beginning to investigate a possible symbiotic relationship between FCVs and battery electric vehicles [23]. While changes in human health characteristics are beginning to be investigated by researchers in the field, this aspect will not be explicitly addressed in this paper.

The purpose of this paper is to provide a general overview of the current research on fuel cells for vehicular applications. This paper is not intended to be all-inclusive. Rather, it will serve as a starting point for future research, or to gain perspective on the field of fuel cells. It should be noted that fuel cell technology is still experiencing significant research and development. The next decade will most likely see some dramatic changes to the general tone of research into these quintessential components of the hydrogen economy.

2. Literature survey

2.1. Technical aspects of FCV development

Fuel cells are a technology which is still seeing significant development. The best fuel cell configuration has yet to be determined, and it will likely be different for various combinations of operating conditions, working loads, and desired sizes. The four major subsystems of any hydrogen fuel cell system are the fuel cell stack, air supply, hydrogen supply, and water and thermal management. An accepted method to study these elements of an FCV is through a dynamic simulation tool such as FCVSim. This program places an emphasis on FCVs, uses logical forward-looking causal structures, incorporates dynamics aspects, utilizes modular topography, and supports hardware-in-the-loop and rapid prototyping. The program can be extended to work with DH (direct hydrogen) in the DH-FCVSim extension [7].

A large portion of the current work in fuel cells is devoted to polymer electrolyte fuel cells, sometimes called proton exchange membrane fuel cells, as they are the most widely suitable fuel cell technology for vehicular applications. One recent study examined the role of reactant feeding, humidification, and cooling systems for two versions of a hybridized energy supply in a PEFC [1]. The specific process by which a fuel cell degrades in vehicular applications over time is a new and expanding field. Table 1 highlights some of the recent studies into PEFC degradation. A comprehensive study of fuel cell degradation can be found in Borup et al., 2007 [24].

In a recent study, potential hydrogen production methods have been forecasted. Hydrogen can be reformed from fossil fuels, produced via water electrolysis, or it can be extracted from biomass via gasification. FCVs may either store hydrogen

Table 1 – Performance degradation research focuses for PEM fuel cells.

PEFC component	Degradation effect	Reference
Entire fuel cell	Trade-off between efficiency and degradation performance	[25]
	Review of literature on effects and potential mitigation of various degradation modes	[26]
	Catalyst decay and membrane failure under near open circuit conditions	[9]
	Freeze/thaw cycles	[27]
	Driving cycle dynamic loading	[28]
	Difference between reversible and irreversible voltage degradation under open circuit conditions	[29]
	Sub-zero operation effect on ice formation	[30]
	Bus city driving cycles effect on voltage degradation	[31]
Catalyst layer	Surface area loss due to carbon corrosion and increasing platinum particle size	[32]
	Fuel and oxidant starvation effects on catalyst and carbon-support degradation	[33]
	Platinum dissolution and deposition on cathode, Pt diffusion in MEA, hydrogen permeation	[34]
	Pt catalyst ripening, electrocatalyst loss or re-distribution, carbon corrosion, electrolyte and interfacial degradation	[35]
	Effect of static and step potential conditions on platinum dissolution and carbon corrosion	[36]
	CO and CO_2 poisoning	[37]
	Toluene-induced cathode degradation	[38]
	Catalyst treatment with acid; effect on decreasing oxygen reduction reaction; Pt/C/MnO_2 hybrid catalyst	[39]
	Increasing particle size of Pt/C catalyst due to dissolution mechanism, oxygen electroreduction at cathode catalyst	[40]
	Degradation due to Cl^-, F^-, SO_4^{2-}, or NO_3^-	[41]
	Degradation effect on oxygen diffusion polarizations	[42]
	High temperature operation effect on carbon corrosion, platinum dissolution, and sintering; Pt/C and PtCo/C catalysts	[43]
Membrane electrode assembly	Air–air start-up, platinum crystallite precipitation	[44]
	Structural changes in PEM and catalyst layers due to platinum oxidation or catalyst contamination under open circuit conditions	[45]
	Excess air bleeding; anode catalyst	[46]
	On/off cyclic operation under different humid conditions	[47]
	Cell reversal during operation with fuel starvation	[48]
	Cathode flooding, membrane drying, and anode catalyst poisoning by CO	[49]
Membranes	Imide function hydrolysis inducing polymer chain scissions, comparison of sulfonated polyimide membranes with Nafion membranes	[50]
	Increasing hydrogen gas crossover, comparing Nafion 212 and Nafion 112 membranes	[51]
	Effect of water uptake on cyclic stress and dimensional change, hydrogen crossover; Nafion NR111 membrane	[52]
	Effect of hygro-thermal cycle on membrane stresses	[53]
Diffusion media	Elevated temperature and flow rate effect on mechanical stress and material loss	[54]
Sealing materials	Exposure time effect on de-crosslinking and chain scission; silicone rubber	[55]
	Sealing decomposition effect on catalysts	[56]

from a fueling station or produce it onboard. If FCVs are to refuel with hydrogen at a fueling station, the hydrogen must either be produced locally or transported from a central production facility. The likely sources of hydrogen for transportation have been illustrated diagrammatically in Fig. 1 [12].

The most likely sources of hydrogen, in order of timely implementation, begins with distributed hydrogen by reforming natural gas locally at the fueling station; followed by reforming biofuels such as cellulosic ethanol locally at the fueling station; central production by biomass gasification, coal integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS); and eventually electrolysis from zero-carbon electricity such as nuclear and renewables.

In the area of onboard hydrogen production, the purification process for hydrogen in FCVs has been considered. Purification methods may include fueling of the vehicle with cycloalkane, dehydrogenation in the vehicle, discharge of aromatic from the vehicle, and regeneration in a hydrogenation plant. Swesi et al. analyzed the MTH (methylcyclohexane/toluene/hydrogen) cycle due to its hydrogen storage capacity of 6.1 wt% and good reactivity in dehydrogenation [4].

There are two main separation techniques to extract hydrogen: membranes and adsorption. Studies indicate that separation of hydrogen through zeolite membranes is ineffective for FCV applications because the toluene content in the permeate is too high (>2000 ppm). Palladium membranes are more promising. When toluene was present at high concentrations, the diffusion of hydrogen was hindered due to a strong adsorption of toluene in the membranes [4]. Ultimately, it is more likely that future vehicles will refuel with hydrogen to avoid onboard purification.

Onboard hydrogen storage is one of the paramount hurdles that FCVs are trying to overcome to become competitive with the current fleet of internal combustion engine (ICE) vehicles.

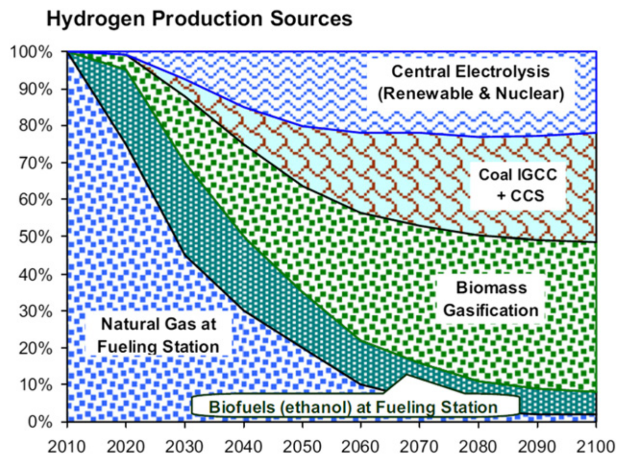

Fig. 1 – Sources of hydrogen over the century, beginning with distributed hydrogen by reforming natural gas at the fueling station; followed by reforming biofuels such as cellulosic ethanol at the fueling station; and central production by biomass gasification, coal integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS), and eventually electrolysis from zero-carbon electricity such as nuclear and renewables.

Storage options include metal hydrides, carbon nanotubes, compressed gas and liquid hydrogen. Currently, all of these options are both heavier and larger than their gasoline tank counterparts, but they are being further developed to achieve that goal [57] (Fig. 2).

The durability of PEFCs in vehicular applications has been the subject of recent research, which is a good indicator of progress toward fuel cell vehicles. Computational fluid dynamics (CFD) models of fuel cells now exist, allowing the study of failure mechanisms to generate much more accurate life prediction models. There are a number of commercially available CFD programs that support PEFC research, including Fluent, CFX-5, STAR-CD, and FEMLAB [58]. The best CFD programs, however, are built in house by researchers looking into specific aspects of fuel cell operation.

Three-dimensional, multiphase, non-isothermal CFD programs can account for all the major transport phenomena in a PEFC: convective and diffusive heat and mass transfer, electrode kinetics, transport and phase change mechanisms of water, and potential fields. This allows investigation into the displacement, deformation, and stresses inside the whole fuel cell as they develop during operation due to changes in temperature and relative humidity. A recent study found that non-uniform distribution of stresses caused by temperature gradients induce localized bending stresses, contributing to delamination between the membrane and gas diffusion layers. These stresses also contribute to delamination between gas diffusion layers and the flow field channels, particularly on the cathode side. These findings help explain cracks and pinholes that develop in fuel cell components during regular operation, and will certainly help guide fuel cell development in the future [8]. Table 2 lists other PEFC research work that has recently been done utilizing CFD programs.

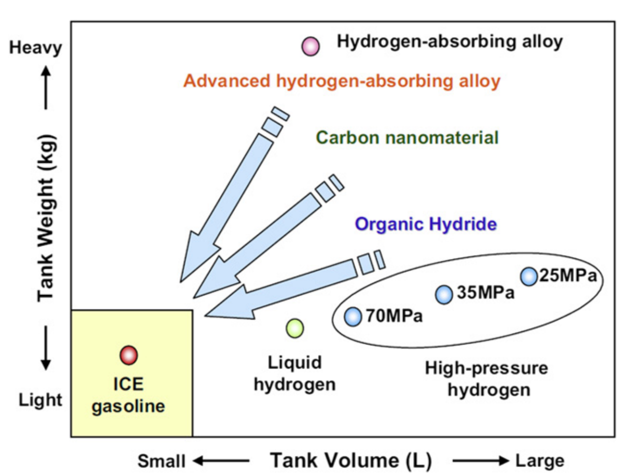

Fig. 2 – Hydrogen storage technologies and targets.

Another study focusing on long-term durability of six-cell PEFCs found two different causes for cell degradation. During a 1600 h test, PEFC cell voltage decreased at an average rate of 0.128 mV/h under close to open circuit conditions. However, the first 800 h had a much slower degradation rate caused by the gradual coarsening of the platinum catalyst, while the second 800 h period had a dramatic degradation rate caused by catastrophic failure of the membrane. Understanding these changes in failure mode is critical in enhancing the durability of polymer electrolyte fuel cells [9].

Logistical thinking has led other researchers to look at the operating conditions in which a fuel cell must work if it were utilized in a passenger vehicle. During the winter months, vehicular fuel cells need to start-up in the same amount of time as present day vehicles. The United States Department of Energy proclaimed that by 2010, a fuel cell vehicle should be able to start-up from −20 °C within 30 s using less than 5 MJ of additional energy. Looking more closely at the cold start scenario, it has been found that reducing the start-up time requires minimizing the freezing of process water in the catalyst layer of the membrane electrode assembly (MEA). The best way to do this was found to be a strategized shut-down, including a 30 min purge with dry gases [6]. Other researchers have looked into start-up/shut-down procedures for PEFCs and their effect on performance and durability, summarized in Table 3.

There has been other logistical work on optimizing hybrid fuel cell vehicle operation during driving. One such study investigated the issue of oxygen starvation during transients in power demand. Oxygen starvation can lead to "burn-through" effects on the membrane surface, which results in permanent damage. The potential solution, albeit costly, was found to be placing one ultra-capacitor at the load to buffer the fuel cell during load changes, and another ultra-capacitor at the compressor to improve phase characteristics of the system. Simulations showed that a controller could find optimum operating points for this hybrid system without requiring previous knowledge of the system dynamics [5].

There are literally hundreds, if not thousands, of specific research interests into the physical operation of hydrogen fuel cells for passenger vehicles. This overview is only intended to shed some light on the current FCV research and the state of the art. It is a topic that is expected to grow until at least 2020, when the first commercial versions of fuel cells are expected to be introduced to the light duty vehicle market.

Table 2 – PEFC CFD programs and recent research implementation.

Isothermal (yes/no)	Multiphase (yes/no)	Dimension (2D/3D)	Research focus and general results	Reference
No	–	3D	Solves for electric and ionic potentials in electrode and membrane, resolves local activation overpotential distribution, and predicts local current density distribution. *Results*: Can predict maximum current densities and underlying losses (ohmic losses, concentration losses, asymmetry parameter, etc.).	[59]
No	Yes	3D	Solves for displacement, deformation, and stresses inside the whole cell during cell operations due to changes in temperature and relative humidity. *Results*: Temperature gradients create non-uniform stress distributions that induce bending stresses, causing delamination between membrane and gas diffusion layers, and gas diffusion layers and flow field channels on cathode side.	[8]
No	No	3D	Solves for current density distribution across catalyst layer, anode and cathode activation overpotentials, oxygen transport limitations, and ohmic loss distributions. *Results*: There are non-uniform distributions of current density across catalyst layer, differences in anode and cathode activation overpotentials, oxygen transport limitations, and ohmic losses distributions.	[60]
No	Yes	3D	Solves for species profiles, temperature distribution, potential distribution, and local current density distribution in airflow-channel and air-breathing fuel cells. *Results*: Air-breathing designs achieve higher power densities, have a better gas replenishment rate at catalyst sites, and have a more uniform local current density distribution.	[61]
Yes	No	3D	Used as a direct problem solver to work with simplified conjugate-gradient method optimizer to solve for optimal gas channel width fraction, gas channel height, and thickness of gas diffusion layer. *Results*: This model can be used as a direct problem solver in optimizing geometric parameters of PEFCs given a set of base case conditions, always leading to a unique final solution.	[62]
No	No	3D	Solves for local activation overpotentials and local current density distribution *Results*: Varied, study analyzed multiple operating conditions for electrochemical and transport phenomena, and identified various limiting steps and components under different operating conditions.	[63]
No	No	3D	Solves for species profile, temperature distribution, potential distribution, and local current density distribution in tubular shaped PEFCs. *Results*: Varied, study analyzed multiple operating conditions for electrochemical and transport phenomena, and study identifies various limiting steps and components under different operating conditions.	[64]
No	Yes	3D	Solves for local current density distribution, wetting behavior of gas diffusion layers, and conditions that may lead to pore plugging. *Results*: This model can effectively identify parameters for wetting behavior of the gas diffusion layers, it can also identify conditions that may lead to the onset of pore plugging.	[65]
Yes	No	2D	Solves for effects of channel geometry and water management. *Results*: High current density operations require smaller width channels and bipolar plate shoulders, higher porosity electrodes result from increasing electrode area under bipolar plate shoulder, relative humidity in anode gas stream is more important for FC performance than relative humidity in cathode gas stream.	[58]

2.2. *Environmental impacts of FCV*

While the total cost of FCVs might still be higher than fossil fueled vehicles, the environmental impacts of fuel cell vehicles are very small compared to fossil fueled vehicles. One detailed paper studied the change in emissions if FCVs come to dominate the US market. It was assumed that fossil fuel on-road vehicles (FFOV) would be replaced with hydrogen FCVs. Emissions were analyzed after production of hydrogen via decentralized steam reforming of natural gas, decentralized electrolysis powered by wind power, and centralized coal gasification. Conservative assumptions were made to strengthen the credibility of results, which were compared against a 1999 vehicle fleet base case [13].

The reductions in emissions are the true advantage of FCVs over fossil-based technologies. In nearly every case, net quantities of nitrogen oxides (NO_x), volatile organic compounds (VOCs), particulate matter ($PM_{2.5}$ and $PM_{2.5-10}$), ammonia (NH_3), and carbon monoxide (CO) would decrease significantly. The conversion to either hybrid vehicles or to hydrogen vehicles derived from natural gas, wind, or coal would reduce the global warming impact of greenhouse gases (GHGs) by 6, 14, 23, and 1%, respectively. Remarkably, even for an inefficient hydrogen supply chain, where the FCVs are fueled by natural gas, no carbon is sequestered, and there is a 1% methane leak from feedstock, the scenario still achieves a reduction of 14% in CO_2 equivalent greenhouse gases [13].

Table 3 – Recent research in start-up/shut-down procedures for PEFCs.

Research area	Effect(s) studied and general results	Reference
Cold start	Adding hydrophilic nano-oxide SiO_2 to catalyst layer of cathode to increase water storing capacity. *Results*: Cold start process is strongly related to cathode water storage capacity; SiO_2 slightly decreases cell performance under normal operating conditions but drastically improves cold start (−10 °C) running time before cell voltage drops to zero; SiO_2 does not accelerate cell degradation compared with cells without SiO_2 layer.	[66]
	Cell voltage, initial water content and distribution, anode inlet relative humidity, heat transfer coefficients, cell temperatures. *Results*: Heat-up time can be reduced by decreasing cell voltage; effective purge is critical; humidification of the supplied hydrogen has negligible effect; surrounding heat transfer coefficients significantly affect heat-up time.	[67]
	Product water: absorbed in ionomer in catalyst layer, taken away as vapor in gas flow, and frozen into ice in catalyst layer pores. *Results*: Increasing membrane thickness increases water capacity but decreases water absorption process, increasing ionomer volume fraction increases ionomer water capacity and enhances membrane water absorption; cell start-up is better under potentiostatic condition than galvanostatic condition.	[68]
	Ionomer content in catalyst layer in galvanostatic cold start. *Results*: Start-up from −30 °C improves significantly with higher ionomer content in catalyst layer due to increased oxygen permeation of ice formation in catalyst layer.	[69]
	Operation under constant current and constant cell voltage conditions. *Results*: Water vapor concentration in cathode gas channel affects ice formation in cathode catalyst layer; the membrane plays important role in start-up by absorbing product water and becoming hydrated.	[70]
	Residual water effects on performance, electrode electrochemical characteristics, and cell components. *Results*: During start-up from −5 °C, residual water did not alter the electrochemically active surface area or charge resistance at low current density; less water was stored in the catalyst layer than in the rest of the cell.	[71]
	Energy requirement based on one-dimensional thermal model. *Results*: An optimum range exists for current density given a stack design for rapid cold start-up; thermal isolation of the stack reduces start-up time; end plate thickness has no effect beyond a certain threshold; of internal/external heating options, flow of heated coolant above 0 °C is the most effective way to achieve rapid start-up.	[72]
	Start current density dependence on membrane hydration, operation voltage, and gas flows. *Results*: Start-up below 0 °C depends on membrane hydration and operation voltage; current decay depends on constant gas flows of reactant gases; ice formation does cause degradation effects in the porous structures that leads to performance loss.	[73]
	Shut-down strategy importance on freezing of process water on catalyst layer of membrane electrode assembly. *Results*: The degree of dryness in the stack significantly influences cold start-up ability, increasing dryness improves performance; the optimal shut-down strategy allows start-up from −6 °C without any performance loss, lower temperatures will see temporary performance loss.	[6]
	Ice formation and inner-cell temperature increase dependence on water vapor concentration in cathode gas channel, initial water content in membrane, current density, and start-up temperature. *Results*: Ice precipitation can be delayed by decreasing interfacial water vapor concentration at gas diffusion layer and gas channel surface on cathode side; start-up performance improves by decreasing operation current density, decreasing initial water content in membrane, and increasing start-up cell temperature.	[74]
	Buildup of ice in cathode catalyst and electrode structure, operations near short-circuit conditions. *Results*: Near short-circuit conditions improves start-up below −20 °C by maximizing hydrogen utilization, producing waste heat absorbed by stack, and delaying loss of electrochemical surface area to ice formation; bipolar plates should be made from metal instead of graphite.	[75]
	Water freezing phenomena at interface between gas diffusion layer and membrane electrode assembly. *Results*: Ice formation at the gas diffusion layer and membrane electrode assembly interface causes gas stoppage, causing a drop in cell performance.	[76]
	Develop procedure to assist start-up: react hydrogen and oxygen in the FC flow channel to heat it up. *Results*: At temperatures below −20 °C, a catalytic hydrogen reaction in fuel cell flow channel is an effective and safe way to heat up the fuel cell, hydrogen concentration must be less than 20 vol%; gas flow rate, gas concentration, and active area are the key interdependent factors in this process.	[77]
	Initial water in membrane, operating voltage, cell temperature, current. *Results*: Ice formation in cathode layer pores and in active reaction sites increases electrical resistance and decreases performance; performance reduces less than 1% per cold start-up.	[78]

Table 3 (continued)

Research area	Effect(s) studied and general results	Reference
Normal start	Endplate effects on temperature profile. *Results*: An asymmetric temperature profile develops due to greater heat generation on cathode side; membrane swelling phenomena, caused by continuous water content variation, increases electrical and thermal resistance; latent water heat produced at catalysts can be stored in the stack; the non-uniform temperature distribution can be minimized by coupling coolant for central cells with the end cells.	[79]
	Liquid water, temperature, gas diffusion layer thickness and porosity. *Results*: Liquid water increases time for current density to reach steady state; temperature does not have significant effect on current density; increasing porosity decreases mass transport time scale; increasing gas diffusion layer thickness delays influence of liquid water.	[80]
	Cathode, anode, and membrane potentials during startup and shut-down. *Results*: Hydrogen/air boundary at anode creates voltage between membrane inlet/outlet and voltage at interface of cathode and membrane outlet, causing carbon corrosion.	[81]
	Internal currents during open circuit conditions. *Results*: Internal currents are caused primarily by capacitive effects; carbon oxidation occurs simultaneously and has negligible contribution to internal currents.	[82]
	Gasoline, methanol, ethanol, dimethyl ether and methane effects on hydrogen production. *Results*: Modeled overall efficiencies were 37% for gasoline, 38.3% for methanol, 34.5% for ethanol, 38.5% for dimethyl ether, and 33.2% for methane.	[83]
	Hydrophobic treatment (HT) and micro-porous layer (MPL) addition to gas diffusion layer (GDL) effect on water balance. *Results*: HT without MPL increases liquid water accumulation at electrode, limiting oxygen transport to catalyst and lowering cell voltage, also decreases water at GDL; HT with MPL addition suppresses water accumulation at electrode, increasing current; increasing air permeability of GDL increases current, also improving start-up performance.	[84]
Normal shut-down	Close/open state of outlets and application of dummy load effect on degradation of membrane electrode assembly. *Results*: Using a thin electrolyte membrane, outlets should be closed to limit degradation during on/off operation; using a thick electrolyte membrane, the dummy load should be applied to limit degradation.	[85]

Greenhouse gas pollution is one of the primary concerns with new vehicle technology. While the Intergovernmental Panel on Climate Change has suggested that 60–80% cuts in 1990 light duty vehicle emissions are required to achieve necessary CO_2 reductions. Identifying which future technology platform can achieve this goal is not a simple matter. Projecting forward to 2100, emissions scenarios have a wide range of possibilities, as shown in Fig. 3 [86].

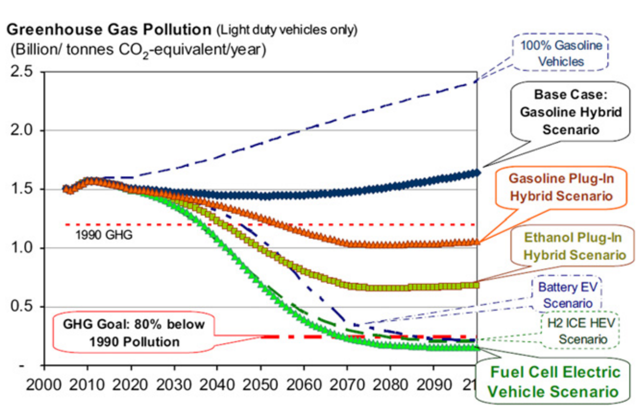

Fig. 3 – Primary model output showing the greenhouse gas pollution over the century for a reference case with no alternative vehicles, the four main vehicle scenarios and two secondary scenarios; the upper dotted horizontal line corresponds to the 1990 light duty vehicle GHG pollution, and the lower line represents an 80% reduction below the 1990 level.

China is becoming more and more interested in transitioning their vehicle fleet to FCVs as they look forward into this century. In 1999, China imported 23% of its oil demand, largely to support their growing private vehicle fleet. By 2030, if the number of vehicles per 1000 people reaches 100, then there will be an additional demand of 130 million metric

Table 4 – Supply pathways analyzed by Huang and Zhang 2006 [14].

Pathway	Feedstock	Fuel
Reference	Petroleum	Gasoline
1	Natural gas	GH_2 central plant
2	Natural gas	GH_2 refueling station
3	Natural gas	LH_2 central plant
4	Natural gas	LH_2 refueling station
5	Petroleum based naptha	GH_2 central plant
6	Petroleum based naptha	LH_2 central plant
7	Coal	GH_2 central plant
8	Coal	LH_2 central plant
9	Electricity with Shanghai generation mix	GH_2 refueling station
10	Electricity with Shanghai generation mix	LH_2 refueling station

Table 5 – Urban air pollution costs ($/metric tonne) [86].

	Delucchi average	Litman	EU AEA (average of 4)	EU (Holland & Watkins)	ANL damage cost	ANL control cost	Average air pollution costs
VOC	1086	17,706	2,722	3412	3940	16,195	7510
CO	76	534				4420	1677
NO_x	17,129	18,934	11,714	6825	7860	17,319	13,297
PM_{10}	138,257	6,565		22,750	10,599	6,005	36,835
$PM_{2.5}$	165,019		72,085				118,552
SO_2	69,094		15,506	8450	4733	11,581	21,873

tonnes of oil per year over today's standards. This equates to more than 50% imported oil needs, creating a serious energy security issue. Furthermore, in downtown Shanghai, fossil fueled vehicles account for 86% of total CO emissions, 96% of VOC emissions, and 56% of NO_x emissions. Converting the private vehicle fleet to FCVs would greatly improve the local air quality in Shanghai [14].

Following a WTW (well-to-wheels) assessment of hydrogen FCVs in Shanghai through ten different supply pathways (Table 4), six conclusions were reached. First, all hydrogen supply pathways could reduce emissions by at least 20% compared to petroleum use. Second, all but two hydrogen pathways (#7 and #8) significantly reduce WTW emissions in urban areas. Third, natural gas based pathways have the best energy efficiency (30–58%), electrolysis pathways have the worst (15–21%), and four of ten supply chains have higher energy efficiencies than supply chains from coal. Fourth, changes in WTW greenhouse gas emissions follow WTW energy use almost exactly. Fifth, all pathways achieve significant reductions in CO and VOCs. Other emissions, NO_x, PM10, and SO_2, can be reduced through some supply chains but not others. Lastly, it was found that the WTW assessment was necessary to adequately evaluate fuel/vehicle systems [14].

China's concerns about energy security are rightly justified as, internationally, we continue to rely on oil as our primary energy source for transportation. Looking forward to 2100, the demand for oil will greatly surpass the supply should there ever be political unrest in the OPEC nations. Our choice of future vehicle platform will weigh heavily on energy security concerns [86].

Let us expand on the idea of total vs. urban emissions for a moment. While total emissions are critical for global climate change, urban emissions are a subset of total emissions and have a large impact on human health in cities. The cost of urban emissions can be separated from total emissions and quantified. Current US urban air pollution costs are shown in Table 5 [86].

The total cost of urban emissions throughout this century will depend greatly on our choice of future vehicle platform, as shown in Fig. 4 [86].

Urban emissions have been the driver of many "new" fuels such as corn or switch-grass based ethanol. One study found that using E85 corn-based ethanol in flexible-fuel vehicles increases total emissions but reduces urban emissions by up to 30% because the main emissions are related to farming equipment, fertilizer manufacture, and ethanol plants, all of which are typically located in rural areas. Hybrid electric vehicles can reduce both total and urban emissions due to higher fuel efficiency. Battery electric vehicles (BEVs) may increase total PM emissions by 35–325%, but they reduce urban PM emissions by over 40%. FCVs increase both total and urban PM emissions. These results point to the use of BEVs in cities, where the vehicles typically have shorter driving ranges, and FCVs in suburban and rural areas, where they require longer diving ranges and the emissions cause fewer adverse effects on human health [17].

In Beijing, a life cycle assessment was performed for 11 supply streams to analyze energy efficiencies and emissions reductions. This study found the most efficient supply chain to be coal gasification and pipeline transport, with a total energy efficiency of 30%. Environmentally, the best option was to produce hydrogen via steam reformation of natural gas and pipeline transport based on the criteria of global warming, human toxicity, photochemical oxidation, acidification, and eutrophication. The best overall option was coal gasification with cylinder tank truck delivery when considering energy, the environment, and the economy in Beijing [16].

A similar life cycle assessment of hydrogen FCVs was performed in Canada, again seeking the optimal supply chain. From an environmental standpoint, the best option was found to be wind power production of hydrogen via electrolysis, followed by application in a PEFC vehicle [2]. Another study, focused on types of vehicles, found that an electric car with the capability of onboard electricity generation would be

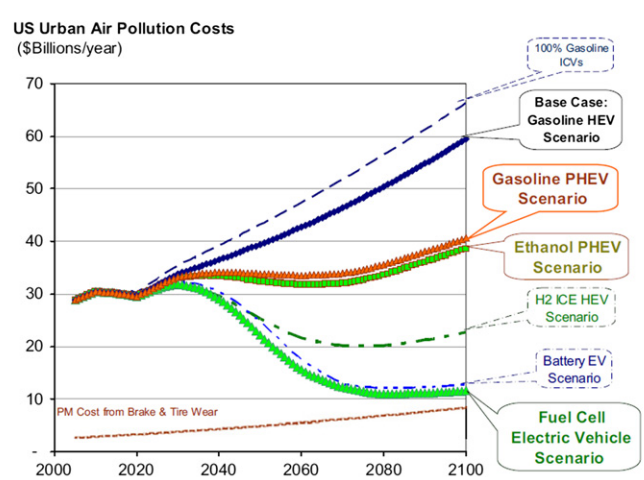

Fig. 4 – The costs of urban air pollution for the major alternative vehicle scenarios over the century; the bottom line shows the particulate matter costs from brake and tire wear that are common to all vehicles.

a worthy future investment since it could be nearly environmentally benign [15].

In the United States, some research is rightly devoted to using coal for transportation, due to the large, indigenous supply of this fossil fuel (approx. 250 yr supply at current consumption). Coal can be used to create liquid fuels, hydrogen, or electricity to power BEVs. Results of one study found that coal-to-liquid fuels and coal-to-hydrogen will most likely increase emissions, while coal-to-electricity combined with carbon capture and sequestration could cut 100 yr emissions in half using short range (60 km) plug-in hybrid electric vehicles (PHEVs) for some of the vehicle fleet demand. In reality, this study proved that coal for transportation could be argued for increased energy security [18]. However, coal-based electricity with carbon sequestration costs as much as, or more than, wind power does today, the cost of photovoltaic electricity is steadily falling, and the latter indigenous resources are renewable.

2.3. *Economic analysis of FCVs*

Cost effective, investor friendly economics of FCVs have yet to be demonstrated. Conventional vehicles have had the great advantage of over a century of time to mature to the current status of the market, where consumers expect a vehicle that is reliable, durable, has a long range, strong acceleration, and good power characteristics. FCVs are still in the research and development phase, so they are not as advanced as fossil technologies. In the Beijing case study, the optimal supply chain involved onboard methanol reforming, although this was not competitive with gasoline powered systems [16]. In an Austrian case study, FCVs do not look attractive until at least 2030, assuming very favorable key parameters to develop the hydrogen infrastructure [21].

The best scenario for vehicle introduction results in FCV market penetration in the coming decade, followed by a slow increase until about 2040, followed by rapid market share control. This scenario is presented in Fig. 5 [57].

Before we continue probing the possible FCEV scenarios of this century, it is worthwhile to understand the cost of

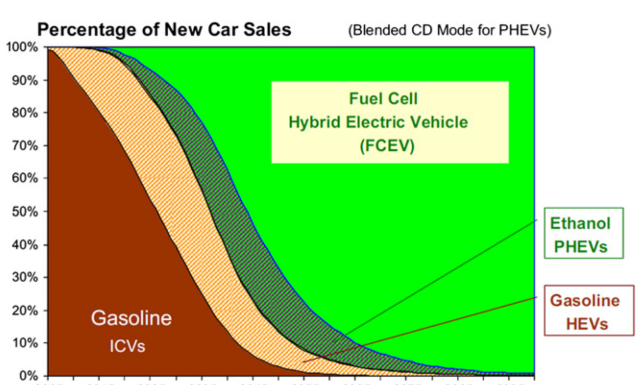

Fig. 5 – Fraction of light duty vehicle sales for the fuel cell electric vehicle (FCEV) scenario; the long-range BEV scenario and the hydrogen ICE hybrid electric vehicle (HEV) use this same sales profile over time with the BEV or hydrogen ICE BEV replacing the FCEV.

Table 6 – Estimates of the annual military costs of securing petroleum (US$ billions) [57].

	Low	High
Klare	132	150
Copulos, National Defense Council Foundation	49	138
Kimbrell, International Center for Technology Assessment	48	113
Danks, National Priorities Project	100	210
Average	82	153
Per barrel military costs based on total oil consumption	$11.7/bbl	$21.8/bbl
Per barrel military cost based on imported oil	$17.1/bbl	$31.9/bbl

continuing to use oil as our primary source of transportation energy. In addition to the urban costs of oil use shown in Table 4, there are military, economic and social costs of oil dependence as well, shown in Tables 6–8 [57].

These mounting costs indicate that the longer we wait to transition from oil, the more expensive it becomes. Total societal costs including greenhouse gas pollution, urban air pollution, and economic and military costs of continuing to import oil are shown in Fig. 6. Note that these costs are additional to the price consumers pay for their vehicles and refueling. Putting off the transition away from fossil fuels will increase these costs [57].

According to a life cycle assessment comparison between FCVs and gasoline vehicles, PEFC efficiency, when using hydrogen produced from steam methane reforming, was found to need to be 25–30% higher than a gasoline power source to be competitive. It would be better for the environment to produce hydrogen from wind power and electrolysis, but this method was found to depend strongly on the ratio of costs of hydrogen and natural gas. When this ratio is 2:1, production of hydrogen from natural gas is about five times cheaper than that from wind [2].

Another study compared the economic viability of conventional, hybrid, electric, and hydrogen FC vehicles to determine which would be cheapest. It was found that economic efficiency of electric cars depends substantially on the source of electricity. If the electricity comes from renewable sources, the electric car is advantageous to the hybrid. If the electricity comes from fossil fuels, the electric car can only be competitive with electricity generation onboard. Electricity

Table 7 – Estimates of the economic costs of oil dependence (US$ billions) [57].

	Low	High
Transfer of wealth	100	150
Loss of production capacity	10	50
Disruption Losses	50	170
Totals	160	370
Per barrel economic cost based on total oil consumption	$22.8/bbl	$52.7/bbl
Per barrel economic cost based on imported oil	$33.4/bbl	$77.1/bbl

Table 8 – Summary of estimated societal costs of US petroleum dependence [57].

	Low	High	Average
Average annual military oil supply protection costs ($US billions/yr)	82	153	118
Average annual economic costs of oil dependence ($US billions/yr)	160	370	265
Total annual costs of oil dependence ($US billions/yr)	242	523	383
Per barrel oil dependence cost based on total oil consumption	$34.5/bbl	$74.5/bbl	$55/bbl
Per barrel economic cost based on imported oil	$50.5/bbl	$109/bbl	$80/bbl

efficiency of a gas turbine on the order of 50–60% may also make the electric car advantageous [15].

One seemingly overlooked option in recent research is the idea of a fuel cell plug-in hybrid electric vehicle (FCHEV). This essentially combines the fuel cell electric vehicle (FCEV) with the battery electric vehicle (BEV). All three platforms utilize an electric drivetrain, and appear to be the contenders for the vehicle fleet after about 2030. Using this 2030 scenario, one study found that powertrain life cycle costs for an FCEV range from $7360 to $22,580, for a BEV range from $6460 to $11,420, and for an FCHEV range from $4310 to $12,540. Also, vehicles in 2030 will be relatively insensitive to electricity costs but quite sensitive to hydrogen costs. The principal advantage of the FCHEV is that it can overcome the short driving range of BEVs using a fuel cell range extender. Also, refueling a hydrogen tank takes minutes, whereas recharging a battery takes hours. Capital cost reduction must continue to be a key target for all three platforms, and recycling of platinum and lithium should be of key concern. It is most important to realize that BEVs and FCEVs are not necessarily antagonistic, either/or options, but both technologies should continue to be supported and pursued [23].

Hydrogen production weighs heavily in the consideration between FCVs and BEVs. At the production scale necessary to produce hydrogen to supply the vehicle fleet (10 quads), the most economically attractive renewable energy source is wind power, contributing about 70% of the total required energy in the US at a cost 40% lower than solar photovoltaic. Moreover, Class 4 wind resources (increasing class means increasing average wind speeds) may be utilized more than Class 5 or Class 6 resources because of their proximity to population centers and consequently lower transmission costs. Producing hydrogen via electrolysis, and assuming an electricity price of 4–8 cents/kWh, the hydrogen cost would be $2.75–4.50 per gallon of gasoline equivalent. One of the inefficient supply chains for hydrogen is production of liquid hydrogen fuel (which consumes 30% of the heating value), shipping it to distribution centers, and using it to fuel an ICE [13].

In California, some researchers are applying a marketing approach to the fuel cell vehicle. This mentality was premised on the idea that new consumer values must drive hydrogen FCV adoption. New solutions are part of a larger idea called Mobile Energy (ME) innovation. This notion accepts the fact that FCVs will not be superior to today's vehicles on dimensions conventionally valued by consumers, therefore product value must flow from other sources. Hydrogen fueled vehicles have some unique advantages over conventional vehicles that should be emphasized in their marketing. One opportunity for FCVs comes from their ability to produce clean electrical power for uses other than propulsion [19]. This Mobile Energy may be used "on the go," "in need," or "for a profit" [20].

Mobile Energy is consistent with the slow convergence of transportation and other energy systems. The studies into ME sought initial household market segments, finding only about 4 million out of 34 million California residents would most likely be able to adopt ME-enabled FCVs, not accounting for taste or purchase behavior. There does appear to be a trade-off relationship between ME-power and driving range, as well as

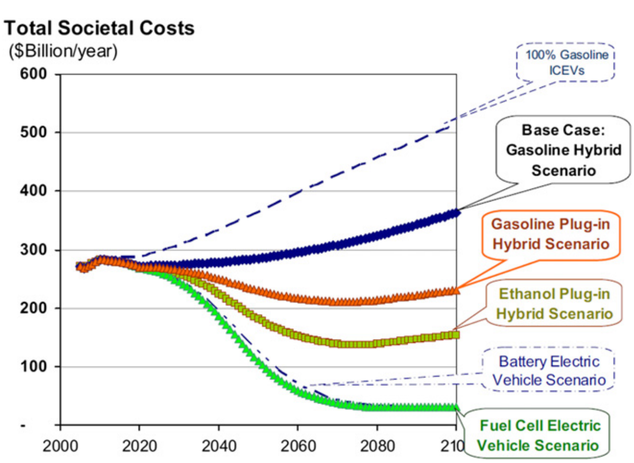

Fig. 6 – Estimate of the total societal costs of greenhouse gas pollution, urban air pollution, and the economic and military costs of imported oil for the major alternative vehicle scenarios.

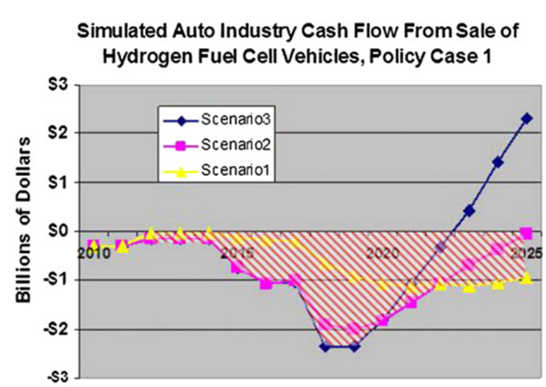

Fig. 7 – Simulated auto industry cash flow from sale of hydrogen fuel cell vehicles. Policy case assumes 50/50 incremental cost share government/industry, US$15 billion investment.

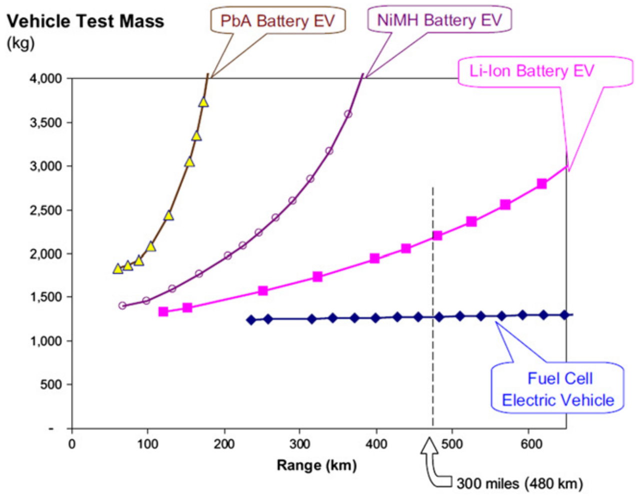

Fig. 8 – Calculated mass of fuel cell electric vehicles and battery electric vehicles as a function of the vehicle range: the power trains of all vehicles are adjusted to provide a 10s 0-60mph acceleration time.

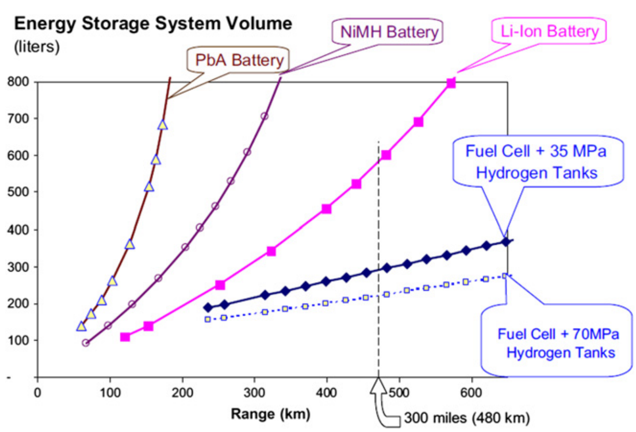

Fig. 9 – Calculated volume of hydrogen storage plus the fuel cell system compared to the space required for batteries as a function of vehicle range.

similar give-and-take situations within the supply framework. However, as questions arise over BEVs, market forces may well be opening the door for Mobile Energy innovation in the FCV sector [19,20].

One niche role for Mobile Energy may be in the use of PEFC auxiliary power units (APUs) onboard long-haul trucks. These trucks are idling overnight, but still demand auxiliary power beyond what is produced by the engine. The US has recently passed anti-idling regulation to limit pollution caused when idle. As a result, there is a window of opportunity for PEFCs. If PEFCs can meet US Department of Energy 2015 targets in terms of efficiency (40%), and specific cost (<400 US$/kW), and European Commission 2015 Development targets in terms of durability (40,000 h), this market offers looser constraints on APU volume, weight, and start-up time than the passenger vehicle market. Altogether, there may be 450,000 diesel trucks in the US and EU looking to install these PEFC APUs by 2020. While the long-term prospects of this technology are uncertain, the short- and medium-term prospects of demand make it rather promising [10,22].

A different study of the PEFC APU market found similar opportunities to advance the hydrogen economy through such niche applications. Regardless of whether the first APUs use hydrogen, direct methanol, or solid oxide fuel cells, the hydrogen economy can be supported by this market as it develops common characteristics for all these technologies, such as the proper regulatory setting, legal framework, marketing, and external affairs. Any market growth would alert consumers of FC technology possibilities and may spur a servicing and refueling infrastructure. This market may change consumer behavior to demand increased availability of power, favoring FC technology. Consumer exposure to the market itself would help by building expectations and confidence in fuel cells as a generic technology [87].

Government policies could be used to incentivize the creation of PEFC APU markets in the near future. It has been found that an incentive of $1500 would create an amortization timeline of only 2 yr, "the time horizon required by the fleet industry" [87]. This incentive could be in the form of capital grants or tax credits for the fleet owners. Of course, all of this is dependent upon the delivery of effective FC APU technology. The development of this technology is in the demonstration and refining stage, and current research should be devoted to optimizing reversible electrolyzer/fuel cell systems [88].

From a manufacturer's standpoint, the switch to FCVs will be expensive. Because of the nature and maturity of the ICE vehicle fleet today, the initial FCVs cannot enter the transportation industry as rudimentary models that can evolve slowly over time. Even though a small number of FCVs are manufactured and sold in the US and Japan, significant amounts of research

Table 9 – Estimated minimum fueling time for battery EVs and fuel cell EVs [12].

Vehicle range (km)	Battery electric vehicles					Fuel cell EVs
	Energy required from grid (kWh)	Level I charging time (h)	Level II charging time (h)	Level III charging time (h)		Hydrogen tank filling time (h)
		120 V, 20 A 1.9 kW	240 V, 40 A 7.7 kW	480 V, 3 Φ 60 kW	 150 kW	
241	56	29.2	7.3	0.9	0.4	0.08
322	82	42.7	10.68	1.4	0.55	0.10
483	149	77.6	19.40	2.5	0.99	0.15

Table 10 – FCV, BEV, HEV, and PHEV production costs compared against conventional ICE vehicles.

Technology	Cost (year 2000 $)	Notes	Year	Reference
Incremental costs over ICE				
HEV Cavalier	$4251	Incremental costs over ICE in year 2000 dollars	2003	[91]
HEV Taurus	$4382	All models considered include a moderate package of improvements and full		
HEV Silverado	$6694	hybridization, different HEV packages create different incremental costs		
HEV Caravan	$4827	ranging from $2543 (Cavalier) to $6694 (Silverado)		
HEV Explorer	$5719			
HEV	$3951	Incremental costs over ICE; this study includes multiple cost estimates,	2001	[92]
PHEV 32 km	$5825	from EPRI study performed in 2001		
HEV	$2001	Incremental costs over ICE, alternative EPRI study	2007	
PHEV 32 km	$3337			
HEV	$2007	Incremental costs over ICE Kromer and Heywood estimates	2007	
PHEV 16 km	$2926			
PHEV 48 km	$3595			
HEV	$1589	Incremental costs compared to year 2030 naturally aspirated spark ignition ICE	2007	[93]
PHEV 10 km	$2508			
PHEV 30 km	$3595			
PHEV 60 km	$5100			
FCV	$3010			
BEV	$8528			
FCV	$3010–$4264	Projected incremental cost for mass-produced FCV over 2030 ICE	2007	[94]
BEV 100 mi:				
Compact car	$5251	Incremental cost over 2007 ICE vehicles for 100-mile range BEVS	2007	[95]
Midsize car	$5471			
Full size car	$5572			
Small SUV	$7662			
Midsize SUV	$7303	The last estimate is the incremental cost over a 2030 spark ignition ICE		
Large SUV	$7911	vehicle, with an optimistic cost as low as $6900		
BEV 200 mi	$8528			
HEV	$4611	Incremental costs over ICEs in the near term	2009	[96]
	$1551			
	$3445			
	$3951			
PHEV 20 mi	$13,319			
	$6204			
	$5825			
PHEV 60 mi	$22,958			
	$4980			
	$10,262			
HEV	$1461–$3895	Incremental costs over ICEs in the mid-term	2009	
PHEV 20 mi	$3895–$5842			
PHEV 60 mi	$7205–$9737			
HEV	$2799	Incremental costs over ICEs in the long term	2009	
PHEV 20 mi	$7229			
PHEV 60 mi	$11,387			
FCV 200 mi	$2253	Incremental cost over ICE for FCVs and BEVs with 200 mile and 300 mile range	2009	[12]
BEV 200 mi	$8121			
FCV 300 mi	$1781			
BEV 400 mi	$9649			
Fuel cell stack costs				
FCV	$1187/kW	Fuel cell stack materials cost	2002	[97]
FCV 2000	$1693/kW	Fuel cell stack cost under a medium power density scenario, assuming	2004	[98]
FCV 2010	$154/kW	production increases to 50,000 units by 2010 and 5,000,000 units by 2020		
FCV 2020	$35/kW			
ICE	$54/kW	Cost estimate of fuel cell stack and ICE equivalent by 2016	2006	[99]
FCV	$220/kW			

Table 10 ***(continued)***

Technology	Cost (year 2000 $)	Notes	Year	Reference
FCV 5 kW	$4538/kW	PEFC manufacturing costs for a production scale of 500 units/year	2007	[100]
FCV 50 kW	$1351/kW			
FCV 80 kW	$1182/kW			
FCV 200 kW	$983/kW			
FCV 250 kW	$951/kW			
FCV–40	$1061/kW	Fuel cell stack cost assuming platinum price set to 1990s levels	2009	[101]
FCV–1 million	$12/kW	($15,000/kg) under different scenarios of total number of produced vehicles		
Drivetrain costs				
Gas ICEV	$2239	Estimated mass production (300,000 vehicles per year) costs for vehicle drivetrains	2003	[102]
Gas HEV	$2844			
H_2 HEV	$3924			
H_2 FCV	$4368			
FCV	$28,517	Estimated mass production costs of technology-specific propulsion systems	2004	[103]
BEV	$20,078			
SI ICE	$2299	Estimated drivetrain manufacturing costs for 27 mpg spark ignition	2004	[104]
H_2 FCV	$4291	ICE and 82 mpg gasoline equivalent hydrogen FCV		
BEV 2010	$52,826	Net costs of middle class vehicles for various years	2009	[105]
FCV 2010	$121,059			
BEV 2030	$28,614			
FCV 2030	$33,016			
BEV 2050	$25,312			
FCV 2050	$23,111			
2010:		IEA drivetrain costs for 2010 vehicles		
ICE	$1752			
FCV	$37,739			
BEV	$21,258			
FCHEV	$15,685			
2030 optimistic:		IEA optimistic drivetrain costs for 2030 vehicles	2010	[23]
ICE	$1911			
FCV	$5573			
BEV	$4936			
FCHEV	$3185			
2030 pessimistic:		IEA pessimistic drivetrain costs for 2030 vehicles		
ICE	$2014			
FCV	$11,194			
BEV	$7588			
FCHEV	$5836			
Total Vehicle Costs				
ICE	$13,784	Sale price of different vehicle technologies	2006	[15]
BEV	$37,838			
FCV	$90,090			
ICE	$19,084	Vehicle costs assuming a fuel cell stack price of $50/kW	2006	[106]
FCV	$24,824			
H_2 70 MPa	$3085	Energy storage system costs for FCVs and BEVs	2007	[107]
Lead acid	$12,854			
Ni-MH	$25,707			
Li-ion	$34,276			
FCV	1.2	Vehicle cost ratio estimate of FCVs and BEVs compared to standard ICEs in 2030	2007	[108]
BEV	2.0			
FCV 2020	$27,682	Vehicle production cost assuming total vehicle stock reaches	2008	[109]
FCV 2030	$25,467	550,000 units by 2020 and 4,800,000 units by 2030		

and development will be required before they can be mass produced. After this point, a large number of vehicles will have to be sold before the manufacturer's break even. Currently, many automakers are hoping that the government will subsidize their efforts, as the new fleet will have societal benefits from emissions reductions. According to Frenette (2009), a government subsidy of US$15 billion would result in a potential cash flow for automakers as shown in Fig. 7 [89].

Accordingly, manufacturer's view the transition to FCVs following approximately a 55-yr timeline: design a market-competitive vehicle (~15 yr), penetration up to 35% of new vehicle production (~25 yr), and penetration up to 35% of fleet-miles driven (~20 yr).

2.4. Comparing different hydrogen vehicle technologies: FCV, BEV, ICE

Once a series of fuel cells have been demonstrated to be economical for mass production for vehicles, research can begin to compare the strengths and weaknesses of each FC in a vehicular application. In one study, PEFCs using direct hydrogen (DH) were compared to those using onboard methanol reforming. DH-PEFCs have the clear advantage of producing water as the only by-product, while methanol reforming has the advantage of convenient fuel storage, corresponding to a more established distribution infrastructure [3].

Results found that exergy destruction and various losses associated with the methanol reformer create vehicle efficiencies and fuel economies much worse than those for direct hydrogen. Thus, DH-PEFCs are recommended over onboard methanol reforming on a performance and efficiency basis [3].

Another paper performed a study of DH FCVs, comparing battery-hybrid and load-following designs. Battery-hybrid vehicles assume that regenerative braking energy provides a potentially viable technique for improving vehicle efficiency, even though they have greater complexity, packaging constraints, and higher cost. On the other hand, the potential advantages of using a hybridized engine may be improvement in start-up performance, improved performance, potential efficiency improvements, and durability [10].

As it turns out, only cycles with a large amount of regenerative braking power at low power levels (e.g. city driving) provide significant advantages in terms of overall fuel economy attributable to the hybrid configuration. For other drive cycles, intangibles may be able to give them an advantage, although this advantage will not be seen in improved fuel economy. Regardless, loss characteristics assumed for the hybrid components are key to determine the detailed results. Any improvements in the loss characteristics of these components will change the findings [10].

There has been other research devoted to comparing FCVs with other vehicle technologies. Specifically, the aim is to compare operating characteristics between FCVs and battery electric vehicles (BEVs). Most papers looking purely into vehicle statistics, omitting environmental and economic considerations, find the same result: BEVs are better for shorter ranges, under about 160 km (100 mile), while FCVs outperform them at greater ranges [11,12].

The debate between FCVs and BEVs has staunch supporters on both sides. Depending on the way the data is presented, it can be shown that either vehicle configuration is superior to the other. For example, the energy storage of batteries can be compared to compressed hydrogen tanks per unit mass, and against vehicle range, shown here [12] (Fig. 8):

However, useful energy can also be described in terms of volume against vehicle range, showing electric vehicles are more evenly matched [12] (Fig. 9).

FCVs hold advantages over BEVs in both fueling times and fuel storage costs. These will be key parameters for consumers when deciding which vehicle platform better suits their demands. BEVs have a decidedly longer charging time and storage costs compared to FCVs, as shown in Table 9 [12].

It is also projected that production costs of FCVs will be incrementally smaller than production costs of BEVs compared to costs of advanced ICE vehicles (ICEVs) based on vehicle range. However, despite steady progress in bringing down the cost curve for FCVs, a 2005 look into overall manufacturing costs found that FCVs are about three times more expensive than conventional vehicles in engine cost, and four times more expensive considering the whole supply chain [90]. Table 10 reviews literature estimates of vehicle production costs for various technologies.

One of the very important considerations in the debate between FCVs and BEVs is the primary energy use required for a given transportation distance. This singular fact encompasses the entire supply chain efficiency from well-to-wheels. The better the efficiency, the less primary energy is required. In the case of natural gas, it has been shown that FCVs require less primary energy than BEVs for all vehicle ranges beyond 180 km [12] (Table 11).

Battery electric vehicles do outperform FCEVs when wind power is used as a primary source of energy. This suggests that the near-term future may be more optimistic for FCVs, while BEVs will require less overall energy, when the primary energy comes largely from renewable wind power [12].

An overall comparison of the characteristics of FCVs and BEVs shows that neither technology is definitively better than the other at this time. Two areas that BEVs outperform FCEVs are in primary renewable energy requirement and fuel cost per mile. Both of these are important to consumers and result in mixed attitudes about the future of the light duty vehicle market [12] (Fig. 10).

Table 11 – Ratio of total amount of energy required from primary source to provide given vehicle range [12].

Vehicle range (km)	Natural gas required (MBTU × 100)		Biomass energy required (MBTU × 100)
	FCEV (natural gas reformer): BEV (natural gas combined cycle)	FCEV (natural gas reformer):BEV (natural gas combustion turbine)	FCEV:BEV
180	25:27	25:44	42:49
253	35:40	35:64	56:77
327	55:63	55:96	81:108
400	68:85	68:132	101:148
473	83:120	83:170	125:199

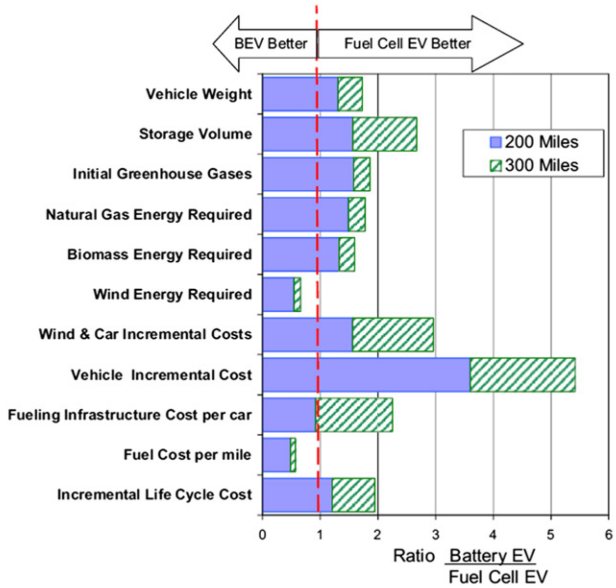

Fig. 10 – Ratio of advanced BEV attribute divided by the FCEV attribute for 200- and 300-mile range, assuming average US grid mix in the 2010-2020 time period and all hydrogen made from natural gas.

FCVs are found to be better than advanced lithium ion full function BEVs because the FCV weighs less, takes up less vehicle space for "fuel", generates less greenhouse gases, costs less in terms of vehicle and life cycle costs, requires less well-to-wheels natural gas or biomass energy, and takes much less time to refuel. However, BEVs have a lower fuel cost per kilometer, lower well-to-wheels wind or solar energy per kilometer, and greater access to fueling capability initially [12]. It may seem odd that BEVs outperform FCVs in wind and solar energy required, while FCVs are advantageous in terms of natural gas or biomass energy required. This is due to energy supply chain efficiencies at each step, beginning with the primary energy. This supply chain has lower efficiency losses for hydrogen production when it is based on natural gas or biomass, but higher efficiency losses for hydrogen production when it is based on wind or solar.

Hydrogen fueled vehicles operating an internal combustion engine, using liquid hydrogen, or containing onboard reforming of liquid fuels such as methanol, have far lower efficiencies than compressed hydrogen. If the perception of what a vehicle should be was to change significantly that could open up an urban market for BEVs. However, such a large change would be difficult to initiate. Ultimately, because of the lack of priority of vehicle characteristics such as cost, durability, range, and well-to-wheel efficiency, there is no clear cut way to identify either FCVs or BEVs as the best choice for the future of the light duty vehicle market [11].

3. Summary and conclusions

FCVs, BEVs, or FCHEVs will probably be the final step in the transition of the transportation sector to environmentally friendly light duty vehicles. For the time being, however, they have many obstacles to overcome. First and foremost, the fundamental operating parameters and configuration of fuel cell systems have not been optimized. Continual research and development into areas, such as separation membranes and overall stack performance is necessary. Batteries continue to face weight-to-energy storage issues, and their very nature requires linear increases in weight and size to increase the vehicle's range. And while BEVs are somewhat market ready, most experts agree that development of the fuel cell stack for automotive applications has at least 10 years before fuel cell vehicles are ready for market saturation.

After FCs have been further optimized, we must also compare them against each other in how well they perform in a vehicle. PEFCs appear as the most likely candidate due to their high efficiency, high performance in a wide working zone, suitable dynamic characteristics, and good working conditions at low temperatures. FCVs maintain a longer range and avoid the long recharge time of electric vehicles, while BEVs are probably better for urban areas both environmentally and based on range requirements. Future fuel cell work should be focused on optimizing the feeding method of hydrogen to the FC, optimizing automatic control architecture, reaching and exceeding modern vehicles in operating characteristics, and improving the processes for direct hydrogen, methanol reforming, or steam methane reforming.

The bright side of FCVs is that they will almost certainly reduce emissions compared to the current vehicle fleet. Carbon emissions will drop to near-zero, while there will be less but non-zero emissions of NO_x. The entire supply chain can achieve reductions in CO_2 equivalent greenhouse gas emissions by 14% even with steam methane reforming, no carbon sequestration, and 1% leakage loss of feedstock methane. In major cities such as Shanghai and Beijing, reductions in local air pollution will greatly improve the quality of life for citizens, and will ultimately reduce health care costs.

The down side of FCVs is that they are not currently economically competitive with conventionally fueled vehicles. Production by steam methane reforming would yield competitive costs if fuel cell efficiencies were 25–30% higher than those of gasoline ICEs. Perhaps the solution to this problem is to market FCVs as a new product entirely, packaged with Mobile Energy innovation which stimulates demand that does not currently exist. It will be interesting to see if this strategy helps the transition, but it is nearly certain that the transition will not be making significant headway for at least 10 years while FC technology matures further.

Hydrogen powered fuel cell vehicles seem to be on track for the transition of the transportation sector within our lifetimes. After another decade of research, we may see the first commercial fuel cell vehicle ready for mass production. As the efficiency of the FC increases, onboard storage of hydrogen issues are solved, and the economics of FCVs become increasingly competitive, we may indeed be a part of a dramatic transformation of the transportation sector as we travel down the road to a hydrogen economy.

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