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 towards 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. This paper aims to highlight some of the research and development work in the past five years on fuel cell vehicle technology with a focus on economic and environmental concerns. It will be observed that the current efforts are divided up into several parts. The mechanics of fuel cell technology continues to be improved, while some fuel cells are ready to be mounted on vehicles and tested. Environmental and economic assessments of the entire hydrogen supply chain with FC (fuel cell) end-use are being carried out by some groups of researchers around the world. The current opinion is that fuel cells need at least five more years of testing and improvements before large scale commercialization can begin. Environmental and economic analyses show that FCVs will be both economically competitive and environmentally benign. Indeed, the transition of the transportation sector to the use of hydrogen FCVs represents one of the biggest steps toward the hydrogen economy.

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Nomenclature

APU: Auxiliary Power Unit

BEV: Battery Electric Vehicle

CFD: Computational Fluid Dynamics

DH-FCVSim: 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: Polymeric Electrolyte Fuel Cell

PHEV: Plug-in Hybrid Electric Vehicle

PM: Particulate Matter

ME: Mobile Energy

VOC: Volatile Organic Compound

WTW: Well-to-Wheels

1. Introduction

Concerns about the finite nature of fossil fuel resources and global climate change due to the burning 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 that represents the majority of petroleum consumption. The properties of hydrogen (H_2) make this a unique fuel and give it certain advantages and disadvantages over conventional fuel.

Hydrogen can be used for automotive applications via a blended mix of H_2 and hydrocarbons, use in an H_2 internal combustion engine (ICE), or use in a fuel cell stack onboard light duty vehicles. The latter option, a fuel cell stack, 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) cover areas such as specific FC mechanics, comparative analyses between fuel cells and other power sources, environmental impacts of FCVs, economics that justify or discredit FCVs, and even papers concerning the effect on human health.

For vehicular applications, the proton exchange membrane (PEM) fuel cell (FC), also known as the polymeric electrolyte fuel cell, seem best suited [1], [3]. There continues to be research into optimal purification methods of fuel cell ready H_2 [4], optimal operating points and automatic control [5], fuel cell start ability in cold weather conditions [6], and many other operating characteristics. Simulation tools recently coming online will assist researchers in the future as they slowly bring FC technology to maturity [7], [8]. Membrane degradation and durability looks to be a critical issue for the practical use of fuel cells [9].

Other researchers take existing data on available FC stacks and compare them to each other to find which FCs are optimal. This work acts as feedback for more specific research and then steers future research in the most promising direction [3], [10], [11], [12].

There is enough fundamental information about FCs that larger analyses can be carried out. An environmental analysis on the impact of FCVs is a popular topic for research and shows up frequently in recent literature. The main interest of these studies is comparing emissions from the entire hydrogen supply chain infrastructure to those of an analogous fossil fuel infrastructure [2], [13], [14], [15], [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 in response to the growing desire for energy security [18].

An environmental analysis can be coupled with an economic analysis to obtain true data about the viability of an FCEV market. Fuel cells are currently being reviewed by marketing experts to determine the best strategies for marketing and growing an FCV economy [19], [20], [21]. Some think that niche roles such as PEM fuel cell 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 tackled by the field of researchers, 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 cells are still under heavy 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 work in progress. The best fuel cell configuration has yet to be determined, and it will likely be different for varying operating conditions, working loads, and desired size. The four major subsystems of any fuel cell are the fuel cell stack, air supply, water and thermal management, and hydrogen supply. 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 prepares for hardware-in-the-loop and rapid prototyping. It can be extended to work with DH (direct hydrogen) in a DH-FCVSim extension [7].

Most current work is devoted to proton exchange membrane (PEM) fuel cells, sometimes called polymeric electrolyte fuel cells, as they are the most widely suitable 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 PEMFC [1]. The specific processes by which a fuel cell degrades in vehicular applications over time is a new and expanding field. Table 1 below highlights some of the recent studies into PEMFC degradation. A comprehensive study of fuel cell degradation can be found in Borup, et al 2007 [24].

Table 1. Performance degradation research focuses for PEM fuel cells

PEMFC component	Degradation effect	Reference
Entire fuel cell	Trade-off between efficiency and degradation performance	[25]
Platinum catalyst	Surface area loss due to carbon corrosion and increasing platinum particle size	[26]
Entire fuel cell	Review of literature on effects and potential mitigation of various degradation modes	[27]
Membrane electrode assembly	Air-air start up, platinum crystallite precipitation	[28]
Catalysts	Fuel and oxidant starvation effects on catalyst and carbon-support degradation	[29]
Entire fuel cell	Catalyst decay and membrane failure under close to open circuit conditions	[9]
Gasket silicone rubber	Exposure time effect on de-crosslinking and chain scission	[30]

Membrane electrode assembly	Structural changes in PEM and catalyst layers due to platinum oxidation or catalyst contamination under open circuit conditions	[31]
Platinum catalyst	Platinum dissolution and deposition on cathode, Pt diffusion in MEA, hydrogen permeation	[32]
Sulfonated polyimide membranes	Imide function hydrolysis inducing polymer chain scissions, comparison with Nafion membranes	[33]
Platinum catalysts, carbon support, Nafion ionomer	Pt catalyst ripening, electrocatalyst loss or re-distribution, carbon corrosion, electrolyte and interfacial degradation	[34]
Entire fuel cell	Freeze/thaw cycles	[35]
Membrane electrode assembly, anode catalyst	Excess air bleeding	[36]
Nafion 212 membrane	Increasing hydrogen gas crossover, comparing to Nafion 112 membranes	[37]
Gas diffusion layer	Elevated temperature and flow rate effect on mechanical stress and material loss	[38]
Platinum catalyst	Potential-static holding conditions and potential step conditions effect on platinum dissolution and carbon corrosion	[39]
Nafion NR111 membrane	Water uptake effect on cyclic stress and dimensional change, hydrogen crossover	[40]
Platinum catalyst	CO and CO_2 poisoning	[41]
Pt/C/MnO_2 hybrid catalysts	Catalyst treatment with acid effect on decreasing oxygen reduction reaction	[42]
Entire fuel cell	Driving cycle dynamic loading	[43]
Platinum catalyst	Toluene-induced cathode degradation	[44]
Pt/C catalysts	Increasing particle size of Pt/C catalyst due to dissolution mechanism, oxygen electroreduction at cathode catalyst	[45]
Pt/C catalysts	Degradation due to Cl^-, F^-, SO_4^{2-}, or NO_3^-	[46]
Membrane electrode assembly	On/off cyclic operation under different humid conditions	[47]
Entire fuel cell	Difference between reversible and irreversible voltage degradation under open circuit conditions	[48]
Membrane electrode assembly	Cell reversal during operation with fuel starvation	[49]
Entire fuel cell	Sub-zero operation effect on ice formation	[50]
Entire fuel cell	Bus city driving cycles effect on voltage degradation	[51]
Sealing material	Sealing decomposition effect on catalysts	[52]
Electrode porous catalyst layer and gas diffusion layer	Degradation effect on oxygen diffusion polarizations	[53]
Pt/C and PtCo/C catalysts	High temperature operation effect on carbon corrosion, platinum dissolution, and sintering	[54]
Cathode, membrane, and anode	Cathode flooding, membrane drying, and anode catalyst poisoning by CO	[55]
Fuel cell membranes	Effect of hygro-thermal cycle on membrane stresses	[56]

In a study of potential hydrogen production methods, a forecast for H_2 production has been estimated. Hydrogen can be reformed from fossil fuels, produced via water electrolysis, or it can be extracted from biomass via gasification. Onboard purification techniques are discussed below. However, if FCVs are to refuel with hydrogen at a filling station, how will the hydrogen be produced? The likely sources of hydrogen for transportation have been broken down in Figure 1 [12].

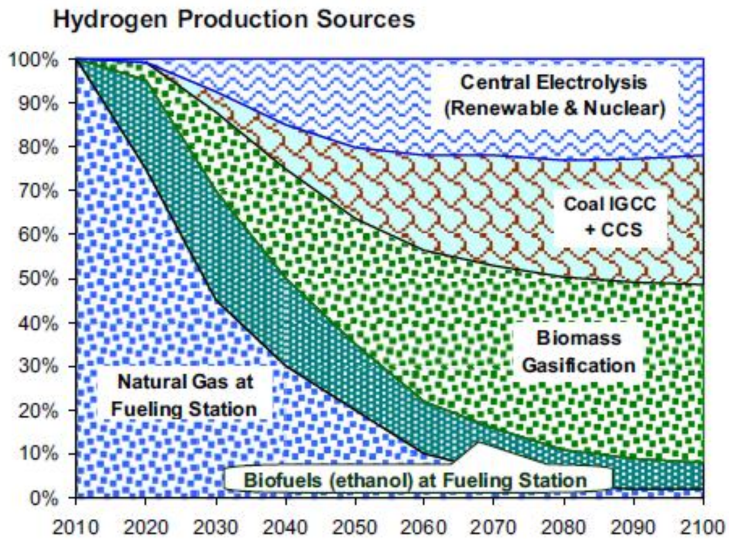

Figure 1. Sources of hydrogen over the century, beginning with distributed hydrogen by reforming natural gas at the fueling station; followed by reforming biofuels such as cellulosic ethanol at the fueling station; and central production by biomass gasification, coal integrated gasification combined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

In the area of onboard H_2 production, the purification process for hydrogen in FCVs has been considered. Purification includes fueling of the vehicle with cycloalkane, dehydrogenation in the vehicle, discharge of aromatic from the vehicle, and regeneration in a hydrogenation plant. There are two main separation techniques to extract hydrogen: membranes and adsorption. One paper analyzed the MTH (methylcyclohexane-toluene-hydrogen) cycle due to its hydrogen storage capacity of 6.1wt% and good reactivity in dehydrogenation [4].

Results indicate that separation of H_2 through zeolite membranes is ineffective for FCV applications because the toluene content in the permeate was still too high (>2000ppm). 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 H_2 and 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. 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 slowly working toward that goal [57].

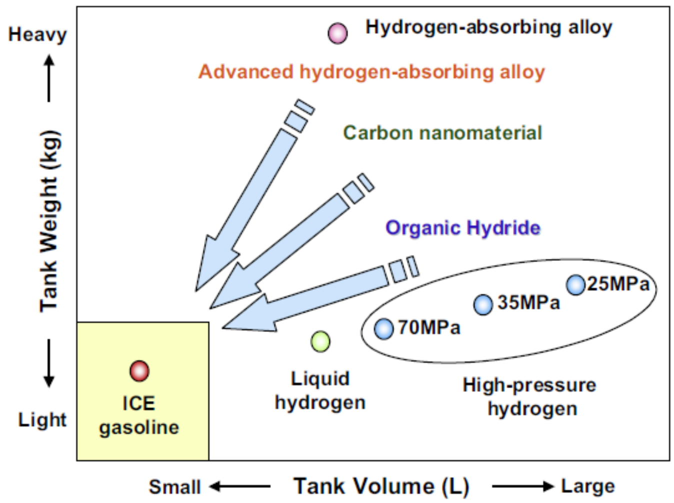

Figure 2. Hydrogen storage technologies and targets.

The durability of PEM FCs in vehicular applications has begun to show up in 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 PEM FC 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, multi-phase, non-isothermal CFD programs can account for all the major transport phenomena in a PEM FC: 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 delaminating between the membrane and gas diffusion layers. These stresses also contribute to delaminating between gas diffusion layers and the channels, particularly on the cathode side. This helps explain cracks and pinholes in fuel cell components during regular operation, and these findings will certainly help guide fuel cell development in the future [8]. Table 2 below lists some other PEMFC research work that has recently been done utilizing CFD programs.

Table 2. PEMFC CFD programs and recent research implementation

Model description	Research Focus and General Results	Reference
Non-isothermal, 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 causes (ohmic losses, concentration losses, asymmetry parameter, etc.)	[59]
Non-isothermal, 3D multiphase	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 delaminating between membrane and gas diffusion layers, and gas diffusion layers and channels on cathode side	[8]
Non-isothermal, 3D single phase	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]
Non-isothermal, 3D multiphase	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]
Isothermal, 3D single phase	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 PEM FCs given a set of base case conditions, always leading to a unique final solution	[62]
Non-isothermal, 3D single phase	Solves for local activation overpotentials and accurate local current density distribution *Results:* Varied, study analyzed multiple operating conditions for electrochemical and transport phenomena, and study identified various limiting steps and components under different operating conditions	[63]
Non-isothermal, 3D single phase	Solves for species profiles, temperature distribution, potential distribution, and local current density distribution in tubular shaped PEM FC *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]
Non-isothermal, 3D multiphase	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]
Isothermal, 2D single phase	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]

Another study focusing on long term durability of six-cell PEM FCs found two different causes for cell degradation. During a 1600 hour test, a PEM FC lost cell voltage at an average rate of 0.128mV/hr under close to open circuit conditions. However, the first 800 hours had a much slower degradation rate caused by the gradual coarsening of the platinum catalyst, while the second 800 hours had a dramatic degradation rate caused by catastrophic failure of the membrane. Understanding these changes in causes for failure is critical in enhancing the durability of PEM 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 in a passenger vehicle. During the winter months, fuel cells need to start similarly to our cars today. The Department of Energy proclaimed that by 2010, a fuel cell vehicle should be able to start up from -20°C within 30 seconds using less than 5 MJ of additional energy. Looking into this freeze start condition, it has been found that minimizing freeze start time requires avoiding freezing of process water on 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 minute purge with dry gases [6]. Other researchers have looked into start-up/shut-down procedures for PEMFCs and their effect on performance and durability, summarized below in Table 3.

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

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]
Cold start	Cell voltage, initial water content and distribution, anode inlet relative humidity, heat transfer coefficients, cell temperatures *Results:* heating-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 heating-up time	[67]
Cold start	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]

Cold start	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]
Cold start	Operations 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]
Cold start	Residual water effects on performance, electrode electrochemical characteristics, and cell components *Results:* during start-up from -5C, residual water did not alter the electrochemical active surface area or charge resistance at low current density; less water was stored in the catalyst layer than in the cell	[71]
Cold start	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]
Cold start	Start current density dependence on membrane humidity, operation voltage, and gas flows *Results:* start-up below 0°C depends on membrane humidity 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]
Cold start	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]
Cold start	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 performances improves by decreasing operation current density, decreasing initial water content in membrane, and increasing start-up cell temperature	[74]
Cold start	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 het absorbed by stack, and delaying loss of electrochemical surface area to ice formation; bipolar plates should be made from metal instead of graphite	[75]
Cold start	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 air gas stoppage, causing a drop in cell performance	[76]
Cold start	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 effective and safe way to heat up the fuel cell, hydrogen concentration must be less than 20vol%; gas flow rate, gas concentration, and active area are the key interdependent factors in this process	[77]
Cold start	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]
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]
Normal start	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	[80]

	scale; increasing gas diffusion layer thickness delays influence of liquid water	
Normal start	Cathode, anode, and membrane potentials during startup and shutdown *Results:* hydrogen/air boundary at anode creates voltage between membrane inlet and outlet and voltage at interface of cathode and membrane outlet, causing carbon corrosion	[81]
Normal start	Internal currents during open-circuit conditions *Results:* internal currents are caused mostly by capacitive effects; carbon oxidation occurs simultaneously and has negligible contribution to internal currents	[82]
Normal start	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]
Normal start	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 shutdown	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]

There has been other logistical work on optimizing hybrid fuel cell operation during driving. One such study attacked the issue of oxygen starvation during the transients of power demand increases. Oxygen starvation can lead to “burn-through” effects on the membrane surface, which is 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 fuel cells for passenger vehicles. This overview is only intended to shed some light on the current FCV research and state of the art. It is a topic that is expected to grow at least until 2020, when the first commercial versions of fuel cells are expected to hit the light duty vehicle market.

2.2 Environmental impact 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 after FCVs 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 H_2 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 the 1999 vehicle fleet base case [13].

The reductions in emissions are the true advantage of FCVs over fossil 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 H_2 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 H_2 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].

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 necessary to achieve necessary CO_2 reductions, the question is: which future technology platform can achieve this goal? Projecting forward to 2100, emissions scenarios have a wide range of possibilities, as shown in Figure 3 [86].

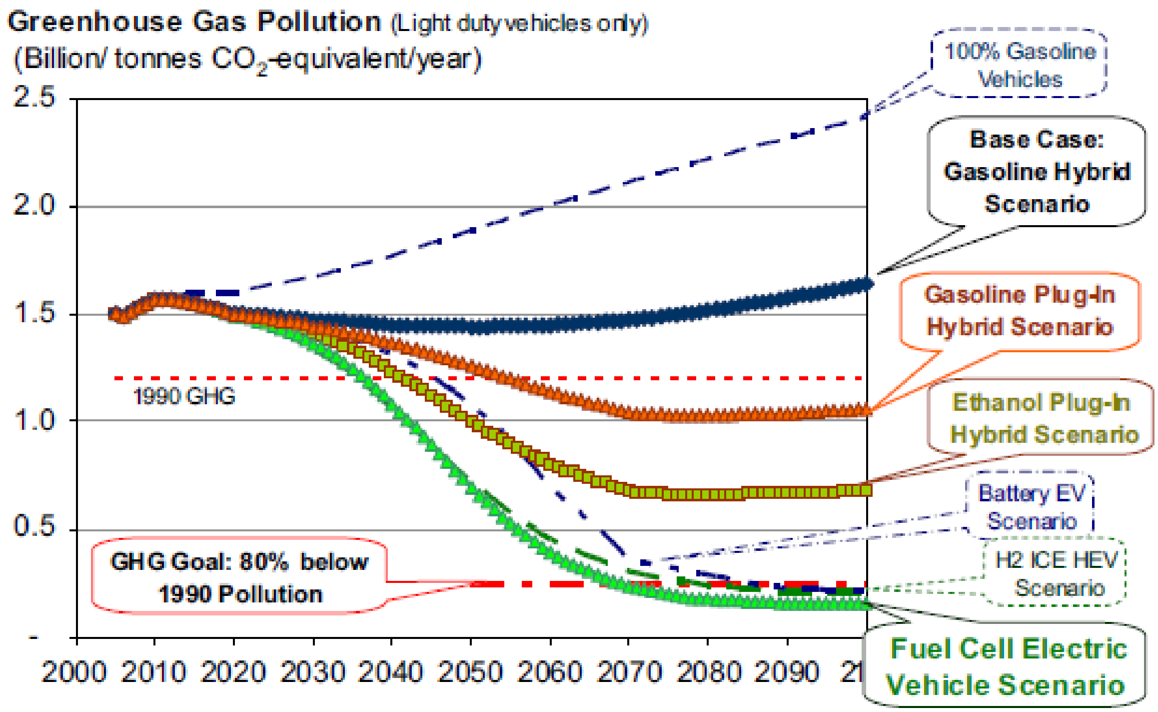

Figure 3. Primary model output showing the greenhouse gas pollution over the century for a reference case with no alternative vehicles, the four main vehicle scenarios and two secondary scenarios; the upper dotted horizontal line corresponds to the 1990 light duty vehicle GHG pollution, and the lower 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 to largely 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 tons 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 air quality in Shanghai [14].

Following a WTW (well-to-wheels) assessment of H_2 FCVs in Shanghai through ten different supply pathways(Table 4 below), 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, PM_{10}, 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].

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

China's concerns about energy security are rightly justified as 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 and quantified from total emissions. Current US urban air pollution costs are shown below in Table 4 [86].

Table 5. Urban air pollution costs ($/metric tonne).

	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	3,412	3,940	16,195	7,510
CO	76	534				4,420	1,677
NOx	17,129	18,934	11,714	6,825	7,860	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	8,450	4,733	11,581	21,873

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

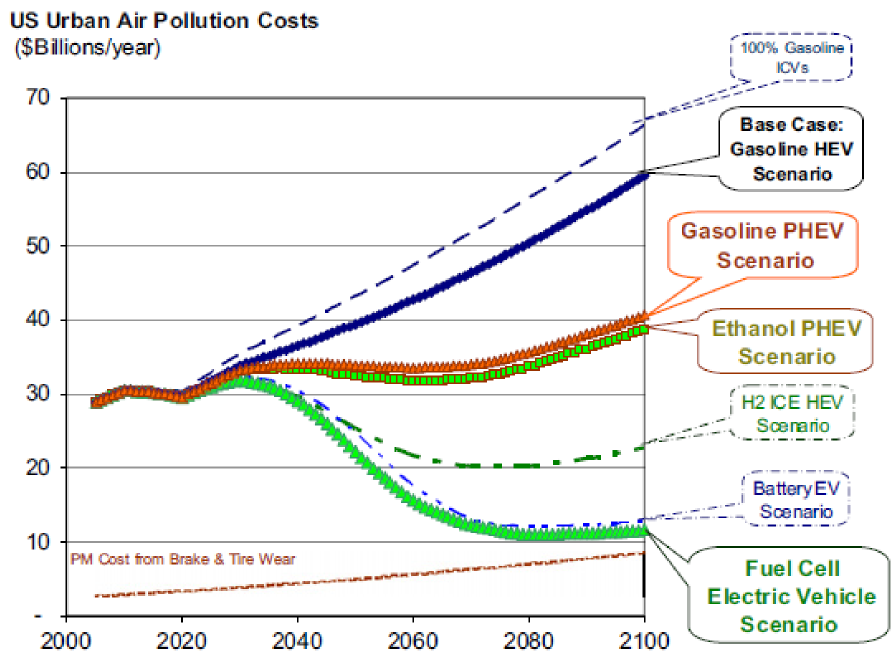

Figure 4. The costs of urban air pollution for the major alternative vehicle scenarios over the century; the bottom line shows the particulate matter costs from brake and tire wear that are common to all vehicles.

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 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 have and require shorter driving ranges, and FCVs in suburban and rural areas, where they require longer diving ranges and the emissions play less into an adverse effect 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 plan was to produce H_2 via steam reforming of natural gas and pipeline transport based on the criteria of global warming, human toxicity, photochemical oxidation, acidification, and eutrophication. The best overall plan was coal gasification with cylinder tank truck delivery when considering energy, environment, and economy in Beijing [16].

A similar life cycle assessment of H_2 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 PEM FC vehicle [2]. Another study, focused on types of vehicles, found that an electric car with the capability of onboard electricity generation would be a worthy future investment since it could be almost 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. 250yr 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 year emissions in half using short range (60km) plug-in hybrid electric vehicles (PHEVs) for some of the vehicle fleet demand. In reality, this study proved that coal for transportation could be an argument for increased energy security [18]. However, coal-based electricity with carbon sequestration costs as much or more than wind power does today, the cost of photovoltaic electricity is steadily falling, and the latter indigenous resources are renewable.

2.3 Economical 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, good acceleration, and good power characteristics. FCVs are still in the R&D phase, so they are really not close to fossil technologies' level of progress. 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 develop the hydrogen infrastructure [21].

The best scenario for vehicle introduction results in FCV market penetration in this coming decade, followed by a slow learning curve until about 2040, followed by rapid market share control. This scenario is presented below [57].

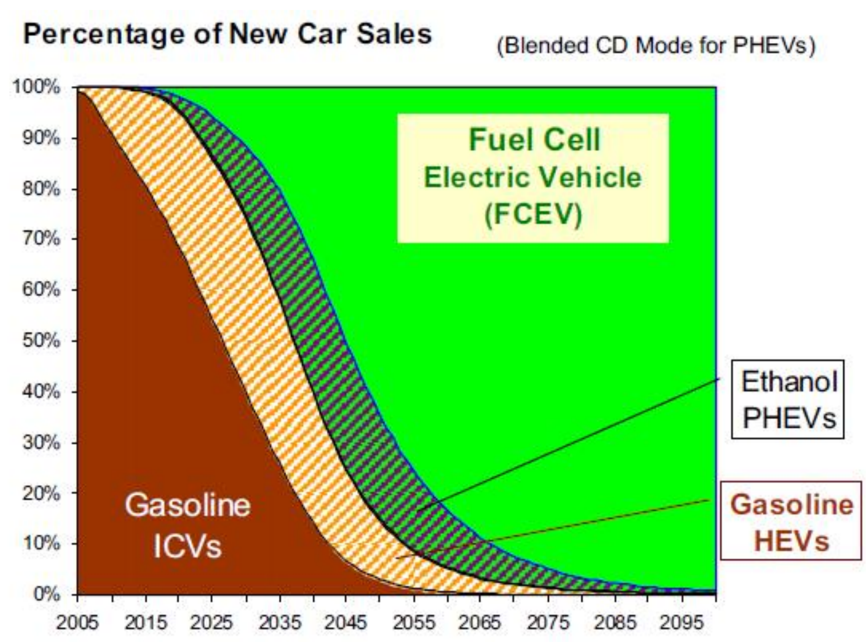

Figure 5. Fraction of light duty vehicle sales for the fuel cell electric vehicle (FCEV) scenario; the long-range BEV scenario and the hydrogen ICE hybrid electric vehicle (HEV) use this same sales profile over time with the BEV or hydrogen ICE BEV replacing the FCEV.

Before we continue probing the possible FCEV scenarios of this century, it is worthwhile to understand the cost of 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 and economic costs of oil dependence as well, shown below in Table 5 and Table 6 [57].

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

	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

Table 7. Estimates of the economic costs of oil dependence (US$ billions).

	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

This leads to the total cost of US petroleum dependence [57].

Table 8. Summary of estimated societal costs of US petroleum dependence.

	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

How does this play into the future? The simple answer is, the longer we wait to transition off 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 Figure 6. Note that these costs are additional to the price consumers pay for their vehicles and refueling. Putting off the transition will increase these costs [57].

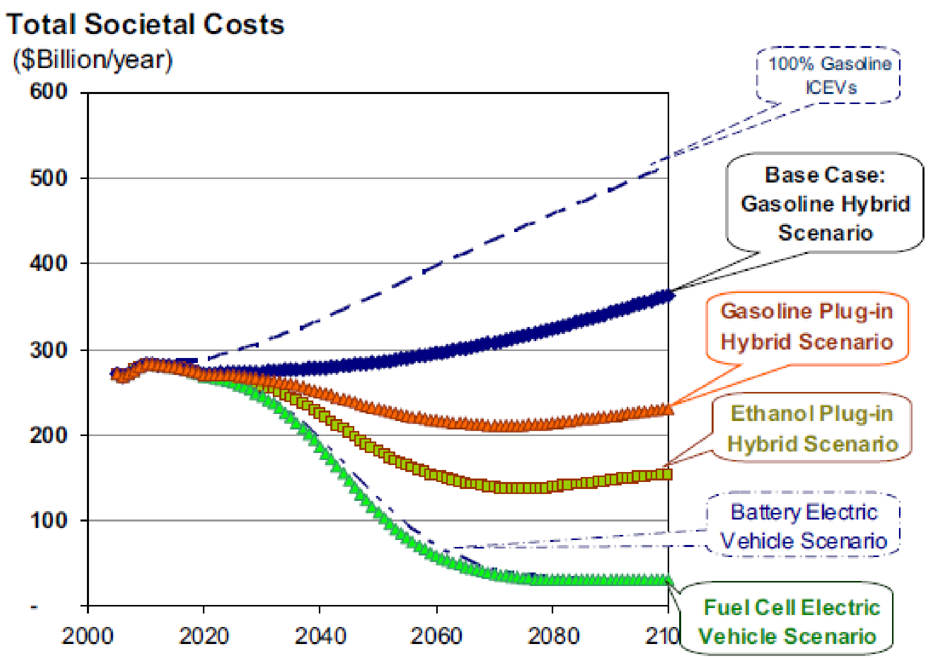

Figure 6. Estimate of the total societal costs of greenhouse gas pollution, urban air pollution, and the economic and military costs of imported oil for the major alternative vehicle scenarios.

According to a life cycle assessment comparison between FCVs and gasoline vehicles, PEM FC efficiency was found to have to be 25-30% higher than a gasoline power source, when using hydrogen produced from steam methane reforming, 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 H_2 and natural gas. When this ratio was 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 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 has been the idea of a fuel cell plug-in hybrid vehicle (FCHEV). This essentially combines the fuel cell electric vehicle (FCEV) with the battery electric vehicle (BEV). All three platforms utilize an electric drive train, and these three seem to be the contenders for the vehicle fleet after about 2030. Using this 2030 scenario, one study found that powertrain lifecycle costs for an FCEV range from $7360-$22,580, for a BEV range from $6460-$11,420, and for a FCHEV range from $4310-$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 drive trains, and recycling of platinum and lithium should be of key concern. Most importantly, 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 more utilized than Class 5 or Class 6 resources because of their proximity to population centers and consequent lower transmission costs. Producing hydrogen via electrolysis, and assuming an electricity price of 4-8 cents/kWh, the hydrogen cost would be $2.75 to $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), trucking it to distribution centers, and using it to fuel an ICE [13].

Out in California, some researchers are taking a marketing approach to the fuel cell vehicle. This mentality was premised on the idea that new consumer values must drive H_2 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 need to be emphasized in their marketing. One of the great opportunities for FCVs comes from their ability to produce clean electrical power for something 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 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 PEM fuel cell auxiliary power units (APUs) onboard long-haul trucks. These trucks are idling overnight, but still demand auxiliary power, and the US has recently passed anti-idling regulation to limit pollution caused when idle. As a result, there is a window of opportunity for PEM FCs. If these fuel cells can meet European Commission Development 2015 targets in terms of efficiency (35%), specific cost (<500 €/kW), and durability (40,000 hours), 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 PEM FC APUs by 2020. While the long-term prospects of this technology are uncertain, the short- and medium-term prospects of demand make this technology rather interesting [22].

A different study of the PEM FC APU market found similar opportunities to advance the hydrogen economy through such niche applications. Regardless of whether the first APUs used 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 FC APU markets in the near future. It has been found that an incentive of $1500 would create an amortization timeline of only two years, "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, it will require generous amounts of research and development 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 auto makers as shown below in Figure 7 [89].

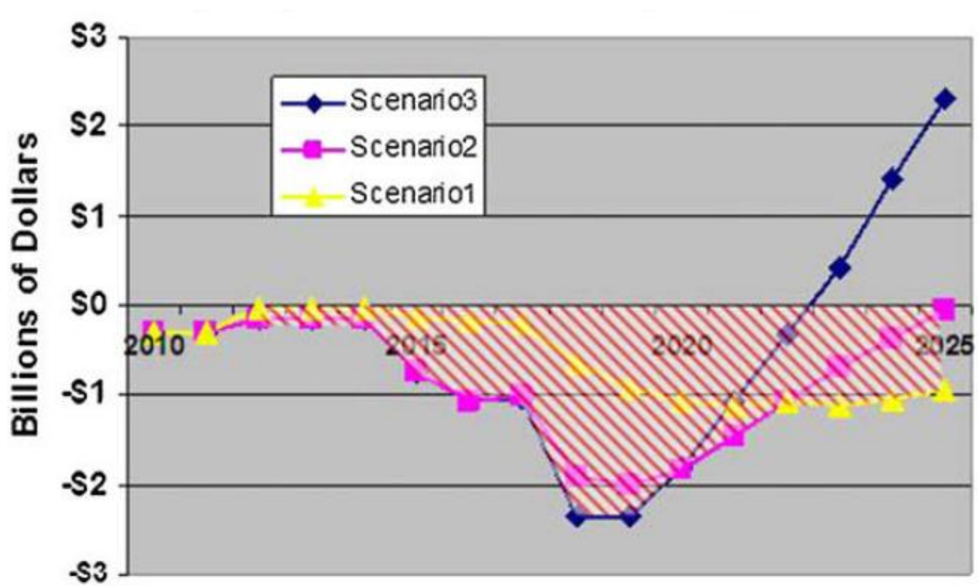

Figure 7. Simulated auto industry cash flow from sale of hydrogen fuel cell vehicles. Policy case assumes 50/50 incremental cost share government/industry, US$15 billion investment.

Accordingly, manufacturer's view the transition to FCVs following, approximately, a 55-year timeline: design a market-competitive vehicle (~15 yrs.), penetration up to 35% of new vehicle production (~25 yrs.), and penetration up to 35% of fleet-miles driven (~20 yrs). **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, PEM FCs using direct-hydrogen (DH) were compared to those using onboard methanol reforming. DH-PEM FCs 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 better 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-PEM FCs are recommended over onboard methanol reforming on a performance and efficiency basis [3].

Another paper performed a comparison study of DH FCVs between 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 (eg. 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 these components loss characteristics will change 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 160km (100 miles), and FCVs outperform them after that range [11], [12].

The debate between FCVs and BEVs has fierce 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]:

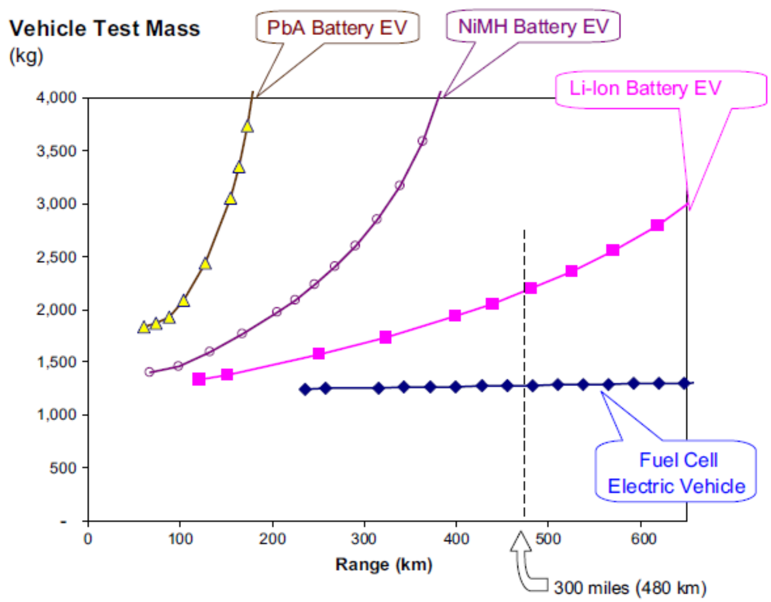

Figure 8. Calculated mass of fuel cell electric vehicles and battery electric vehicles as a function of the vehicle range: the power trains of all vehicles are adjusted to provide a 10s 0-60mph acceleration time.

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

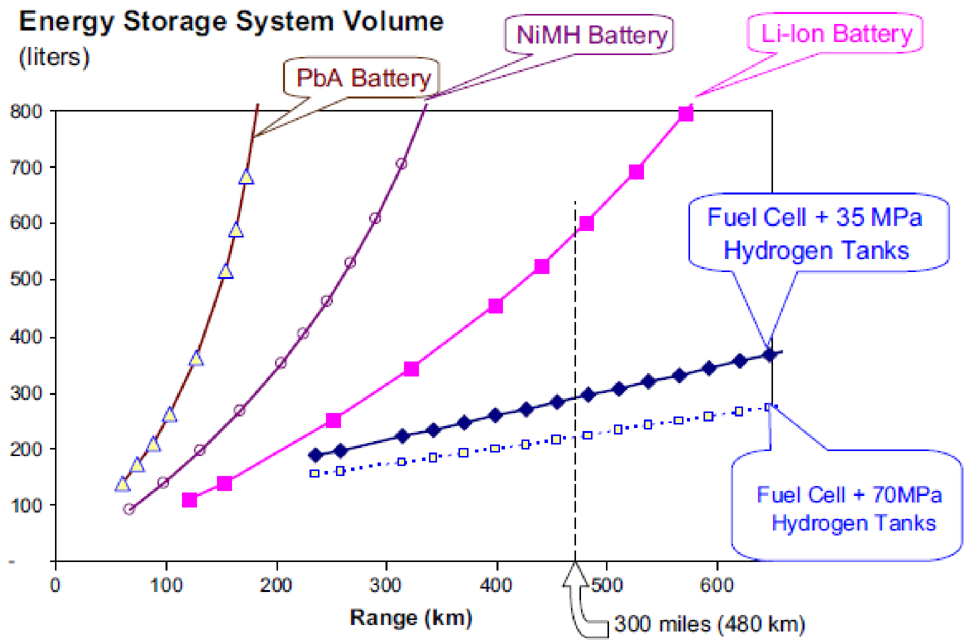

Figure 9. Calculated volume of hydrogen storage plus the fuel cell system compared to the space required for batteries as a function of vehicle range.

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 8 [12].

Table 9. Estimated minimum fueling time for battery EVs and fuel cell EVs.

		Battery Electric Vehicles				Fuel cell EVs
Vehicle Range (km)	Energy required from grid (kWh)	Level I charging time (hours)	Level II charging time (hours)	Level III charging time (hours)		Hydrogen tank filling time (hours)
		120V, 20A	240V, 40A	480V, 3Φ		
		1.9kW	7.7kW	60kW	150kW	
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

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.

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

Technology	Cost (Year 2000 $s)	Notes	Year	Reference
Incremental Costs over ICE				
HEV Cavalier **HEV Taurus** **HEV Silverado** **HEV Caravan** **HEV Explorer**	$4,251 $4,382 $6,694 $4,827 $5,719	Incremental costs over ICE in year 2000 dollars All models considered here include a moderate package of improvements and full hybridization, different HEV packages create different incremental costs ranging from $2,543 (Cavalier) to $6,694 (Silverado)	2003	[91]
HEV **PHEV 32km**	$3,951 $5,825	Incremental costs over ICE; this study includes multiple cost estimates, this one from EPRI study performed in 2001	2001	[92]
HEV **PHEV 32km**	$2,001 $3,337	Incremental costs over ICE, alternative EPRI study	2007	
HEV **PHEV 16km** **PHEV 48km**	$2,007 $2,926 $3,595	Incremental costs over ICE Kromer and Heywood estimates	2007	
HEV **PHEV 10km** **PHEV 30km** **PHEV 60km** **FCV** **BEV**	$1,589 $2,508 $3,595 $5,100 $3,010 $8,528	Incremental costs compared to year 2030 NA-SI ICE (naturally aspirated spark ignition internal combustion engine)	2007	[93]
FCV	$3,010 - $4,264	Projected incremental cost for mass-produced FCV over 2030 ICE	2007	[94]
BEV 100 mi: **Compact car** **Midsize car** **Full size car** **Small SUV** **Midsize SUV** **Large SUV** **BEV 200 mi.**	 $5,251 $5,471 $5,572 $7,662 $7,303 $7,911 $8,528	Incremental cost over 2007 ICE vehicles for 100-mile range BEVS The last estimate is the incremental cost over a 2030 SI ICE vehicle, with an optimistic cost as low as $6,900	2007	[95]
HEV **PHEV 20 mi.** **PHEV 60 mi.**	$4,611 $1,551 $3,445 $3,951 $13,319 $6,204 $5,825 $22,958 $4,980 $10,262	Incremental costs over ICEs in the near term	2009	[96]
HEV **PHEV 20 mi.** **PHEV 60 mi.**	$1,461 - $3,895 $3,895 - $5,842 $7,205 - $9,737	Incremental costs over ICEs in the mid-term	2009	
HEV **PHEV 20 mi.** **PHEV 60 mi.**	$2,799 $7,229 $11,387	Incremental costs over ICEs in the long term	2009	

FCV 200 mi. **BEV 200 mi.**	$2,253 $8,121	Incremental cost over ICE for FCVs and BEVs with 200 mile and 300 mile range	2009	[12]
FCV 300 mi. **BEV 400 mi.**	$1,781 $9,649			
Fuel cell stack costs				
FCV	$1,187/kW	Fuel cell stack materials cost	2002	[97]
FCV 2000 **FCV 2010** **FCV 2020**	$1,693/kW $154/kW $35/kW	Fuel cell stack cost under a moderate with medium power density scenario, assuming production increases to 50,000 by 2010 and 5,000,000 by 2020	2004	[98]
ICE **FCV**	$54/kW $220/kW	Cost estimate of fuel cell stack and ICE equivalent by 2016	2006	[99]
FCV 5kW **FCV 50kW** **FCV 80kW** **FCV 200kW** **FCV 250kW**	$4,538/kW $1,351/kW $1,182/kW $983/kW $951/kW	PEMFC manufacturing costs for a production scale of 500 units/year	2007	[100]
FCV – 40 **FCV – 1 million**	$1,061/kW $12/kW	Fuel cell stack cost assuming platinum price set to 1990s levels ($15,000/kg) under different scenarios of total number of produced vehicles	2009	[101]
Drivetrain Costs				
Gas ICEV **Gas HEV** **H_2 HEV** **H_2 FCV**	$2,239 $2,844 $3,924 $4,368	Estimated mass production (300,000 vehicles per year) costs for vehicle drive trains	2003	[102]
FCV **BEV**	$28,517 $20,078	Estimated mass-production costs of technology-specific propulsion systems	2004	[103]
SI ICE **H_2 FCV**	$2,299 $4,291	Estimated drive train manufacturing costs for 27mpg SI ICE and 82mpgg$_{eq}$ H_2 FCV	2004	[104]
BEV 2010 **FCV 2010**	$52,826 $121,059	Net costs of middle class vehicles for various years	2009	[105]
BEV 2030 **FCV 2030**	$28,614 $33,016			
BEV 2050 **FCV 2050**	$25,312 $23,111			
2010: **ICE** **FCV** **BEV** **FCHEV**	 $1,752 $37,739 $21,258 $15,685	IEA drivetrain costs for 2010 vehicles	2010	[23]
2030 optimistic: **ICE** **FCV** **BEV** **FCHEV**	 $1,911 $5,573 $4,936 $3,185	IEA optimistic drivetrain costs for 2030 vehicles		
2030 pessimistic: **ICE** **FCV** **BEV** **FCHEV**	 $2,014 $11,194 $7,588 $5,836	IEA pessimistic drivetrain costs for 2030 vehicles		
Total Vehicle Costs				
ICE **BEV** **FCV**	$13,784 $37,838 $90,090	Sale price of different vehicle technologies	2006	[15]
ICE **FCV**	$19,084 $24,824	Vehicle costs assuming a fuel cell stack price of $50/kW	2006	[106]
H2 70MPa **Lead acid** **Ni-MH**	$3,085 $12,854 $25,707	Energy storage system costs for FCVs and BEVs	2007	[107]

Li-ion	$34,276			
FCV **BEV**	1.2 2.0	Vehicle cost ratio estimate of FCVs and BEVs compared to standard ICEs in 2030	2007	[108]
FCV 2020 **FCV 2030**	$27,682 $25,467	Vehicle production cost assuming total vehicle stock reaches 550,000 by 2020 and 4,800,000 by 2030	2008	[109]

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 180km [12].

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

Vehicle range	**Natural gas required (MBTU x 100)**		**Biomass energy required (MBTU x 100)**
km	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

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 primary energy comes largely from renewable wind power [12].

An overall comparison of 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].

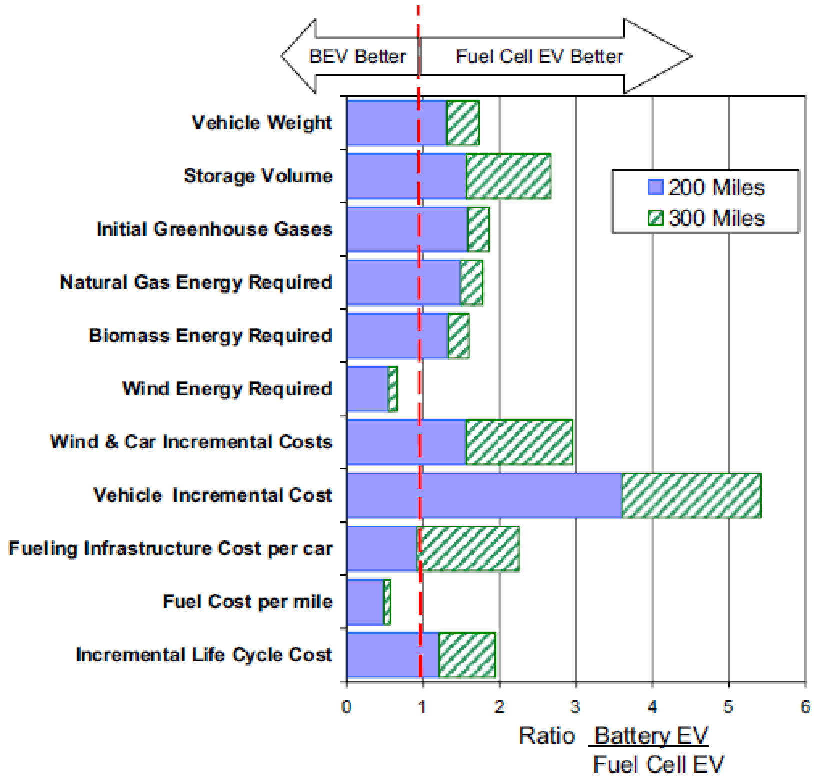

Figure 13. Ratio of advanced BEV attribute divided by the FCEV attribute for 200- and 300-mile range, assuming average US grid mix in the 2010-2020 time period and all hydrogen made from natural gas.

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 contain onboard reforming of liquid fuels such as methanol have far worse efficiencies than compressed hydrogen. If we could change the perception of what a vehicle should be, that could open up an urban market for BEVs, but that is a big *if*. 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 climate friendly light duty vehicles. For the time being, however, they have many obstacles to overcome. First and foremost, the working properties of fuel cells 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 doubling the weight and size to double the 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 cells 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. PEMFCs appear as the most likely candidate due to their high efficiency, high performance in a wide working zone, good 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 modern vehicles in operating characteristics, and considering 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 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 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 that stimulates demand that does not currently exist. It will be interesting to see if this strategy helps the transition, but you can be assured that the transition will not be making serious headway for at least ten years while FC technology develops.

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 more and more 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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