

The Green Vehicle Trend: Electric, Plug-in hybrid or Hydrogen fuel cell?

Fangzhu Zhang & Philip Cooke, Centre for Advanced Studies, Cardiff University, UK, email: zhangf4@cardiff.ac.uk.

1. Introduction

Energy supply security and global warming continue to challenge all countries around the world in terms of global economy and planet environment. Renewable energy technologies are being explored to meet the challenges of energy security and climate change, as well as to boost regional economic development (Zhang & Cooke, 2008). In this review, we will focus on ‘green innovation’ in transport. The transport sector represents a critical percentage of greenhouse gas emission. Transport emissions are estimated to increase by 84% to 2030 (Tomlinson, 2009). Key technologies such as hydrogen fuel cells, electric cars and biofuels are expected to contribute to emission reduction in the long run. Biofuels have been increasingly explored as a possible alternative source to gasoline with respect mainly to transport. The perspectives on biofuels are reviewed in our previous review (Zhang & Cooke, 2009). Recently, hydrogen, electric and hybrid cars have been developed and demonstrated in global automotive exhibitions. Key interests have been attracted to discuss future trends in green vehicles. Major car manufacturers seek leadership in future green vehicle markets. ‘Green vehicles’, as will be shown, directly use renewable energy sources. The current development of green vehicles by major car markers is listed in Table 1. These models are mainly at demonstration stage. In this report, the current technology status and potential development of green vehicles are reviewed and the development barriers of the technology application are discussed in order to get better understanding of the move towards cleaner energy systems.

Table 1. List of green vehicles to be released during 2009-2012.
(Source: Madslie, 2009; Plug-in America.org)

Year	Battery Electric Vehicle	Hybrid Electric Vehicle	Plug-in Hybrid Vehicle	Fuel Cell Electric Vehicle
2009	Sabaru 4 seat	Mercedes S400 HEV	Fisker Karma S PHV	Honda FCX Clarity
	Chrysler EV			GM HydroGen3 FCEV
	Smart for Two EV			Chevy Equinox Fuel Cell
	ZENN city ZENN BEV			Ford Fuel Cell EV
2010	Chevy Volt Extended Range BEV	Ford Fusion HEV	Saturn VUE PHV	
	Chrysler EV	Honda Insight HEV	Toyota PHV	
	Miles EV	Hyundai-Kia HEV		
	Mitsubishi iMiEV BEV	Lexus HS 250h HEV		
	Nissan BEV	Mercedes E Class HEV		
	Ford Battery Electric Van	Porsche Cayenne S HEV		
	Tesla Roadster Sport EV	Prius HEV		
2011	BYD e6 Ford BEV Small Car		BYD F3DM PHV	
	Opel Ampera Extended Range BEV (Europe)		Chevy Volt PHV	
2012	Th!nk Ox		Ford PHV	
			Volvo PHV	

Electricity has been explored as an alternative power source to replace or complement the internal combustion engine for decades. There are three types of electrically powered vehicle, including pure-electrics (such as the *Tesla*); hybrids (the *Prius*) and plug-in hybrids (the *Karma*) (Hickman, 2009). Pure-electrics use batteries to power the motor engine instead of petrol. It is significant because it reduces CO₂ emissions; however, the distance range and lifetime are limited for batteries in pure-electrics. Pure electric cars that rely only on a battery usually have a range of only 30-50 miles. Hybrid vehicles are designed to use both an electric motor and an internal combustion engine. The battery required in hybrids is smaller than all-electrics and also allows the vehicle to travel longer distances than pure-electrics on one battery charge. Hybrids with plug-in capability use a combination of grid electricity, regenerative energy from braking, and power from another onboard source, such as an internal combustion engine or fuel cell. The engines can be configured to operate serially and applied to a variety of vehicles. The ideal scenario to use plug-in hybrids is to charge electric vehicles at night or during off-peak grid use, with power derived from renewable energies such as wind, solar and biomass. High battery performance is the key technology for the application of plug-in hybrids. The Obama administration's Stimulus Bill granted \$14.4 billion for plug-in hybrids. Meanwhile, substantial government grants throughout the world have supported technology development and business market niche through subsidizing the use of electric cars. Electric cars are estimated to have 35% of the car market by 2025, with 10% pure electric cars and 25% of hybrid cars (Harrop & Das, 2009).

Hydrogen can be used as on-board fuel for motive power either through the internal combustion engine or fuel cell to produce electricity which can be used to power an electric traction motor. Hydrogen is considered as CO₂-free energy if produced from renewable and nuclear energy. Fuel cells powered by hydrogen can increase efficiency of energy use. But with the current technologies and processes for hydrogen production, storage, transportation and distribution, and fuel cell technologies, the hydrogen fuel cell vehicle is still too expensive. In terms of emissions, if hydrogen is from renewable energy resources, the hydrogen fuel cell vehicle produces zero CO₂ emission, while plug-in hybrids are still not fully "green" as it is a hybrid model; only partially reducing emissions. In recent decades, much R&D resource has been committed to hydrogen and fuel cell technologies. They have attracted significant interest from government policy makers and private investors. Over 400 demonstration projects are in process in the world and are expected to have commercial application in the next five to ten years (OECD, 2005). However, most hydrogen and fuel cell technologies are considered unproven by government and industry experts. The main challenge is to reduce technology cost. Also required is for governments to give priority to policies that commit to CO₂ emission reduction. Such CO₂ emission saving policy is anticipated to have an impact for the new emerging 'green' economy. The transition from a traditional hydrocarbon economy to a hydrogen economy depends not only on advanced hydrogen and fuel cell technologies, but also on development of other alternative technologies such as biofuel, batteries and plug-in hybrid vehicles. Currently, plug-in hybrid is considered a superior solution to emission reduction under contemporary financial constraints. Hydrogen fuel cells are widely seen as superior in the longer term provided cost can be reduced to an affordable level. Currently, in-service hydrogen fuelled buses exist (e.g. in Orlando and Vancouver) whereas cars remain in prototype.

2. Electric Vehicles

It took over sixty years and six generations of gasoline engines for the Chevy Corvette to develop an electric car that can accelerate the speed to sixty mph within four seconds (Becker, 2009). It has been a long journey to develop electrical car engines from idea to market. The earlier generations of electric vehicles failed to achieve significant market share due to poor performance, high cost and short ranges. With the improvement of battery technology over the past two decades and automotive technology advances, the new generation of affordable, high-performance electric car may be about to enter the global market. More vehicle manufacturers have joined in the race to produce a winning green vehicle, shifting toward to electric car models. If there is significant improvement in battery technology this will help the accelerated to introduction of electric cars into commercial markets.

2.1 All-electric car

An all-electric vehicle only uses batteries to power the motor engine instead of petrol. They produce no tailpipe emissions. All-electric cars rely only on batteries, which are recharged from the grid or by regenerative braking (utilising brake energy as fuel). Modern lithium-ion batteries are much more efficient than old battery technology. Many carmakers have applied this better battery technology in their electric powered cars. *Tesla*, a high performance pure electric roadster vehicle, is the world's first Lithium-ion battery powered car. The version of *Tesla* was first unveiled to public in 2006. Over 700 *Tesla* cars had been delivered to customers in the USA and Europe by September 2009, expected to reach 1000 for the year 2009 at a base price of \$109,000. The company started to make 5% net profit in July, 2009 (Palmeri & Carey, 2009). This car can travel about 244 miles on its lithium-cobalt battery pack, and is able to accelerate to 60 mph in 4 seconds, hence a high performance among current electric vehicles (Figure 2). The high level of redundancy and multiple layers of battery protection in the *Tesla* roadster proved safe to be used in cars. The battery pack of the *Tesla* weighs 900 pounds and has a cooling system to keep the Li-ion cells at their optimum temperature. It has recently received US government loan guarantees and collaborates with the German auto manufacturer Daimler to mass produce a pure-electric Sedan by 2011. The Sedan model (\$49,000) is less expensive than the *Tesla* roadster (\$109,000), but still relatively speedy (Palmeri & Carey, 2009).

Meanwhile, a new electric car manufacturer, Coda Automotive, announced release of a full-performance, all-electric Coda *Sedan* to the California market in 2010. The vehicle features a 33.8KWh, 333 V lithium iron battery pack with an 8-year, 100,000-mile warranty. The batteries are being supplied by Tianjin Lishen Battery (China), one of the world's largest manufacturers of lithium-ion cells. The new *Sedan* takes about six hours to charge, and delivers a range of between 90 to 120 miles, with a top speed of 80 mph. About 2,700 vehicles will enter the market in 2010, with production capacity set to reach 20,000 in 2011. The price of sedan is expected around \$45,000 before the \$7,500 federal tax incentive and any additional state incentives (Green Chip Stocks, 2009).

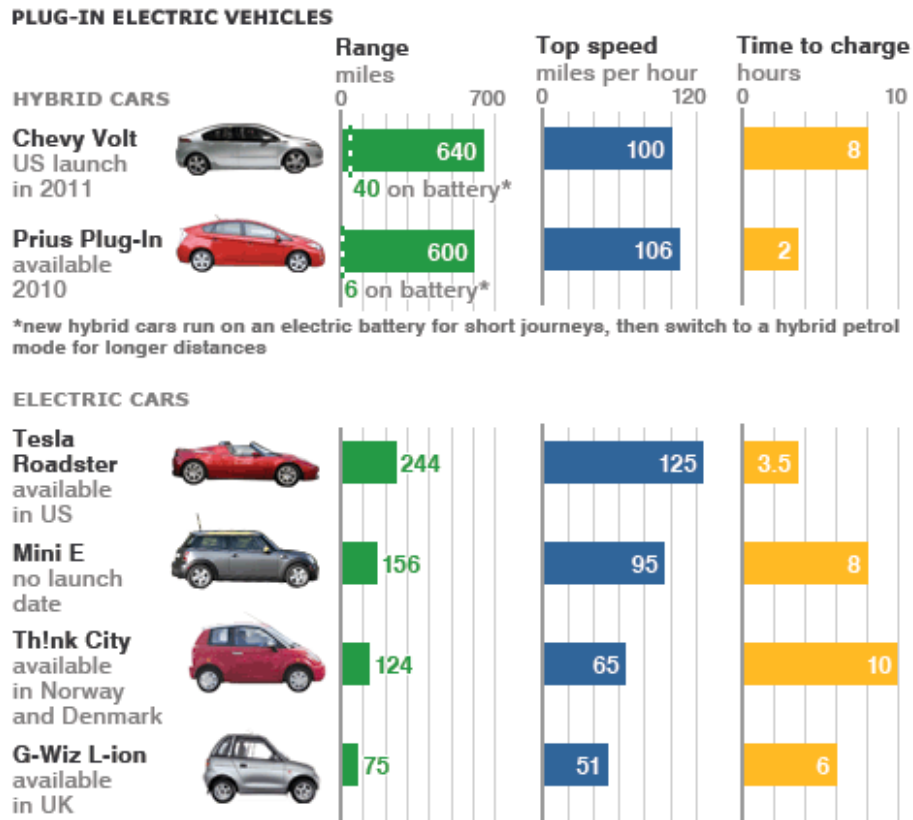


Figure 2. The performances of new electric vehicles (Source: Madslie, 2009)

Electric cars are becoming a more common sight in European, where we can see hundreds of the two-seater G-Wiz in the streets of London. G-Wiz electric cars are considered as an “electronic quadricycle” and use is encouraged with exemption of parking fees and London city’s congestion charge. In April, London Mayor Boris Johnson launched a plan to get 100,000 electric cars onto the streets of London by 2015 and create 25,000 charging stations (Moulson & Moore, 2009). REVA is an Indian version of G-Wiz (in the UK market), produced by the Reva Electric Car Co. (RECC) for city car use. The company, based in Bangalore, India, is currently the world’s leading electric car manufacturing company (www.revaindia.com). It is a joint venture between the Maini Group India and California AEV. In 2006, it received \$20 million from the Global Environment Fund and venture capitalist Draper Fisher Jurvetson. It has sold around 1,800 vehicles to date, half outside India, expanding manufacturing from 6,000 to 30,000 vehicles per year (Wikipedia, 2009). It is gaining traction in European cities, where new emission and congestion fees are planned.

The *Th!nk City* is another fun, safe and urban electric vehicle with a top speed of 100 km/h and a range of 120 miles. It is one of the only two crash tested and highway certified cars in the world (Tesla Roadster is the other one) (Wikipedia, 2009). The developer company, Think Global, was originally founded as Pivco in 1991 in Oslo. The first practical prototype, PIV2, was built around a chassis made of aluminium and carrying a body made of polyethylene thermoplastic. The battery technology was Ni-cd. The development of the production model was stopped in 1999 due to financial constraints, as development took more time and resources than expected. Ford

acquired the company in 1999 to start the production of the *Th!nk City*, but sold the company to KamKopr Microelectronics of Switzerland in 2003. The development of the *Th!nk City* was halted again. Due to government policy to promote use of electric cars in Norway, used *Th!nk City* cars from US and UK have been re-exported to Norway to meet the high demand of electric cars. Electric vehicles are exempt from taxes, have free parking and free pass toll and even are allowed to use the bus lanes to avoid traffic congestion in Norway. In 2006, Norwegian investment group, InSpire, including the original founder Jan Otto Ringdal as partner, acquired the company and renamed it *Th!nk Global*. With partnership with General Electric and battery manufacturer A123 Systems, a new vehicle, the five-seat, 130 km/h *Th!nk Ox* model was unveiled in 2008. Finish Valmet Automotive is investing €3 million to start the production of *Th!nk* electric cars in 2009 (Forbes.com). *Th!nk City* is available across Europe, especially in Norway, Denmark, Sweden, UK, Germany, Spain, Italy, and Netherlands markets.

In Japan, Toyota plans to launch a pure electric car for city commuting by 2012. This electric car is expected to deliver 50 miles on one charge; enough meet the requirement of most urban commuters' daily commutes. Recently, Renault-Nissan has announced that its first electric car, *Leaf*, will be ready for the market by 2012. The *Leaf* has a 100-mile cruising range and a top speed of 90 miles an hour. It has two switchable batteries: a 90-kilowatt battery pack and an 80-kilowatt electric motor.

In early, 2009 at the North American International Auto Show (NAIAS), an all-electric car, *E6*, with a driving range of 250 miles drew great attention from the media and investors. This electric car was developed by Chinese automaker BYD Co., based at Shenzhen, China. The company has developed its own iron-phosphate-based lithium-ion battery after investing in R&D over 10 years. The core battery technology can be applied in all three types of electric vehicles. The battery has a lifetime of over 10 years and can be charge to 50% of its capability in 10 minutes. The entrepreneur, Mr. Wang, with background of metallurgical physics and chemistry, set up BYD in 1999. The company started with supplying batteries to companies such as Nokia and Motorola with success, and then was listed on the Hong Kong Stock Exchange in 2002. The acquisition of Qinchuan Motors in Xian in 2003 gave the opportunity for the company move from parts and battery supplier to car marker, as shown in Figure 3 (Shirouzu, 2009). In 2008, BYD purchased the SinoMOS Semiconductor in Ningbo to facilitate first-tier suppliers and their input chains to accelerate the development of electric vehicles. It has successfully attracted \$230 million from global billionaire investor, Warren Buffett through MidAmerican Energy Holding Co. investment for 10% stake. This investment strategically helped BYD extend its markets of electric-hybrid vehicles from China to global. The share price of BYD has increased up to six fold during 2008-2009, despite the global financial crisis, BYD plans to sell about 9 million electric vehicles by 2025 to surpass GM and Toyota and other global automakers in electric vehicle technology (www.byd.com). BYD's green vehicle is suggestive of China's ability and vision to promote alternative-fuel platforms to reduce the nation's growing dependence on imported oil.

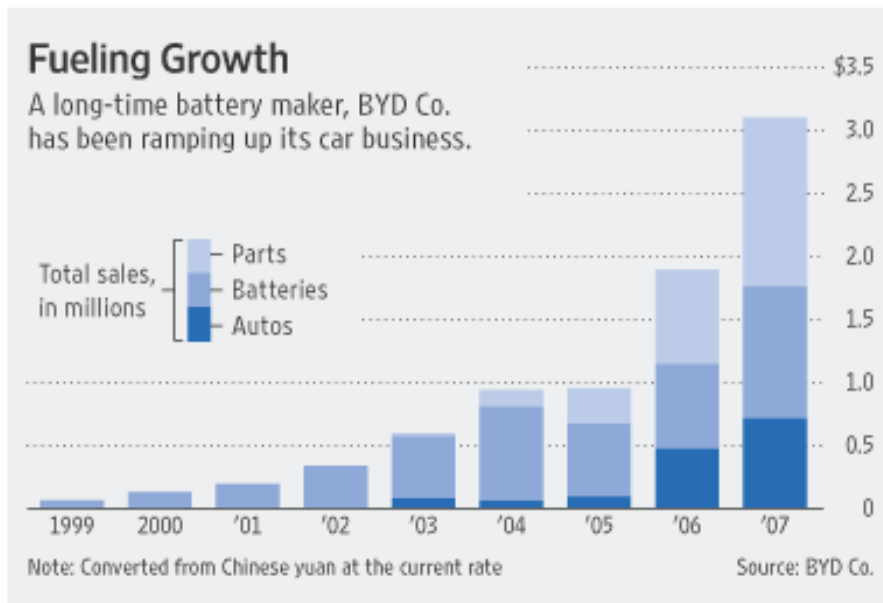


Figure 3. Business transition of BYD Co. during 1999-2007. (Source: BYD, Co.; Shirouzu, 2009)

2.2 Hybrid car

The problem all-electric cars have is that their range is limited, no more than a few of hundred miles with the most advanced *Tesla Roadster*. Better batteries can only extend the range and reduce charging times, but the batteries used in electric vehicles have a limited life cycle. A solution to this problem for hybrid vehicles is as follows. The electric power from the generator is directed to either the electric motor or the batteries, depending on the state of charge of the battery and the power demand of the wheels (Harrop & Dos, 2009). Toyota's hybrid car, *Prius*, has become popular due to its high gas mileage. The car is powered by a battery for the first few miles. Once the engine runs out battery, a conventional petrol engine takes over. *Prius* is expected to deliver up to 50 miles per gallon, while Honda's new *Insight* can deliver 40-43 miles per gallon at a cost about \$3000 less than the *Prius*.

General Motors apply an alternative solution, where a small petrol engine recharges the battery whilst driving. A hybrid is designed to capture energy that is usually lost through braking and coasting to recharge the batteries. The regenerative braking in turn powers the electric motor without the need for plugging in. Hydraulic hybrid vehicles (HHV) technology was developed to use in public buses by a Chinese private company, Beijing-based Chargeboard Electric Vehicle Co. The hydraulic devices can absorb and deposit energy in the process of braking and releasing the energy when the vehicles restart or speed up. They can save more than 30 percent of fuel consumption and reduce 20-70 percent of emissions. Thus, they can serve as city buses which have frequent braking and restarting. 50 HHVs were tested as pilot experiment in Beijing in 2006 and to be introduced in other cities in China if successful (People's Daily, 2006).

Hybrid electric vehicles have the potential to use electricity to power the onboard engine via plugging in appliances. They have the potential to achieve greater fuel economy than conventional gasoline-engine vehicles, as most hybrid electric vehicles will use the power from electricity providers rather than from petrol stations

(Madslie, 2009). Hybrid car still use fossil fuel. Doubling the petrol mileage in hybrid vehicles will reduce fuel consumption, but still is not the best solution regarding the energy crisis and environment protection (Ahn & Lim, 2006).

2.3 Plug-in hybrid cars

The plug-in hybrid electric vehicle (PHEV) is a hybrid vehicle with batteries that can be recharged by connecting a plug to an electric power source. Like the hybrid car, it is powered by an on-board engine and a battery/electric motor. It also has a plug to connect to the electric grid. According to Morgan Stanley research (2008), it is suggested that PHEV has the potential to revolutionize the auto industry over the next decade. This is because PHEV could provide a cost-effective, practical solution to improve automotive fuel economy and reduce emissions. The plug-in system gives PHEV an extended 20-40 mile all electric driving range vs. current hybrid vehicle plus the ability to drive long-distance like a regular car. PHEVs combine the best electric and hybrid drive technologies. They have full functions in either electric or hybrid mode. The cost for electricity to power PHEV for all-electric operation is estimated at less than one quarter of the cost of gasoline (Floyd Associates, 2009).

A typical example of the imminent plug-in hybrid is the Chevrolet *Volt*. It will be produced in 2011 by General Motors. With fully charged batteries, this electric car can travel up to 40 miles. A small 4 cylinder ICE takes over to provide a longer range. *Volt* has a potential range up to 640 miles on a single tank of fuel without external charging station required. The battery can be fully charged by plugging the car into a residential electrical outlet (Harrop & Das, 2009). It is announced that Volvo is working with Swedish energy company, Vattenfall to develop plug-in hybrid electric vehicles. Volvo will manufacture the cars and Vattenfall will develop the charging systems. The new diesel hybrid cars will combine a rear-wheel drive electric motor which is powered by a lithium ion battery pack and a front-wheel drive diesel engine. Meanwhile, Magna International, the Canada-based auto supplier also work with Ford to develop a new Ford battery electric vehicle, planned to be released in 2011.

In 2008, Fisker Automotive signed a contract with Valmet Automotive to build the *Karma* in Finland. Fisker Automotive Inc. is a green American premium car company and Valmet Automotive has plenty of experience building high-quality vehicles. Valmet automotive built a new body welding line for Fisker *Karma* production. The painting and assembly process will also be adaptable for the production of electric and hybrid cars. The Fisker *Karma* is a new four-door hybrid sport Sedan. The hybrid model can run up to 50 miles of full electric travel at a maximum speed of 125 mph. It is estimated for release in late 2009, with an annual production projected to reach 15,000 vehicles, at a price of around \$80,000 (Jackson, 2008; Hickman, 2009).

The Chinese electric car manufacturer, BYD, also plans to develop PHEV. The BYD *F3DM* is the world's first mass produced plug-in hybrid compact sedan which went on sale to government agencies and corporations in China in 2008 (Barriaux, 2008). The *F3DM* is the first locally made hybrid vehicle to enter the local market in China. It is planned to go on sale in Europe during 2010 and in the USA during 2011. The vehicle gets around 60 miles on one charge, and is expected to price at around \$22,000 (BYD.com).

2.4 Plug-in charge station

PHEVs can be charged using electrical sockets at home or commercial establishments. The infrastructure needed for successful implementation of PHEV is the development of “charging station” for charging electric cars at home, commercial office car park or station along the road when needed. It is estimated to cost about £2,000 to install the high-voltage charging point (Madslien, 2009). The future of electric vehicle looks brighter than ever before if the electricity power can be supplied from nuclear power station or alternative renewable energy sources, such as solar or wind. Electricity generated at night or off-peak time can be stored and used for electric car overnight charging. The promotion of PHEV will improve the efficiency of electricity power supply. The power would primary come from power plants such as wind or wave generation facilities that are kept operating even though the electricity is not used for more traditional needs. Thus the utilities cost to generate the power to charge electric vehicles at night or off-peak is low.

Currently, electric cars are more expensive than conventional petrol cars. Carmakers are working hard to make electric and plug-in hybrids affordable. Meanwhile, customers show concern about resale value, maintenance cost and available charging stations. Recently, some manufactures have initiated some marketing innovations to match the technology development and promotion of electric vehicles (EVs). Leasing agreements such as a mobile contract business model will offer one solution to promote EVs. A number of companies, including Better Place, Coulomb Technologies and ECotality, plan to deploy charging infrastructure for electric cars in the US. The business model of Better Place is based on switchable batteries financed with a pay-per-mile service contract. This pay-per mile contract will cover the initial purchase price, maintenance and charging infrastructure network. It allows an operator to subsidize the purchase price of an electric car just as cell phone networks subsidize the up-front price of cell phones. This business model is attractive to potential customers, not only to reduce the price of the electric car to the comparable level of gasoline-powered car, but also overcome the uncertainty over the future operating costs of an electric vehicle, such as the infrastructure network and life-time of battery (Becker, 2009).

Better Place has begun installing public charging infrastructure in Israel. The Israeli government aims to end its use of foreign oil by 2020. It is reported that a plug-in charge station will be installed at the headquarters of Teva Pharmaceuticals in Israel (Hopkins, 2009). Teva is US-listed and the world’s top generic drug maker with offices in Mexico, Singapore, Brazil, Kenya and other countries. Other multinational companies and local companies join in together to support the project called “Better Place” to promote electric cars. Teva’s corporate strategy is to spread and adapt its electric vehicle infrastructure strategies around the world through their business. They urge other companies to join in the vision to use electric car, sharing Better Place’s electric grid.

A solar power company, SolarCity, has joined a Dutch bank, Rabobank, to create an “electric highway” of quick-charge stations linking San Francisco and Los Angeles (Squartriglia, 2009). Five charging stations along highway 101 provide EV drivers free and fast recharge service in a public setting. Most of the charging stations draw power from the grid, but the station in Santa Maria gets the power from a 30 Kilowatt

solar array. The EV advocacy group Plug-in-America believed it could spur the adoption of cars in California.

2.5 Battery technology

For automotive use, the key battery issues are size, weight, capacity, safety, efficiency, reliability and longevity. The cleverest and most expensive part of electric vehicles is the battery. Thin films and nanotechnology have been allied in battery development to enhance battery performance. It is clear that car manufacturers of electric vehicles with the advantage of the higher value battery will increase their advantage in electric vehicles.

2.5.1 Lithium Batteries

Lithium ion batteries have much higher energy density ($150\text{-}250\text{ Wh kg}^{-1}$) than conventional batteries such as lead-acid ($25\text{-}50\text{ Wh Kg}^{-1}$), Ni-Cd ($30\text{-}60\text{ Wh Kg}^{-1}$) or Ni-MH (Wh Kg^{-1}) (Scrosati, 2005) (Figure 4). These batteries are light, compact and have an operational voltage averaging on 3.5 V. These super features make lithium ion batteries as a popular power source for portable electronic devices (Hickman, 2009). Beside high energy density, Li-ion batteries have a long cycle life and can be manufactured at any shape or size. Much R &D seeks to apply lithium ion batteries in the automobile industry. The main goals of research are the replacement of materials: (1) graphite with alternative, higher capacity anode materials; (2) lithium cobalt oxide with lower cost and more environmentally benign cathode materials; (3) the organic liquid electrolyte with a more reliable polymer electrolyte. Researchers at Uppsala University have discovered that the distinctive cellulose nanostructure of algae can serve as an effective coating substrate for use in environmentally friendly batteries. These light-weight batteries coated with this material can store up to 600 mA per cm^3 , with only 6% loss through 100 charging cycles (Nyström et al., 2009)

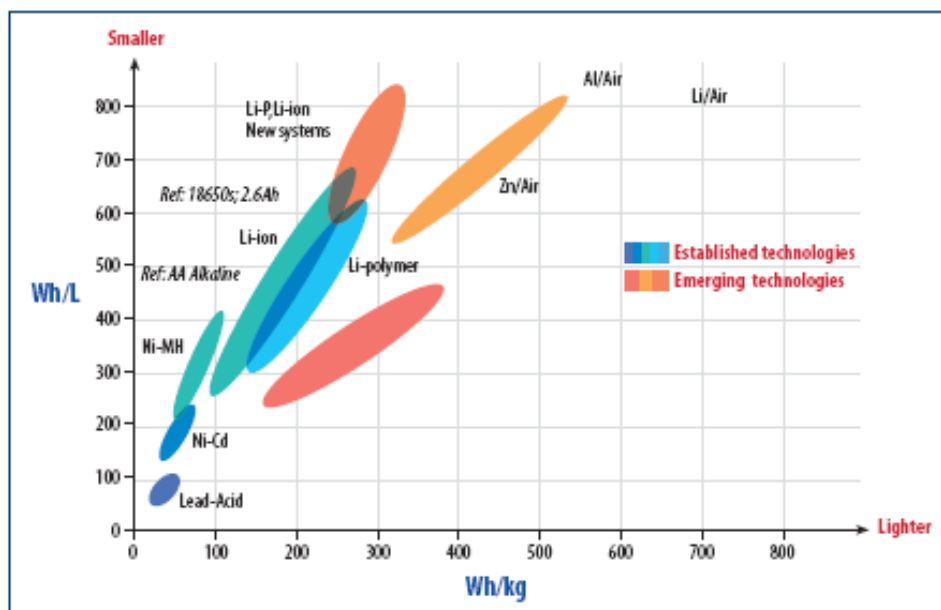


Figure 4. Energy densities of current battery technologies (source: Hickman, 2009)

Lithium electric car batteries which usually last three years, have been developed with up to ten year-lifetime by LG Chem. LG Chem of Korea is fast becoming one of the world's leaders in the production of lithium-ion batteries for automotive use. It supplies hybrid-car batteries to Hyundai Motor Co. and also plans to produce batteries for General Motor's *Volt* extended-range electric car from next year. It plans to invest over \$800 million on electric car battery plant over the next four years. When its first U.S. plant becomes fully operational in 2013, it will have the capacity to build battery cells that could support up to 250,000 electric vehicles in the US.

The global market for automotive Li-ion batteries is growing, reaching to \$30-40 billion by 2020, as forecast by Deutsche Bank (2008). Although the Li-ion battery is currently expensive, the cost is predicted to fall with volume manufacturing. Some companies have gained huge market potential through the collaboration with car makers, including A123, Ener1 Inc., BYD Auto and LG Chem. The battery performance requirements are different depending on vehicle applications. The battery of an all-electric vehicle only depletes during operation, while a typical hybrid electric vehicle maintains the battery state of charge within bounds (charge sustaining). A PHEV battery will experience both discharges as EV and maintain the battery for power-assist in charge sustaining HEV mode, as illustrated in Figure 5.

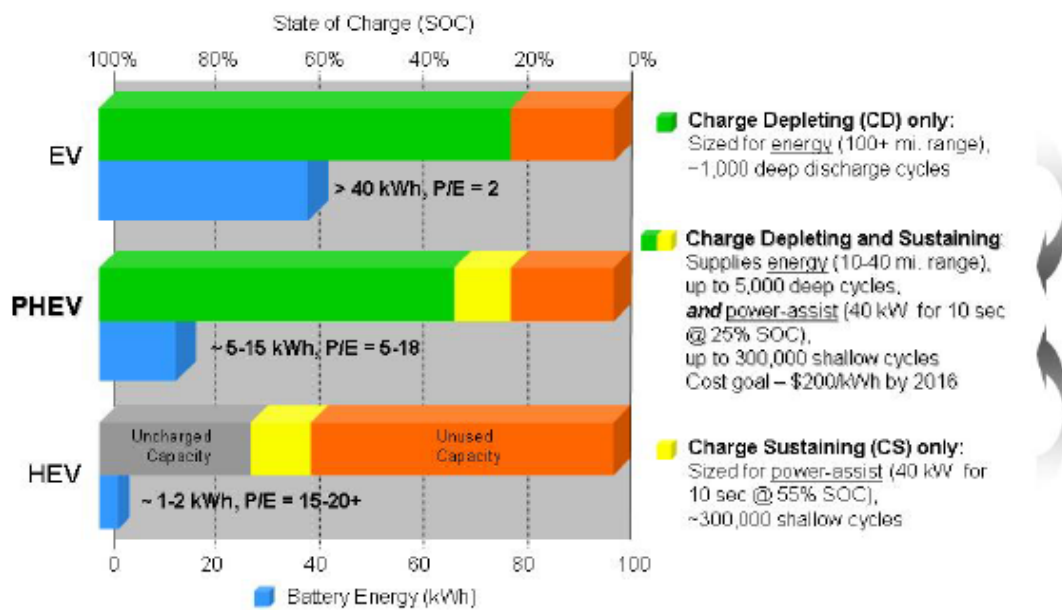


Figure 5. Battery performance requirements versus vehicle application (Source: US Department of Energy (DOE), 2007).

2.5.2 Zinc air battery

Zinc air batteries and zinc-air fuel cells are electro-chemical batteries powered by oxidation of zinc with oxygen from the air. These batteries have high energy density and the materials are very inexpensive. They are used in hearing aids and watches. The zinc-air system, when sealed, has excellent shelf life with a self-discharge rate of only 2 percent per year, but it is sensitive to extreme temperature and humid conditions. To date, only a few companies, such as Leo Motors in Korea, are working with this technology for vehicle application.

Batteries are charged by electrodynamic regenerative braking or by plugging the car into a charging point. Car companies also seek the next generation of power from photovoltaic cells. Traditional silicon photovoltaic cells may not be the best option because they have to be orientated correctly in bright sunlight in order to contribute enough power. Organic photovoltaic cells are now becoming possible for green vehicle application as they can work in poor sunlight and flexibly. Other alternative energy harvesting is going to provide major competitive advantage in the age of “the battery is the car” as the battery costs 35-55% of the ex factory cost of the car (Harrop & Das, 2009).

2.5 Economic development

The clean vehicle research initiative is a public-private effort that aims to produce more fuel-efficient automobiles and introduce hydrogen as a transportation fuel. Three objectives of this clean vehicle research initiative are: (1) use less fossil fuel; (2) produce lower quantities of greenhouse gas and carbon emissions; (3) lower the overall cost of driving (Hickman, 2009). The motivation to explore a new electric car other than the conventional combustion engine is driven by the cost when the price of oil spiked to more than US\$150 per barrel during summer 2008. Though the oil prices have fallen, climate change concerns still persuade manufacturers to continue the search for technologies to use renewable energies.

The penetration and development of green vehicles depends on the regional or national economic growth, fuel resources and government taxation/subsidy policy. Different global regions have different taxation/subsidy policies regarding to the retail oil price. The oil-exporting regions, such as Middle East, often subsidize local fuel consumption heavily, while Western Europe taxes fuel heavily. Countries such as the US have little taxation or subsidy. The increase of oil price has different effects on oil price, as shown in Figure 6 (set \$75 per barrel as moderate case) (McKinsey, 2009).

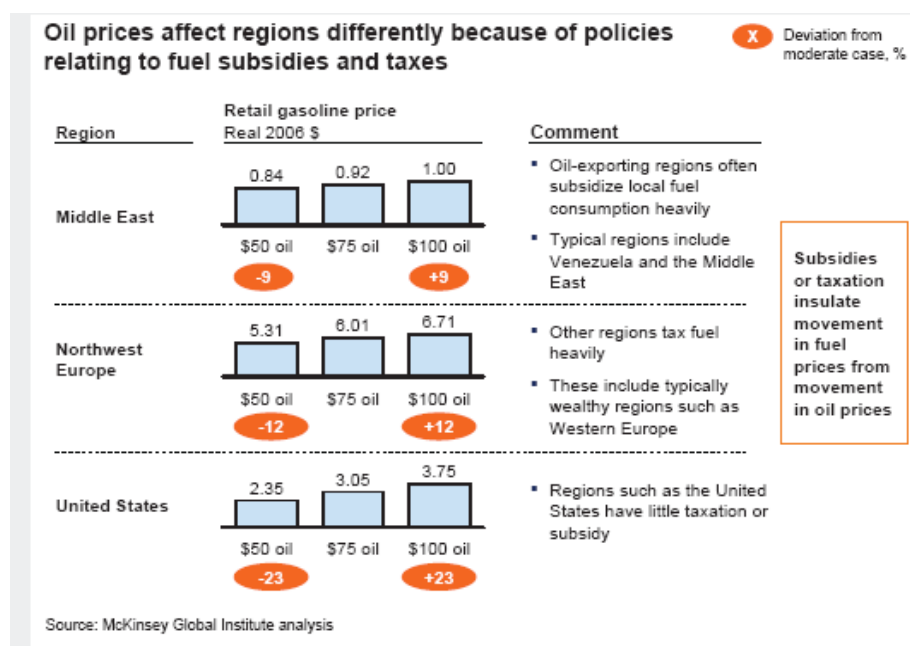


Figure 6. The different effects of oil price on global regions (Source: McKinsey, 2009)

Globally, the vehicle stock is estimated to grow at 3.3% per year between 2006-2020 (Figure 7), with China and India having the fastest growth at 12% and 10.7%, respectively (McKinsey, 2009). From Figure 7, we can see electric vehicle penetrating most heavily in the Europe, where high petrol prices resulting from high taxation make shorter term payback on batter investment for electric vehicles. In contrast, there isn't much increase of the share electric vehicles to total vehicle stock in Middle East by 2020 because of very low subsidised oil price. There is low economic incentive in Middle East for the investment on electric vehicle.

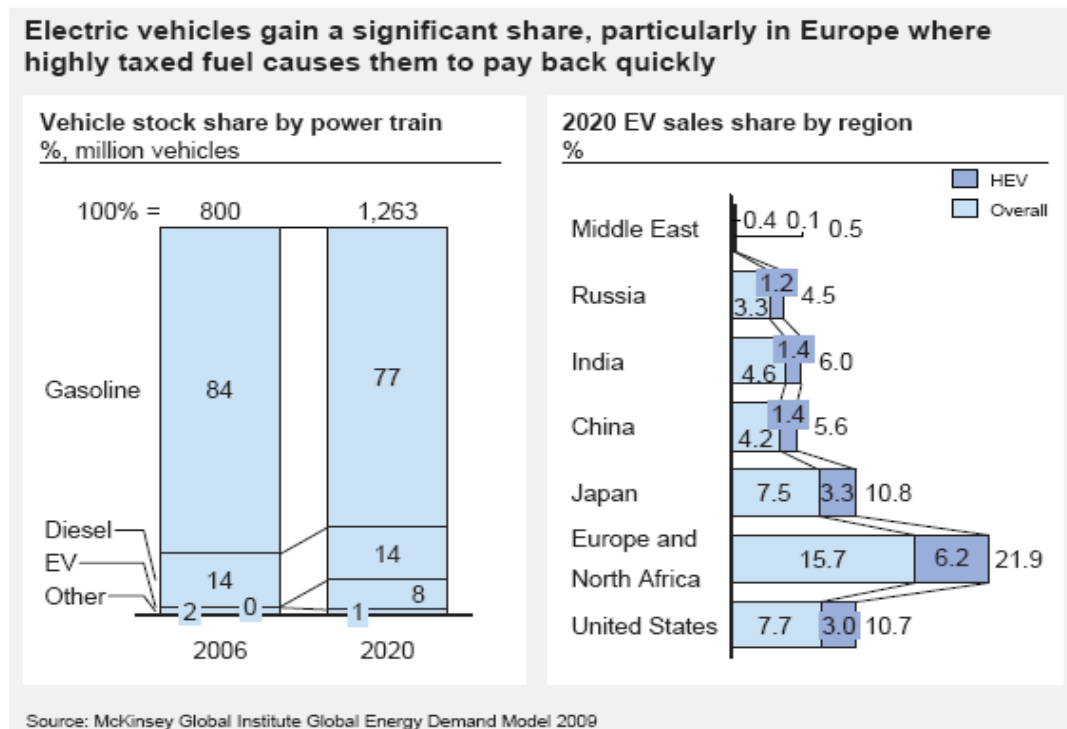


Figure 7. Global and regional electric vehicles share by 2020 (Source: McKinsey, 2009).

The global hybrid vehicle market is expected to surge by 18-20% per year from 2009-2012. Moreover, hybrid and electric vehicles will account for an estimated 10% of all auto sales by 2015 (Green Chip Stocks, 2009). The estimation will vary depending on the petrol price scenarios among different economic estimate models. For example, different projections of electric vehicle and hybrid vehicle market by 2020 are estimated from several studies on US market, as shown in Figure 8. In high-gas-price scenarios: \$100 a barrel, the full sales share of electric vehicles is reached by 2020 in the US (McKinsey, 2009).

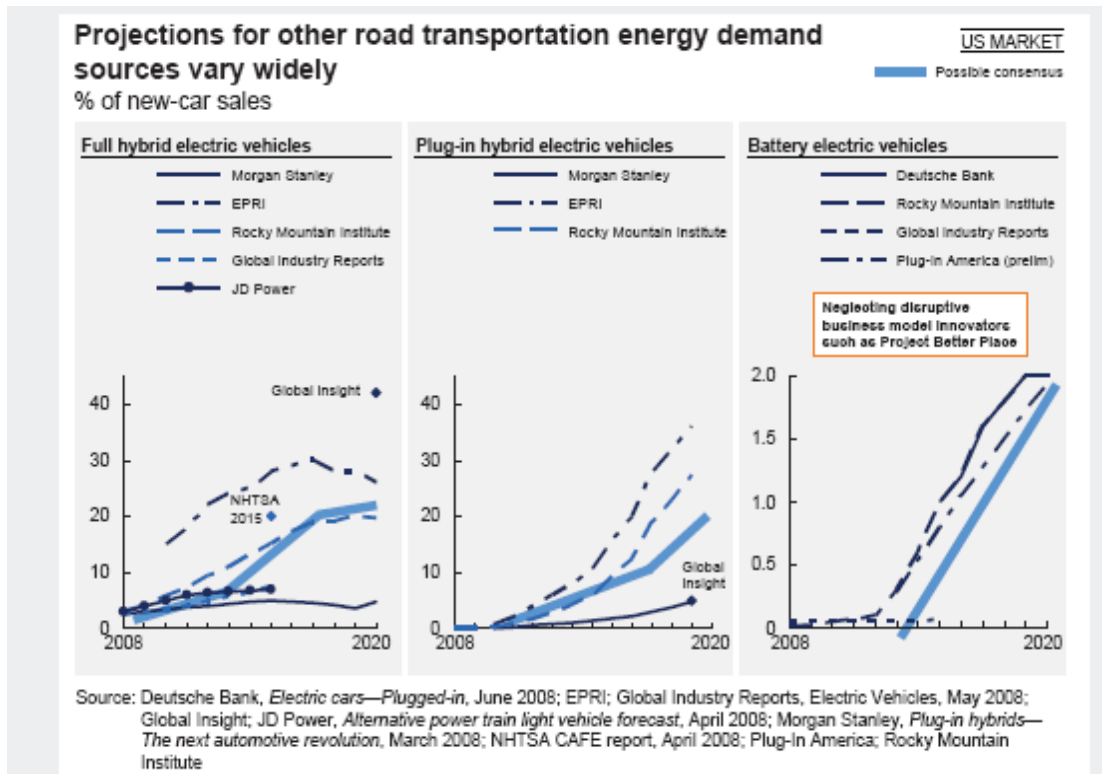


Figure 8. The electric vehicles share projections (Source: McKinsey, 2009)

2.5.1 USA

The global electric vehicle markets are mainly in Europe, the US and Japan. In 2009, The Obama Administration announced the aim to develop 1 million plug-in cars on the road by 2015. Recently, \$14.4 Billion has been allocated for the plug-in program in the stimulus bill, including battery manufacturing (2 billion); Vehicle Tax Credit (2 billion); deployment of plug-in infrastructure and vehicles (\$400 million), public purchase of commercially available high-efficiency vehicles (\$300 million) and etc (Figure 9) (Plug-in America, 2009). The \$6 billion additional to Innovative Technology Loan Guarantee program could go to plug-ins. This program provides loan funding to help automakers retool to make much more fuel efficient vehicles like EVs and PHEVs. The new automobile purchase sales tax credit (1.7 billion) will also apply to plug-ins. The bill provides all taxpayers with a deduction for State and local sales and excise taxes paid on the purchase of new cars, light truck, recreational vehicles, and motorcycles through 2009. The consumer who purchases an automobile with at least a 16 kWh battery will receive \$7500 federal tax credit when EVs are first introduced to market in mass production in 2012. It is limited to 200,000 cars per manufacturer (Plug-In America, 2009). This initial government subsidy will make electric cars less expensive to purchase than comparable gasoline-powered vehicles while allowing manufacturers to achieve economies of scale in the production process (Becker, 2009).

\$14.4B for Plug-ins in the Stimulus Bill

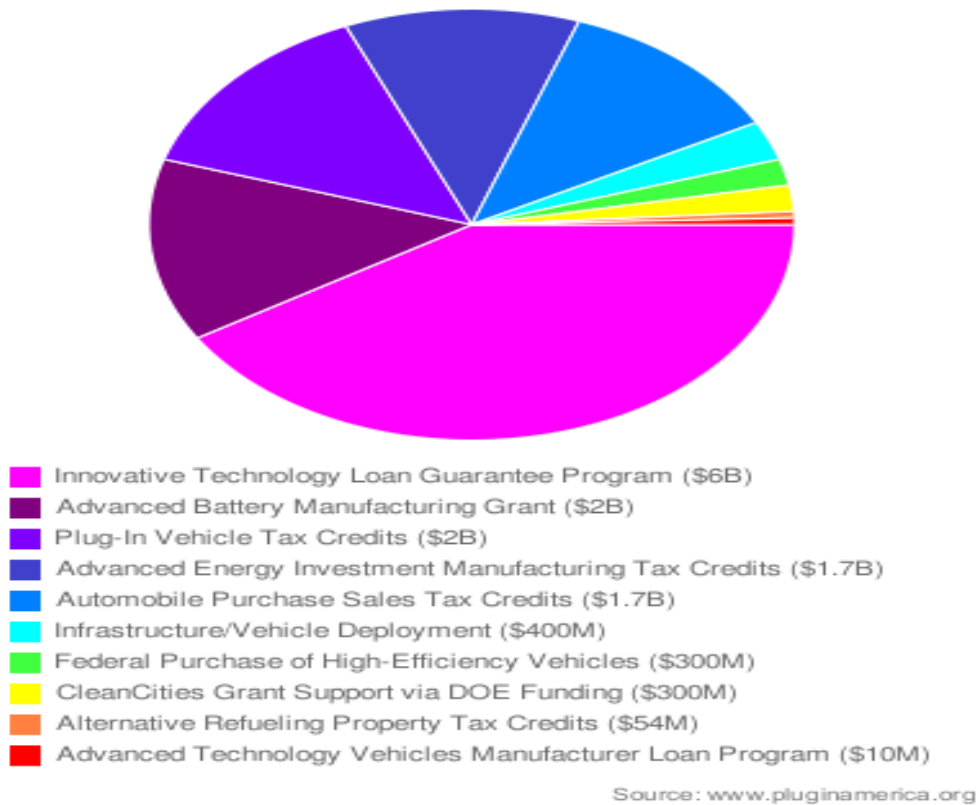


Figure 9. The investment for plug-ins in the US stimulus bill (Source: Plug-in-America, 2009).

The adoption of electric cars will likely occur first in the West coast states in USA. Each state has initiated important legislation to facilitate an early deployment of electric cars. The mayors of the San Francisco Bay Area agreed to ease permit requirements to install charging infrastructure; while Hawaii issued \$45 million to fund charging infrastructure deployment. Washington exempted electric vehicle batteries and installation of charging infrastructure. Due to this government initiative, California, Oregon, Washington and Hawaii are predicted as four states that will likely have the highest number of electric cars in between 2012 and 2014 in Becker's modeling study (2009). After 2014, the network of switchable electric cars is deployed across the USA. The number of electric cars sales in the USA is estimated to reach 2.7 million by 2020, as shown in Figure 10.

Roger Duncan, deputy general manager of Austin Energy, the city-owned utility, has a vision to popularize the next-generation hybrid vehicle. The proposed hybrid car has dual gasoline and electric engines, but different from today's hybrid, such as Toyota's popular *Prius*, which recharges car battery packs only during driving. Plug-in hybrid cars can also be recharged from the electrical grid by plugging into wall sockets. It is estimated to be on market as early as 2010 (Kintisch, 2008). In 2006, Austin created the Plug-In Partners national campaign to support hybrid-car technology development through non-binding pledges to car companies to buy plug-ins once available. This campaign includes 77 cities from California to Washington. There are some technology challenges such as the storage of the larger battery pack in the car, four

times larger than those of *Prius*, recharging capacity, and the change of national power grid network. In Duncan’s vision of Austin, plug-in is a two-way street. During the daytime, commuters would leave cars plugged in and allow the city grid to draw electricity from the cars during afternoon peak demands.

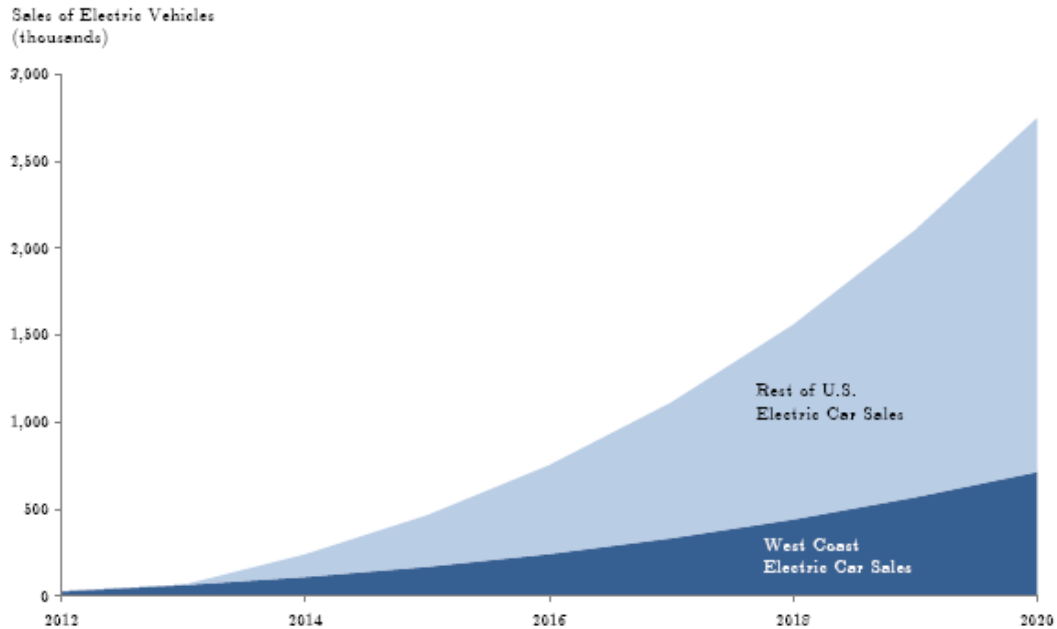


Figure 10. Forecast US electric car sales from 2012 to 2020 (Source: Becker, 2009). *Note: west coast includes four states: California, Oregon, Washington and Hawaii. The deployment of electric car in the west coast is forecast to begin in 2012 and in the rest of the USA in 2014.

2.5.2 Europe

The UK government announced its £250 million green car strategy in April, 2009, aiming to decarbonising road transport in order to help the UK meet its targets of reducing CO₂ emission by 26% by 2020 and 80% by 2050 (Jha, 2009). Consumers are to be offered incentives of up to £5,000 to purchase an electric car. The Joint-Cities Plan, launched by the Energy Technologies Institute (ETI) in Sep. 2009, aimed to build up a national network of charging points across the UK. Nine cities including London, Oxford, Birmingham, Glasgow and Newcastle joined in this £11 million-plan to create the charging points that will enable plug-in hybrid vehicles to be easily used and recharged. Also, the government introduced a £25 million scheme to co-ordinate the world’s largest electric car trial from the end of this year. The scheme is designed to accelerate the introduction of electric cars to the UK. Around 340 electric vehicles, including electric Minis, Smart city cars, sport cars and electric vans, are involved in this long-term trial of several cities in the UK. Power companies, regional development agencies and universities will work together to coordinate the experiment. Through the Joint-Cities Plan, ETI aims to attract private investors to work together with government to develop a self sustaining mass market of electric vehicle and make the UK a world leader in green vehicles.

Similarly, The French government has unveiled plans to invest €1.5 billion on infrastructure measures to aim for two million electric and hybrid cars on the roads in France by 2020. This investment will mainly focus on building infrastructure, but also supply subsidies for both makers and buyers of green vehicles. It is proposed that from 2012 all new apartment blocks with parking lots in France will have to include charging stations. The charging network will grow to a total of 4 million charging points by 2020, the equivalent to two points per vehicle (Pearson, 2009). The government also supply hundreds of million euros to car makers to support building up electric car manufactory capacity in France. For example, the state contributes € 125 million to help Renault to build up a battery plant at Flins, near Paris. Other carmakers including Peugeot and Daimler will also receive financial support to develop electric cars.

The electric car market is moving in Europe at last. The Danish government has brought in world-class companies such as IBM, Siemens and national energy company DONG to make 10% of Danish cars plug-ins within next decade (Young, 2009). Nissan Motor Co. announced its plans to invest \$700 million to build two plants in the UK and Portugal to produce lithium-ion batteries for electric cars. A research project called “Mobile Energy Resources for Grids of Electricity”, funded by the EU is to develop the European electrical system for the mass-scale of electric vehicle. This system will adapt the charging of electric vehicle batteries to the availability of energy resources and of the electric grid infrastructure.

2.5.3 China

The Chinese government aims to become the world’s largest producer of electric cars, producing 500,000 electric vehicles a year by 2011. Multinational auto manufactures like BMW and Toyota, some big global investors like Warren Buffet, and emerging domestic Chinese carmakers like BYD believe that the market for electric vehicles in China is about to take off. It is estimated that electric vehicles sale could be reach to 1.5 million globally if the vehicles are priced around €10,000 (about 100,000 CNY). About 200,000 electric vehicles are operating in the China market alone (Lamure et al., 2009). In China, the most likely consumers of electric vehicles are highly price sensitive. They worry about the cost of purchase price and maintenance ownership, unlike premium “eco-friendly” customer in the developed countries, who are willing to pay higher price of EV in return for “eco-prestige”. Chinese domestic manufacturers will have advantage in developing electric vehicles for the local market. After setting up mass production of EV, these Chinese auto manufacturers will challenge global major players via using China’s huge industrial capacity, internal demand and cost advantages.

It is noted that the business model of Chinese EV manufactures is different from the US one. When a Chinese OED decides on which battery he will use in his EV, he will buy the battery company and own the battery technology, then import the manufacturing line for mass production, where the OED in the US have used battery manufacturers as supplier only in the past, hoping the multiple customers would lower unit costs (Smith, 2009). China is leading the pack when it comes to plug-in vehicles. The country’s largest electric power company, the State Grid Corporation of China, is

setting up charging stations in larger cities like Beijing and Shanghai. The investment from the Chinese government on alternative fuelled vehicles is impressive. It is clear that China is moving forward aggressively. The country has even begun taking advantage of the Western auto-industry slump to draft in some of the recently laid-off engineering talent.

3. Hydrogen fuel cell vehicles

3.1 Hydrogen technologies

3.1.1 Hydrogen

Hydrogen is an energy “carrier” with great potential to increase energy security and to reduce greenhouse emission. It can be produced from a wide range of primary energy resources, such as natural gas, coal, nuclear and renewable energy. Hydrogen is considered as CO₂ –free energy if produced from renewable and nuclear energy. In principle, if hydrogen is used in fuel cells, burned with pure oxygen in a conventional combustion process, it results in only pure water. But if it is burned with air, depending on the combustion condition, it will produce nitrogen oxides. The emissions of a hydrogen-based energy system depend on the primary energy source and process used for hydrogen production.

Fuel cells powered by hydrogen can increase efficiency of energy use. The technologies and processes for hydrogen production, storage, transportation and distribution, and fuel cell technologies will make a contribution to energy security and greenhouse emission reduction. Especially, they have the potential to create paradigm shifts in transport and distributed power generation (OECD, 2005). The biggest market for hydrogen fuel cell vehicles will be the automotive industry. But the cost of the fuel cell vehicle is far too expensive, which is the biggest barrier for mass production in automotive industry. Major automakers invest huge funds in research and development on hydrogen fuel cell technologies, trying to reduce the cost. Major car makers are racing to become the first car maker of a commercial hydrogen car.

3.1.2 Hydrogen production

Today, most hydrogen is produced using fossil energy resources. The most common way to produce hydrogen is to employ steam to separate it from carbon in petroleum or natural gas. Hydrogen can also be produced from water by electrolysis. The electricity for the electrolysis process can be produced from a variety of energy sources such as oil, coal, nuclear energy and renewable energies such as solar and biomass. The efficiency of hydrogen production varies depending on the energy sources used, as listed on Table 2. Other methods such as chemical reduction using chemical hydrides or aluminum can also produce hydrogen (Wikipedia, 2009). Hydrogen is possible to be produced in bio-reactors from the photosynthesis process with algae. Solar powered bio-H₂ production via algae will be possible as a sustainable alternative if photon conversion efficiency can be improved via large-scale algal bioreactors, as discussed in a previous SAL3 DIME_GRIEG report (Zhang & Cooke, 2008).

Table 2: Renewable energy consumption, request estimated for H₂ production in 2050 (Source: data from Mabán & Valdés-Solís, 2007).

Renewable energy	Primary energy (2004, Mtoe/year)	Electricity production (2004, Mtoe/y)	H ₂ production (Efficiency, %)	Required for H ₂ production (2050, Mtoe/y)
Wind (onshore)	30	82	Electrolysis (>50%)	25,000
Solar (PV)	2	3	Electrolysis	42,000
Solar (thermo.)	49		Thermo-chemical cycles	22,000
Biomass	1350	164	Bio-ethanol; bio-diesel (35%) Bio-methanol from syngas (65%) Reforming (73%)	12,900 Transport 4,600 3,750
Geothermal	6	55	Electrolysis	7,400
Hydraulic	634	2854	Electrolysis	15,000

So far, fossil fuels will continue to form an important part of the worldwide energy economy in the transition towards hydrogen. In the transition to a hydrogen economy, biomass, as one of the renewable energy resources, can be employed as a clean energy mainly through the following three processes:

1. Transformation to bio-fuels that are directly burnt in the internal combustion engines (ICEs). Brazil is far ahead of other producers, as biomass constitutes around 13% of its energy demand. USA produces bio-ethanol from corn, while Brazil produces bio-ethanol from sugar cane. Spain is the leader in bio-ethanol in the EU, while Germany and France are the biggest European producers of bio-diesel (Zhang & Cooke, 2008). There is controversy over biofuel application in transportation. The first generation of biofuel production uses some amount of fossil fuel during the bio-fuel production. Another concern is to use cultivable land for biofuel production instead of food production, leading to the recent “food and fuel” debate. The second generation of biofuel production has advantage that lignocellulosic crops do not compete with alimentary crops without constraint of cultivable land. However, biofuel can be mixed with standard gasoline or used alone with only minor modification to current combustion engines. It is an alternative way to reduce the consumption of gasoline in the short-term.
2. Transformation to bio-methanol though syngas (CO+H₂) produced in the biomass gasification process. Bio-methanol is stored in vehicles provided with a reformer in which the bio-methanol reacts with water to produce H₂, which is fed to the FC engine later. This process increases energetic efficiency compared with bio-fuels in the first process. The auto-thermal process would produce hydrogen with 104% of the energy existing in the reacted methanol. The second process doesn't require the storage of H₂ and would allow use of the current liquid fuel distribution network (Mabán & Valdés-Solís, 2007). However, it is an expensive option and a technological challenge (IEA, 2005).
3. Direct transformation of biomass to H₂. This is applied in a central reforming system or in H₂-electricity cogeneration systems. The gasification or

reforming process produces a gas mixture of H₂, CO and CO₂. CO is further reacted with water to produce more H₂ and CO₂, which is captured and stored. This process is based on large scale use of biomass for centralized energy production and requires the transportation and distribution network of hydrogen. (McDowall & Eames, 2006). Economies with biomass deficit supply will have to import raw material, and thus rely on the global market, which is similar to current oil market.

3.1.3 Hydrogen storage and infrastructure

Hydrogen has a low volumetric energy density at ambient condition, meaning that a given volume of hydrogen contains a small amount of energy. But by mass compared to gasoline, it has a three times higher energy density. It can be stored as liquid hydrogen in a cryogenic tank or in a compressed hydrogen storage tank. It is currently transported by pipeline or by road via cylinders, tube trailers and cryogenic tankers. Due to the energy intensive nature and cost associated with hydrogen distribution via high-pressure cylinders, this method of distribution has a range limited up to 200km (IPHE, 2009). The energy consumed to compress the hydrogen reduces the efficiency of the high pressure storage. Safety is another issue to challenge the hydrogen economy. Current research on future storage technology includes metal hydride and chemical hydride.

If hydrogen is produced at large-scale central locations, it requires the development of a dedicated infrastructure to store and transport hydrogen to end use destination. Transportation and distribution costs add considerably to the total hydrogen supply cost. The cost ranges from \$5-10/GJ H₂ for large-scale supply systems (IEA, 2005). Hydrogen transportation by pipeline seems to be the lowest cost option to distribute hydrogen. In that case, the hydrogen infrastructure consists of industrial hydrogen pipeline transport and filling station. However, because of its low energy density, hydrogen pipelines are twice as expensive as natural gas pipelines. Pipelines, owned by hydrogen producers, are limited to small areas where large hydrogen refineries and chemical plants are concerned. Hydrogen use would require the alteration of industry and transport on a large scale. A hydrogen supply infrastructure for road transport would cost over several hundred billion US dollars. If centralized production is adopted, the cost of a worldwide hydrogen pipeline system would be between \$100 billion to \$1 trillion. The incremental investment costs of hydrogen global re-fuelling stations are about \$200 billion for centralized production and \$700 billion for decentralized production (IEA, 2005). A new hydrogen station is estimated to cost about \$20 billion in the US and \$4.6 billion in the EU (Wikipedia, 2009). It was suggested that earlier retirement and partial replacement of existing natural gas supply system would significantly reduce the cost (IEA, 2005). So far, there are about 400 demonstration projects in progress world wide, but a large pipeline system dedicated to transporting large volumes of hydrogen does not yet exist.

3.1.4 Hydrogen vehicles

Hydrogen vehicle use hydrogen as the on-board fuel for motor power, converting the chemical energy of hydrogen to mechanical energy in two ways: internal combustion or electrochemical conversion in a fuel-cell. In hydrogen internal combustion engine vehicles, the hydrogen is combusted via heating, similar to a traditional internal

combustion engine. This process is called thermolysis, utilizing natural gas, coal or biomass. The production of hydrogen from fossil energy resources uses high volume of heating and still produces greenhouse gases. Currently, hydrogen vehicles utilizing hydrogen produce more pollution than vehicle consuming gasoline, diesel in modern internal combustion engine, and far more than plug-in hybrid electric vehicles. Although hydrogen fuel cells generate no CO₂, the production of hydrogen creates additional emissions. It would be possible to produce hydrogen from renewable energy resources, such as solar or wind. In fuel-cell conversion, the hydrogen is reacted with oxygen to produce water and electricity, the latter being used to power an electric traction motor. The fuel cell electricity is produced from combining hydrogen and oxygen. If pure hydrogen were used in the fuel cell reaction, the only byproduct is water. Therefore, using hydrogen is very environmentally-friendly. More detail about fuel cell technology is discussed in the next section.

Hydrogen vehicles include automobiles, bus, bicycles, airplanes and rockets. Many automobile companies are doing the researches to build hydrogen cars. The manufacturers had begun developing hydrogen cars. Key players include Daihatsu, Ford Motor Company, General Motors, Honda and Hyundai Motor Company. Most hydrogen cars are still at demonstration stage or limited numbers of construction. They are not yet ready for public use due to limitation of power charge and costing.

3.2 Fuel cell

3.2.1 Fuel cell concept

Fuel cells use hydrogen and oxygen to produce electricity through an electrochemical process. A fuel cell consists of two electrodes—a negative anode and a positive cathode and an electrolyte between two electrodes. As illustrated in Figure 11, they operate by feeding hydrogen to the anode and oxygen to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons. The electrons go through an external circuit, creating electricity that can be utilized, while protons pass through the electrolyte to the cathode, where they reunite with oxygen and electrons to produce water and heat. Proton exchange membrane fuel cells are particularly suitable technology for the transportation application due to their fast start-up time, favorable power density and power-to-weight ratio. They also represent 70-80% of the current of small-scale fuel cell market (IEA, 2005).

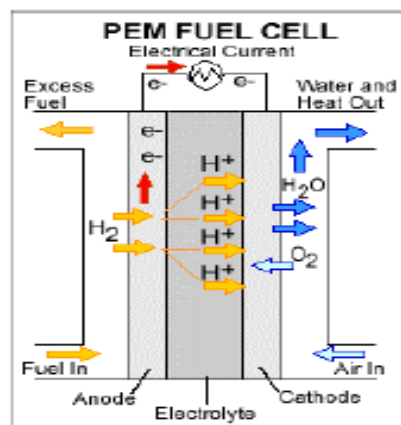




Figure 11. The proton exchange membrane fuel cell concept (Source: IPHE).

3.2.2 Fuel cell vehicles

Comparing to conventional engines, fuel cell vehicles have higher fuel efficiency due to direct conversion from chemical energy to electrical energy. The overall efficiency of fuel cell from well-to-tank and tank-to-wheel can be as high as 40%, over 15% higher than current hybrid car. The characteristic comparison between electric and fuel cell car is shown in Table 3, the E6 model made by BYD Company as an example of electric car and the FCX Clarity made by Honda as an example of fuel cell car. The curb weight of FCX Clarity fuel cell car is lighter, and refill time is fast than BYD E6. The energy storage could reach up to 136 k for fuel cell car. Thus fuel cell hydrogen vehicle has huge potential for future transportation application.

Table 3. Comparison between electric car and hydrogen fuel cell car
(Source: Energy Research Center the Netherland. Note: a: even statements of 400 km; details about conditions n/a; b: combined EPA cycle: average speed 48km/h).






Vehicle type	Electric car	Fuel cell hydrogen car
Example		
L x W x H (m)	4.55x1.82x1.63	4.83x1.85x1.47
Curb weight (Kg)	2100	1600
Max. power (kW)	115-200	100
Max. speed (km/h)	160	160
Range (km)	>300 ^a	430 ^b
Energy storage: type kWh	Li-ion battery pack >60	Hydrogen (at 350 bar) 136 (4.1 kg H ₂)
Refill time: home fast	>20 hours 50% in 10 min	- 2-3 min

Hydrogen fuel cell can be applied in various forms, including bicycle, boat, passenger car, bus and even the space rocket. It provides a sustainable transportation choice for the future. However, it is hard to predict when and how many will be on the street due to uncertainty of technology and infrastructure. Automotive firms are also seeking to become the first FCV car maker world-wide just as making the first electric car. GM/Opel developed the project 'Drive Way' to stimulate deployment of the Equinox fuel cell SUV in some regions in the US, such as California, New York and Washington D.C. By 2008, GM HydroGen 4 was deployed in Germany, China, Korea and Japan. GM still has the goal to be the first car makers to sell 1 million FCVs (Ahn & Lim, 2006). But GM suffered enormously in the financial crisis and priorities changed.

Several automakers are known to be active in the development of fuel cell vehicles, including Honda, Toyota and Ford, as listed in Table 4. They have all set up strategic plan for mass production in the near future. The Honda FCX Clarity and the new Daimler F-cell are very close to delivering the same performance as a conventional

vehicle. Honda continues to develop its FCX Clarity model to selected customers in the US and Japan. It has selected a dealer network near to hydrogen fuelling stations that will service the vehicles. Vehicles are purchased on lease contract with 36 month period at \$600 per month (Bunzeck, 2009). Recently, *BMW* has extensively promoted its Hydrogen 7, based on a regular 7-series model with a hydrogen internal combustion engine that can run both on petrol and hydrogen. Korean OED Kia-Hyundai Automotive Group has developed the fourth-generation *Kia Borrenge* fuel cell SUV for a road test in California and Korea. The new model called i-blue can reach the speed of 165km/h and range of 600 km. Hyundai is targeting to start up series production of i-blue by 2012 (Bunzeck, 2009).

Table 4. Several fuel cell vehicle developments (source: Ahn & Lim, 2006)

	FC Vehicle	Production Plan							status
		'02	'04	'06	'08	'10	'12	'14	
Honda		▼ (02.12) Lease sale					◆	★	<ul style="list-style-type: none"> • '02.12 : Lease sale (USA, Japan) • '05.12 : 20 cars running ✓ 2012 : Production (goal)
Toyota		▼ (02.12) Lease sale					◆		<ul style="list-style-type: none"> • '02.12 : Lease sale (USA, Japan) • '05.12 : 30 cars running ✓ 2010 : Production (goal)
GM		▼ '06.12					◆		<ul style="list-style-type: none"> • '05.12 : 20 cars running ✓ 2010 : Production (goal) • 2020 : multi-million prod. (goal)
DCX		▼ '08.01					◆	★	<ul style="list-style-type: none"> • '05.12 : 100 cars running ✓ 2012 : Sale's to public (goal) ✓ 2015 : 50,000 production (goal)
Ford		▼ '04.12							<ul style="list-style-type: none"> • '05.12 : 30 cars running (USA, Canada)

The Oak Ridge National Laboratory conducted a scenario analysis of three fuel cell vehicle penetration rates to assess the costs and infrastructure needs to meet growth to two, five and ten millions of fuel cell vehicles in the US by 2025 (Greene et al., 2008). The analysis found that with targeted deployment policies in place during 2012-2025, the fuel cell vehicle market share could grow to 50% by 2030 and 90% by 2050. The number of fuel stations in the regions is very critical for fuel cell vehicle early deployment. A conceptual roadmap plan is illustrated by California Fuel Cell Partnership (CaFCP) (2008) in Figure 12. The commercialization includes technology introduction (2007-2010), pre-commercial stage (2011-2013) and early commercial stage (2014-2016). The technology refinement and early market preparation could be tested in a couple of regions such as California and New York, and then commercial deployment into the mass market will be conducted in other metropolitan regions.

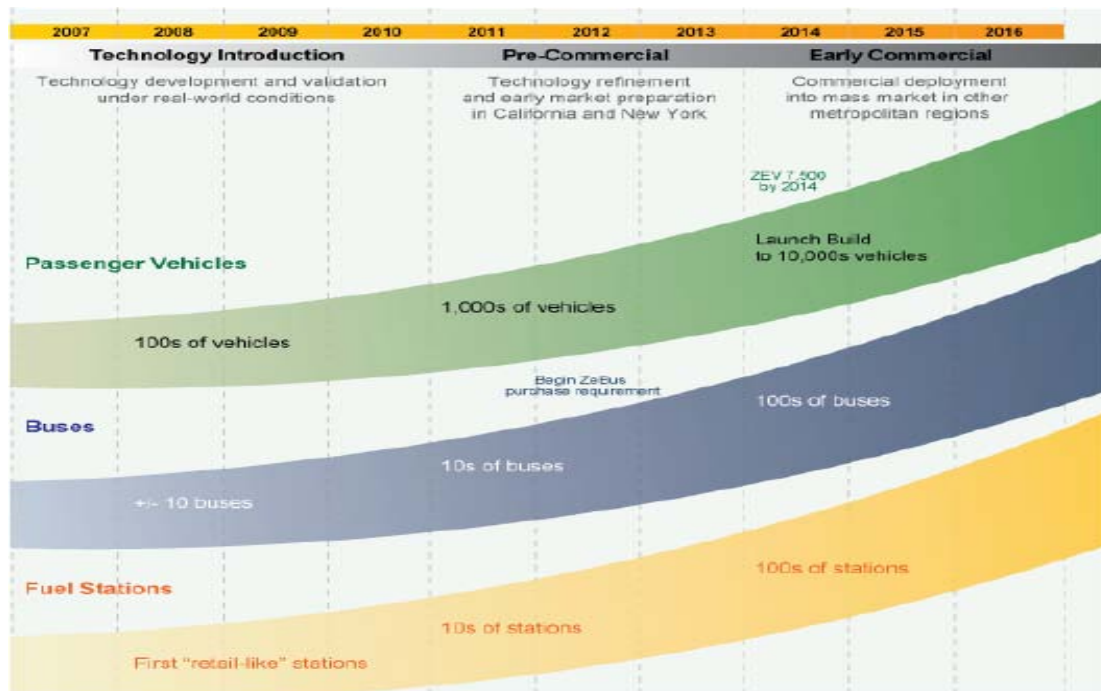


Figure 12. Conceptual overview of fuel cell vehicles (Source: California Fuel Cell Partnership)

3.2.3 Challenges for fuel cell technology

Fuel cell cost:

The Fuel cell is considered as one of most promising products of 21st Century, as it can compete with batteries, the internal combustion engine and power grid in terms of high efficiency. The challenge is whether fuel cell will be made with a reasonable price. Proton exchange membrane fuel cells (PEMFCs) can be used for both stationary and transport applications. But it requires rather high quality of hydrogen. The current cost of PEMFCs is possible to reduce to \$100/KW with mass production.

Freezing condition:

Most fuel cell designs are not yet robust enough to survive in below freezing temperature. In operation, fuels cells have an internal vaporous water system that could solidify below 0°C. But the fuel cell membrane would be heated up by the car battery quickly. So the problem could be solved with special design.

Life-time (durability)

The lifetime of a fuel cell is critical to its overall operating cost. Average life-time for PEMFCs is about 2200 hours. The target is to increase the lifetime to 3000-5000 hours for cars and 20, 000 hours for buses (OECD, 2005).

3.3 Hydrogen economy

Hydrogen, as an energy carrier, can be utilized to store clean energy produced both from traditional fuels and from renewable energy sources. It can be used in hydrogen-powered vehicles, combining with fuel cell technology. The hydrogen energy system described below offers totally clean energy supplies with no pollution (Figure 13). The system is based on renewable energy sources for electricity and uses hydrogen as

an energy carrier in hydrogen fuel cell vehicles (www.hydrogen.co.uk). Water which comes from rain is converted into hydrogen and oxygen by electrolysis using clean renewable electricity. The produced hydrogen can be delivered to where energy is needed and used as transport fuel or industrial electricity. At some point, the hydrogen combines with atmosphere to form water, returning to the atmosphere as water vapour. No CO₂ emission is produced in this hydrogen energy system, as water and oxygen is balanced within the atmospheric cycle.

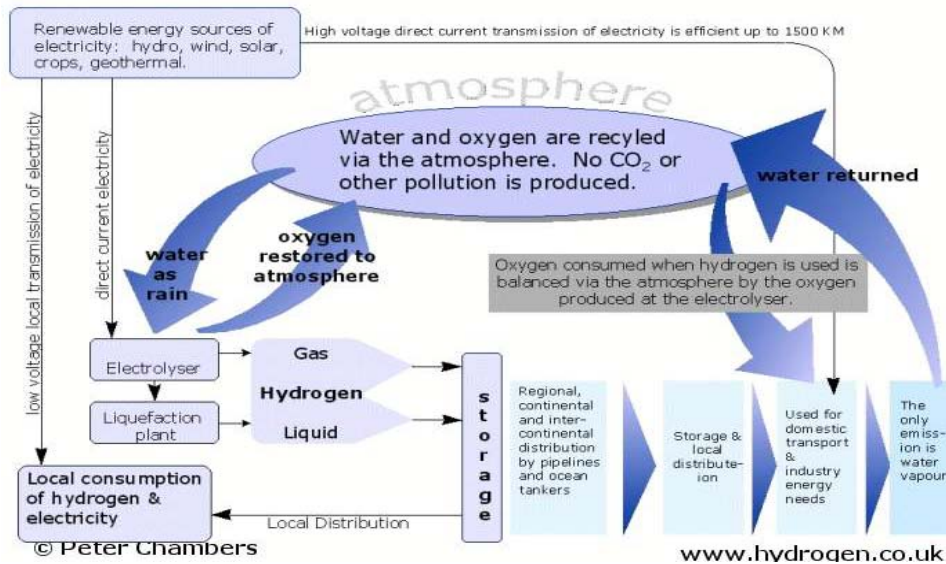


Figure 13. Hydrogen energy system (Source: www.hydrogen.co.uk).

In 1999, Grant proposed the super-grid vision: a combination of superconducting cables with a hydrogen economy. He proposed pumping liquid hydrogen into a pipe in which the superconducting cable runs down the middle, creating a “super-cable” that carries both electricity and hydrogen into a city. Fuel stations could tap into coolant to power electric fuel-cell cars. Hydrogen could also be burned for domestic heating and cooking. It can be converted into electricity if demanded (Clery, 2008). Hydrogen can be expected to allow integration of some renewable energy sources. For example, a photovoltaic solar panel (or wind mill) can be linked to a reversible fuel cell, which uses a part of electricity to produce hydrogen during the day, then consumes the hydrogen during the night to produce electricity. However, the system is less efficient at current technologies (Mabán & Valdés-Solís, 2007). It is predicted that a hydrogen economy will emerge in the future, beyond 2050 when oil will not be an energy source any longer and more than 25 Gtoe of primary energy is consumed, as indicated in Figure 14.

Hydrogen and fuel cells may have a major role in the future energy market if government gives high priorities to reduce CO₂ emissions and invest research and development in hydrogen technology to reduce the technology cost. Government would need to adopt policies that give financial incentives to the industry which could reduce CO₂ emission. It is estimated that if those favorable conditions are met, then 30% of global vehicles (equivalent to 700 million vehicles) could be powered by hydrogen fuel cells by 2050 (OECD, 2005). The two energy distribution networks of electricity and hydrogen will be integrated to form global network system. In the electricity network, traditional energy resources such as gas and coal will be

transformed in co-generation thermal plants to produce H₂ and electricity. CO₂ will be confined inside underground formations (Mabán & Valdés-Solís, 2007). Renewable energy sources will play a predominant role in the electricity generation in the future.

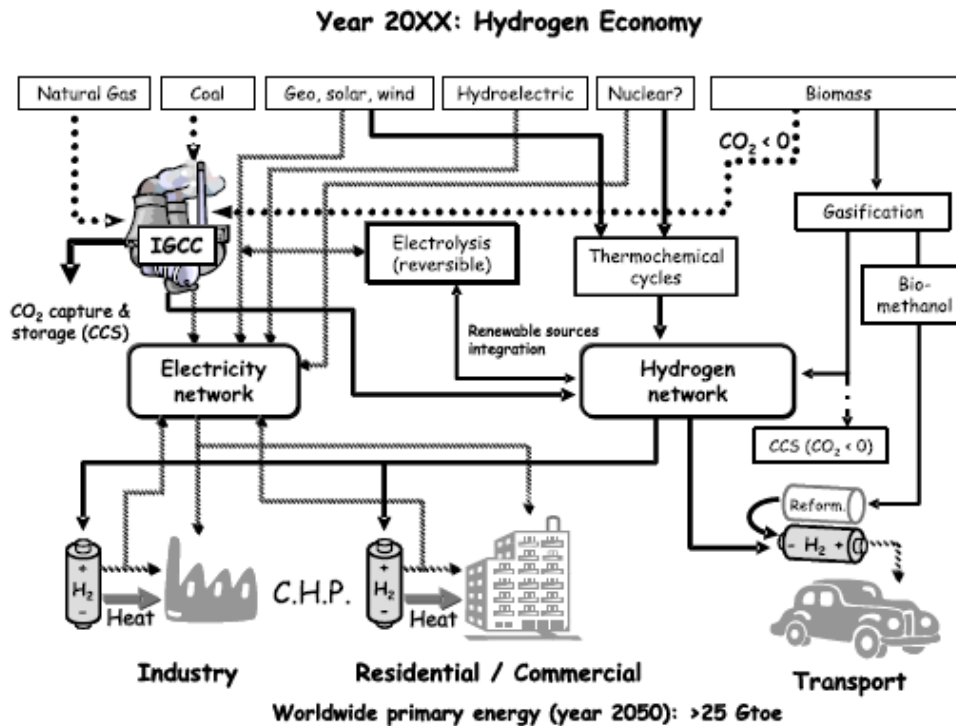


Figure 14. Hydrogen economy in the distant future by year 20XX. (Source: Mabán & Valdés-Solís, 2007)

The hydrogen economy is a long-term project to combine the cleanliness of hydrogen as an energy carrier with the efficiency of fuel cells as devices to transform energy into electricity and heat (Mabán & Valdés-Solís, 2007). The infrastructure of hydrogen production, transport, distribution and storage play an important role for the potential of hydrogen-based economy. Because of low gas density and permeability into material, hydrogen transportation via pipeline is much more expensive than natural gas. Hydrogen storage is another issue for the potential of hydrogen application. McDowall & Eames (2006) proposed two possible futures of hydrogen systems: Centralized system reliant on nuclear energy or carbon-sequestration and decentralized system based upon small-scale electrolysis, steam methane reforming of natural gas or renewable electricity. In the case of centralized hydrogen production, the transportation and distribution cost and the refueling cost for transport vehicles add considerable cost to the total hydrogen supply cost. In the case of decentralized system, hydrogen pipelines are twice as expensive in cost and require five times more energy to operate than natural gas pipeline. It is estimated that a hydrogen supply infrastructure for road transport would cost about several hundred billion US dollars and the cost of a worldwide hydrogen pipeline system for transport sector could range from \$0.1 trillion to \$1 trillion (OECD, 2005). Transitioning to a hydrogen economy requires the government to design an economic incentive system to encourage the building of hydrogen infrastructures and the market development of hydrogen fuel cell vehicles. As technology learning and economy of scale will drive down the cost of new technology, hydrogen fuel cell technology will expand and become cost-effective in the future (Tseng et al., 2005).

3.4 Economic development

Governments across the world are reported to provide over \$4 billion in R& D in hydrogen energy. Some countries such as Japan, USA and Germany have led the way to explore new hydrogen technologies. They have some major ongoing programs to develop a global hydrogen system with new technologies for power plants, cars, buses, planes, ships and rockets, all fuelled with renewable hydrogen. If ambitious climate and energy-security policies are adopted, the regional potential for hydrogen and fuel cell seems to be high in the OECD regions and in the China. Transport applications dominate the hydrogen market in all regions. The share of hydrogen FCVs varies across the regions. In the most optimistic scenario, China would be the region with the highest FCV share (60%) in 2050, as predicted by an OECD study (2005). The FCV share would be about 42% in the US; 36%-38% in Europe and only 22% in Japan (Figure 15). Difference in hydrogen fuel cell vehicle penetration across regions depends on economic conditions, infrastructure, energy and fuel taxes and government policies.

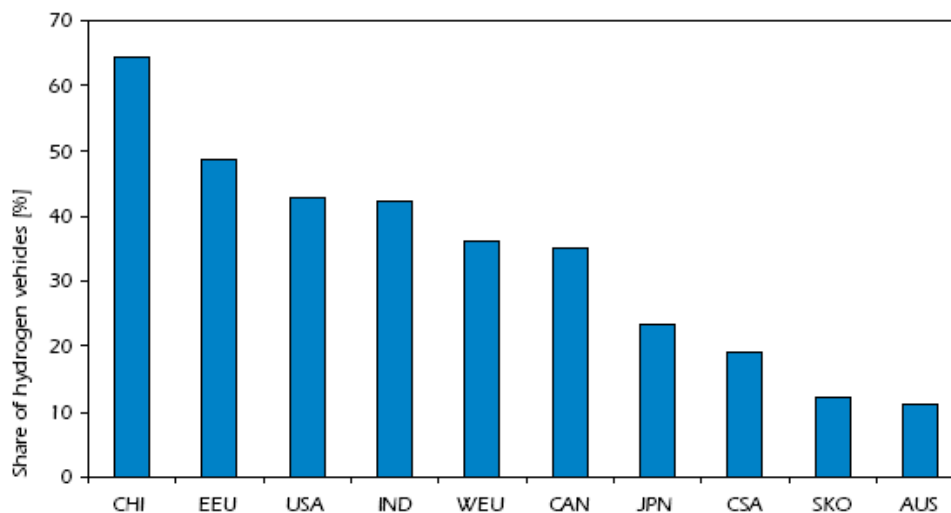


Figure 15. Stock share of hydrogen fuel cell vehicles in key regions in the most optimistic scenario by 2050 (Source: OECD, 2005).

Note: optimistic scenario with strong new world-wide CO₂ policies and rapid technological development.

Abbreviations: CHI: China; EEU: East Europe; IND: India; WEU: West Europe; CAN: Canada; JPN: Japan; CSA: Central and South America; SKO: South Korea; AUS: Australia and New Zealand.

3.4.1 USA

Melendez and Milbrandt (2007) found that consumer demand for hydrogen fuel cell vehicles is greatest in major urban areas because of their high population densities and favorable population characteristics. Southern California and New York City are ranked as top areas of projected hydrogen energy demand, as shown in Figure 16. These two areas were targeted for early infrastructure introduction during hydrogen program phase I (“Initial introduction”) (Greene *et. al.*, 2008). Southern California and several states in the Northeast represent the most attractive initial market for hydrogen-fueled vehicles. The next phase, called Targeted Region Growth, would

focus on an additional eight selected cities with a potential market. Three early corridors: Los Angeles-San Francisco; New York-Boston-Washington D.C.; and Chicago-Detroit are planned to set up during this phase. Ohio, California, New York, and Connecticut are examples of a few states that have adopted policies and regulations to hasten the adoption of hydrogen fuel cell power in those states. Phase III, called Inter-Regional Expansion, is to expand the infrastructure to 10 additional urban centers with populations of 1.5-5 million and adds more corridors connecting the urban centers. Figure 17 illustrates the fully deployed transition infrastructure image with red, blue and yellow representing deployment Phase I, II and III, respectively.

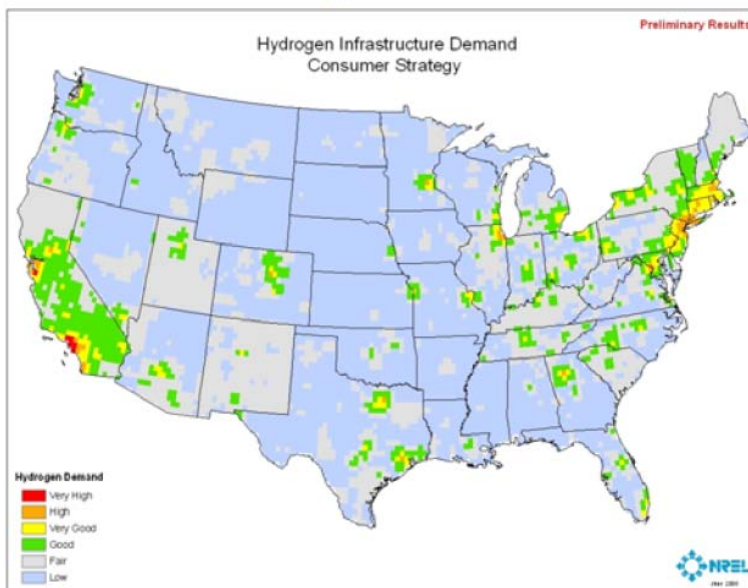


Figure 16. Areas of projected hydrogen energy demand in the US ((Source: Melendez & Milbrandt, 2007).

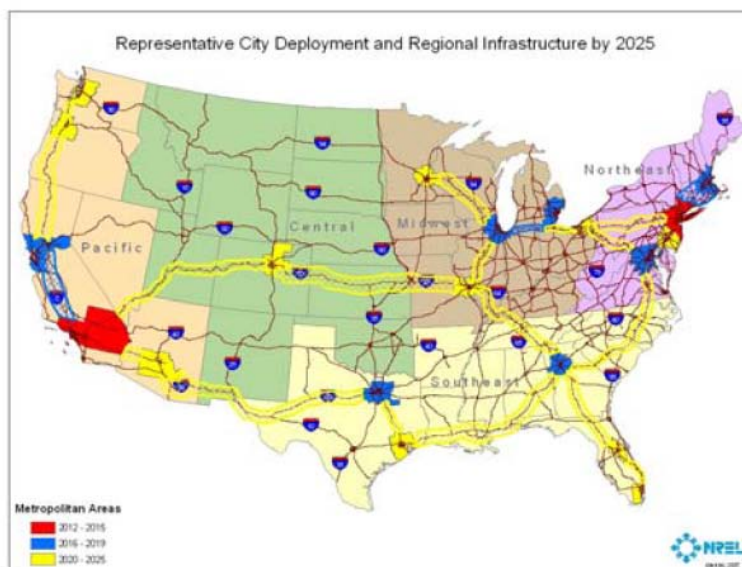


Figure 17. Representative city deployment and regional infrastructure in the US. (Source: Melendez & Milbrandt, 2007)

In order to lead the world to build sustainable hydrogen energy system, The Bush administration proposed \$1.2 billion in research funding on developing clean, hydrogen-powered automobiles (Turner, 2004). Many new research laboratories or centers have been set up to focus on the technologies for hydrogen production, storage, transportation, fuel cell and energy efficiency across the nation, as shown in Figure 18. The US Department of Energy, in conjunction with national laboratories and industry has developed several models to estimate the cost of hydrogen economy (Greene et al., 2008). Up to date, hydrogen vehicles driven in demonstration projects and field trials have very high production cost because of their innovation technology and low production figure. In the automobile industry, production costs are expected to come down only when production volumes grow (beyond 10,000 units). In the early stages, the cost gap between expensive hydrogen vehicles and conventional vehicle is proposed to be covered by government support.

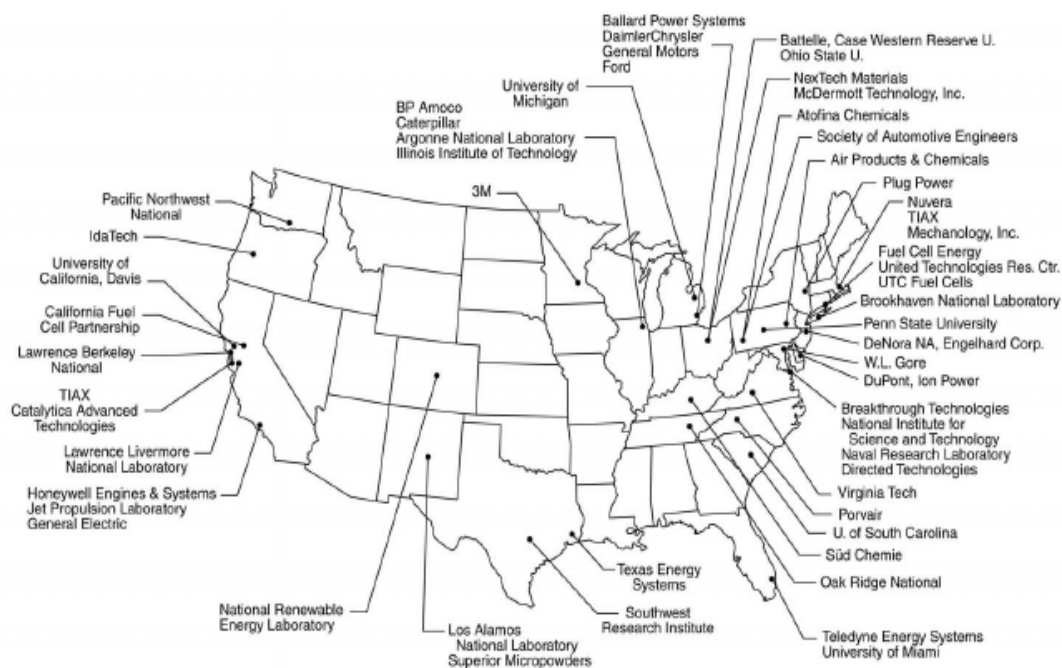


Figure 18. Map of research and development on hydrogen activities across the US (Source: DOE).

Policy support for hydrogen infrastructure is critical for the deployment of hydrogen application. Currently, the U.S. Department of Energy is implementing the “Freedom Car Program” and the “Hydrogen Fuel Import Program” to support hydrogen and fuel cells and fuel cell vehicle research and development and demonstration. DOE has achieved several significant progresses in cost reduction of fuel cell vehicles through its supported programmes. For example, the cost of automotive fuel cells has been reduced from \$275/kw in 2002 to \$73/kw in 2008 and targeted at cost of £30/kw by 2015 (Figure 19). The durability of fuel cell systems in vehicle under real-world condition has increased more than double, from 950 hours in 2006 to 2000 hours in 2009. The production cost of hydrogen from both renewable resources and natural gas has also been reduced to an equivalent cost of \$3/gallon which is competitive cost with gasoline (DOE, 2009).

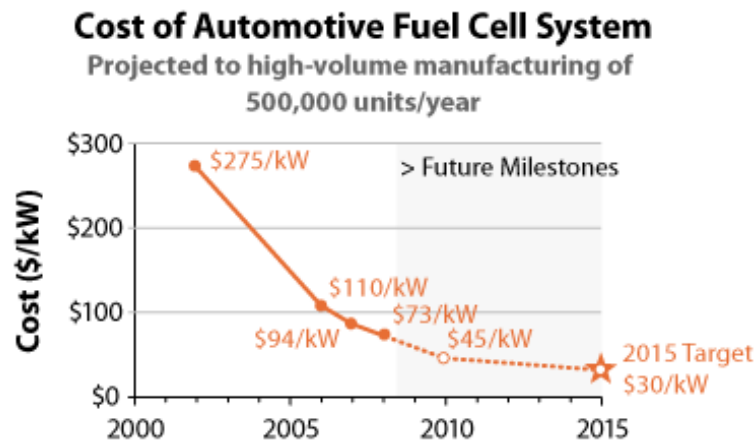


Figure 19. Cost of automotive fuel cell system (Source: DOE).

Since 1999, the California Fuel Cell Partnership have successfully operated demonstration project for more than 200 hydrogen vehicles and tens of hydrogen fuel stations. These demonstrations have proven that hydrogen fuel cell vehicles and transit buses have the potential to meet customer demands and provide significant environment and energy benefits to meet California goals. Hydrogen can also be explored for power service in the future. In 2006, BP announced it was to invest \$1 billion to construct a hydrogen plant in California, separating natural gas from CO₂. The hydrogen plant would capture around 90% of the CO₂ produced and generate 500 megawatts of power, supplying 325,000 homes (Macalister, 2006). The State of Florida together with Ford Motor Company had a demonstration project to put hydrogen-fuelled Ford E-450 buses in all Orlando roads. The pilot trial is part of the state's broader plan to move toward a greater application of alternative fuels. To enhance its hydrogen internal combustion engines, Ford is conducting additional research to create its next generation hydrogen internal combustion engines as direct injection to improve power and fuel economy (Johanssen, 2007). It is proposed that the hydrogen infrastructure should be constructed using a combination of industry and government support. Several different approaches should be evaluated and specific funding models developed to optimize the government investment. CaFCP (2008) proposed the following approaches for government to support hydrogen application:

1. Cost share hydrogen stations through one-time grants
2. Provide ongoing incentives based on the volume of dispensed hydrogen (\$/kg)
3. offer incentives to station owners

In May, 2009, US Energy Secretary Mr. Chu announced his proposal to reduce current research into hydrogen-based energy technology by 60%, from 168million this year to \$68 million in 2010. He suggested hydrogen fuel cell technology is too costly, uncertain and long-term commitment. Biofuel and batteries are suggested to offer a better short-term pathway to reduce oil use and greenhouse-gas emission (Wald, 2009). This proposal surprised both business people and researchers on hydrogen technology development. Hydrogen's advocates made a good progress to retain the funding budget for hydrogen technology. On 17th July, the House of Representatives voted to restore \$85 million to the hydrogen research budget. Although the final bill is not released yet, some level of funding for hydrogen vehicle research is likely to survive (Tollefson, 2009). Despite US government funding cuts for hydrogen transport application, several car markers such as Toyota still continue their commitments to develop commercial hydrogen fuel cell cars for the future.

3.4.2 Europe

International Energy Agency set up the Hydrogen Co-ordination Group, consisting of ten countries: Australia, Austria, Canada, France, Germany, Japan, the Netherlands, Spain, the United Kingdom, and the United States, to improve international collaboration on hydrogen fuel cell technology. The European Union is also enthusiastic about hydrogen and invested around € 616 million dedicated to hydrogen and fuel cell technology in 2007 (Figure 20) (EC, 2009) . EU FP6 funds for H₂/FC research projects reaches €70 million annually. Public national R&D investment of EU Member States presented about 28% of total R&D investment in EU. These figures may vary among different data resources. Total public investment found from the most recent report (EC, 2009) is €240 million, lower than data from HY-CO project, which estimated over €275 million in 2005 and expected further increase (Neef, 2008). Overall, Figure 20 shows that France, Germany, Italy and Denmark have invested the most R&D on hydrogen and fuel cell. Total co-operative R&D investment is over €375 million, indicating that many multinational companies have considered hydrogen and fuel cell as a strategic research field. These companies include not only car manufactures, large energy and chemical companies, but also some small and medium enterprises with specialised fuel cell and battery technologies. It is reported that EU has increased its budget for H₂ car development to \$1.29 billion, surpass US budget in 2010 (EHA, 2009). These funds mainly focus on hydrogen cars, H₂ production and infrastructure development. The European Union Joint Technology Initiative (JTI) for hydrogen and fuel cells will give a strong push for hydrogen technology in Europe. The main goal of the JTI is to commercialise hydrogen and fuel cell technologies between 2010 and 2020.

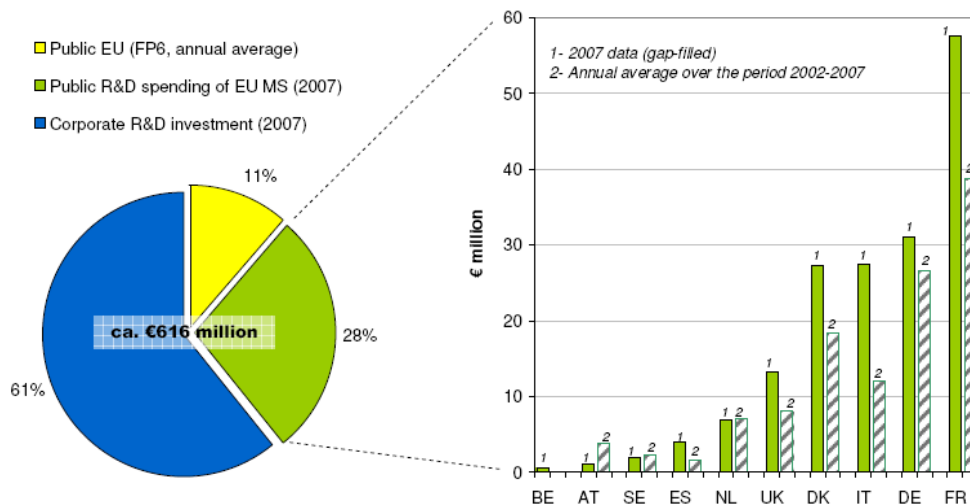


Figure 20. R&D investment from public and private sectors (Source: EC, 2009)
 Note: The data for the Netherlands is from ECN (Energy Research Centre of the Netherlands, France data is from l'Association Francaise de l'Hydrogen.

HyFLEET: CUTE has been established under, and is financially supported by the European Commission's Framework Research Programme. The project brings together 31 partners from industry, government, academic and consulting

organisations. It is an important demonstration project with about 47 hydrogen powered buses testing in 10 cities in the world wide (Reykjavik, Amsterdam, London, Berlin, Hamburg, Luxemburg, Madrid, Barcelona, Beijing, Perth). The aim of this project is to test and demonstrate hydrogen buses in order to develop new technology to reduce CO₂ emissions and move away from fossil fuels (www.global-hydrogen-bus-platform.com/).

Germany plans to develop and implement a long-term strategy to introduce hydrogen as transport fuel nationwide. The German Federal Ministry for Transport, Building and Urban Development funded the Clean Energy Partnership to promote hydrogen as a vehicle fuel. Berlin and Hamburg had joined the hydrogen powered bus test in CUTE project. HydroGen4 vehicles have been tested on the road in Berlin for six months from December 2008. The vehicles have shown the fourth generation of GM/Opel fuel cell cars are reliable and the future of hydrogen technology and fuel cell vehicles is viable.

It is reported that Norway opened an over 350-mile-hydrogen highway between its capital city Oslo and North Sea oil hub Stavanger recently (Moskwa & Larvik, 2009). There are several hydrogen filling stations between these two cities and more than a dozen hydrogen-powered cars were rallying along this route. It is estimated that a kilogram of hydrogen in these hydrogen-powered cars can run twice the mileage of a gallon of gasoline in conventional cars. In the long term, this hydrogen highway may link the road to a hydrogen autobahn in northern Germany.

Denmark has also developed big plans for hydrogen fuel cell and electric cars, doubling annual national support for R&D and demonstration of new energy technologies to €134 million. Copenhagen Municipality Climate Plan provides strong support for the Electric & Hydrogen car initiatives, as listed in the following:

1. All new car procurement in the municipality is to be electric & hydrogen from 2011.
2. Free parking in Copenhagen for electric & hydrogen cars
3. 25% Reduction of CO₂ emission from buses is targeted through use of electric & hydrogen, with a vision of becoming CO₂ neutral municipality in 2025.

The research done by the European project Road2Hycom found that regions with the highest level of hydrogen fuel cell (HFC) activities are clustering at the region with partnership or co-operative HFC initiatives (Figure 21) (Bader et al., 2008). In Southern Scandinavia the regions match the location of “The Scandinavian Hydrogen highway Partnership”. This partnership is a collaboration among three national bodies: The HyNor (Norway) The Hydrogen Link (Denmark) and Hydrogen Sweden, focusing the regions of South/South-eastern Norway, the Swedish west coast and Denmark. In Western Germany, North-Rhine-Westphalia has an active hydrogen network called “Fuel Cell and Hydrogen Network NRW”. A local hydrogen partnership was established in London in 2002. There are some major hydrogen and renewable energy initiatives in the UK, but still at an early stage. Northeast Spain and Northern Italy also have some hydrogen initiatives around their regions. Additionally, the German cities Hamburg and Berlin also ranked as high HFC activities regions, as well as Iceland, Nord-pas-se-Calais in France, Wales and North East England.

In 1999, Iceland declared a national goal to convert its economy to hydrogen energy by 2030 (Solomon & Banerjee, 2006). It has successfully developed hydroelectric and geothermal energy resources to supply over half of its energy requirements and almost 100% of its electricity needs. They hope to provide sufficient renewable hydrogen for its entire transport sector, transiting from oil-dependent transport system. In 2003, the first public hydrogen refueling station was opened in Reykjavik to serve three public transport buses built by DaimlerChrysler. The station produces the hydrogen it needs through an electrolyzing unit and doesn't need refilling. Royal Dutch Shell is a partner in this project. However, the progress of hydrogen economy has been slow down due to financial crisis in the last year. Iceland seems to switch to plug-in electric cars rather than hydrogen-powered cars as planned (Motavalli, 2009).

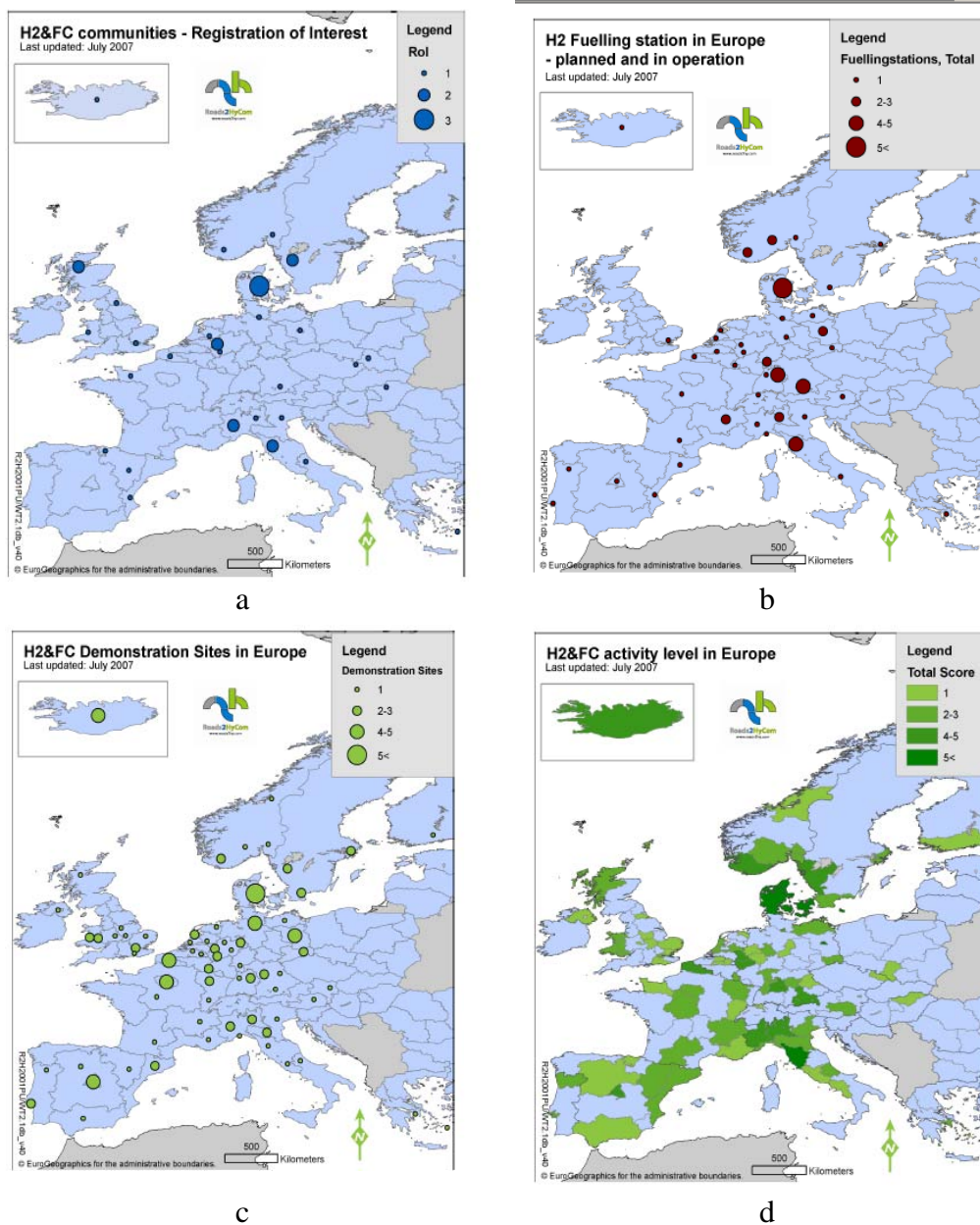


Figure 21. Hydrogen and fuel cell activities across the Europe:
a) HFC communities -registration of interest Total number;
b) Total H₂ fuelling stations in planning and in operation;

c) Total number of demonstration projects including in planning, in operation, finished, and interrupted ones;

d) HFC activity level.

(Source: Bader et al., 2008).

These geographical patterns of H₂/FC activities indicate some European regions are building up critical mass of H₂/FC (Figure 21d). It also suggested that the regions which are active in pursuing H₂/FC deployment are generally innovative regions. Regional innovation systems in these innovative regions are playing an important role for the development of emerging technologies. Clusters of automotive, power generation, oil and gas, chemical products and production technology have shown strong impacts on development of H₂/FC innovation regions, as the industries provide technology end-use application and market development (Bader et al., 2008).

3.4.3 Japan

Japan is one of the most important players in developing a hydrogen economy, not only in R&D investment but also production plans. Japan's hydrogen highway system was set up as part of Japan Hydrogen Fuel Cell (JHFC) project (Figure 22). JHFC conducts research and activities for the practical use of fuel cell vehicles and hydrogen stations. The aim of this project is to develop the roadmap for full-scale mass production of FCVs. Major automakers such as Toyota, Nissan, Honda, GM and Mitsubishi, and several energy companies like Cosmo Oil, Tokyo Gas and Taiyo Nippon Sanso have joined this project.



Figure 22. Japan's hydrogen highway system (Source: hydrogencarsnow.com)

Twelve hydrogen fueling stations have been built in 11 cities in Japan (Table 5). The Kawasaki hydrogen fueling station is the world's first station to produce hydrogen from methanol reforming. This method is suggested to be safer than natural gas reforming because the hydrogen production can be done at lower temperatures with less energy expended during methanol reforming. Two hydrogen fueling stations were built for Expo 2005 in Seto-North and Seto-South. Eight Toyota / Hino FCHV buses were refueled at these stations for the World Exposition Fair of 2005. The stations

dispensed 1,300 kg of hydrogen gas during the Expo (hydrogencarsnow.com). Lessons learned from the operation of these stations will be applied in the future development of hydrogen infrastructure across the country. The JHFC project has also tested fuel-cell cars and buses under a variety of real-life conditions to evaluate the performance, reliability and fuel consumption of hydrogen fuel cell vehicles. The joint public/private program aims to commercialize 5 million fuel cell vehicles and 10 GW of stationary fuel cells in Japan by 2020 (Solomon & Banerjee, 2006).

Table 5. Hydrogen refueling stations in 2005 in Japan (Source: OECD, 2005)

Location	Company	Hydrogen production	Year
Tokai, Aichi	Toho Gas Co.	Steam reforming	2002
Kasumigaseki, Tokyo	Taiyo Nippon Sanso	Bundle of high-pressure cylinders	2003
Yokohama, Kanagawa	Cosmo Oil	Reforming of clean gasoline	2003
Yokohama, Kanagawa	Nippon Oil	Naphtha reforming	2003
Ariake, Tokyo	Iwatani Intl. Corp. & Showa Shell Sekiyu KK	N/A	2003
Kawasaki City, Kanagawa	Japan Air Gases	Methanol reforming	2003
Senju, Tokyo	Tokyo Gas & Taiyo Nippon Sanso	LPG reforming	2003
Hadano, Kanagawa	Idemitsu Kosan	Kerosene reforming	2004
Sagamihara, Kanagawa	Kurita Water Industries, Itochu Enex & Shinanen	Water electrolyses	2004
Ome, Tokyo	Babcock Hitachi & Taiyo Nippon Sanso	Natural gas reforming	2004
Seto-South, Aichi	Toho Gas & Taiyo Nippon Sanso	Natural gas reforming	2005
Seto-North, Aichi	Nippon Steel & Taiyo Nippon Sanso	Natural gas reforming	2005

3.4.4 China

China has recently become one of the largest potential markets for hydrogen fuel cell use, primarily in the transport sector. Research and development in hydrogen and fuel cell technologies have been pushed by the central government's commitment to reduce air pollution emissions from transportation and enhance energy security. The number of automobile sales in China has increased dramatically in recent years and it is expected that about one in ten Chinese people will own a car by 2020. The booming domestic car market will offer a unique opportunity to push fuel cell development in China.

Research on fuel cells in China started in the mid-1950s. For example, The Dalian Institute of Chemical Physics under the Chinese Academy of Science (CAS) embarked on fuel cell research in 1957. This institute successfully developed two types of alkaline fuel cell systems. More research investment on fuel cell vehicles was launched in the '863' science and technology program in 1986, leading to the release of many prototypes of hydrogen fuel cell vehicles in 1990s-2000s. Hydrogen-fuelled car, ChaoYue III was released in 2006 in China, with maximum speed of 122km/h

and a range of 230 km (HyWeb, 2006). The first fuel cell bus in China was developed through a joint development and manufacturing of Shanghai Jiaotong University, Shanghai based fuel cell company Shenli High Tech Co. and Chinese automaker Suzhou King Long. The Chinese government has joined the CUTE project to test hydrogen-powered buses in Beijing. The pilot test of six fuel cell buses is also undertaken in Shanghai. There are two refueling stations in Beijing and Shanghai. Beijing Hydrogen Park, opened in 2006, is a demonstration site for new energy development. It was supported by the United Nations Development Program (UNDP)/the Global Environment Facility (GEF) and Minister of Science and Technology, Chinese government. Most hydrogen in the program is produced from natural gas. Several sustainable development programmes are exploring production of hydrogen from renewable energy resources in China.

Four Chinese fuel cell technology companies have emerged over the past few years, including the Dalian Sunrise Power Company, the Beijing Fuyuan Century Fuel Cell Power Ltd., the Beijing Green Power Company, and Shanghai Shen-Li High Tech Co. Ltd. Shanghai Tongji University is leading in the fuel cell car project and Tsinghua University in Beijing is leading the bus project under 863 fuel cell vehicle program (Qian *et al.*, 2008). More international companies have also been attracted to join in fuel cell development in China. Palcan Fuel Cells of Canada has a joint venture with Shanghai Mingliang Plastic Co. to manufacture about 20,000 PEM fuel cell stacks each year. Meanwhile, Taiwan Fuel Cell Partnership has also been created to promote fuel cell development. General Motors signed a cooperation memo with Shanghai Automotive Industry Company on fuel cell vehicles, while Volkswagen has collaborated with Tongji University on fuel cell vehicles too. International collaboration helps not only to reduce R&D cost, but also to expand global market opportunities more rapidly.

4. Conclusion

Under the energy crisis and global warming challenge, there is urgent need to develop green vehicles with zero emissions to replace a large fraction of gasoline cars. Electric cars or hydrogen cars will only be practical until they offer performance comparable with that of conventional combustion engine cars. The promising new technologies (electric car or hydrogen car) haven't transited from the labs to the large commercial scale in reality yet. Major large auto-markers have been seeking to develop new and more fuel-efficient green vehicles. What is the potential of the new green vehicles under uncertain oil price and a big financial recession? It seems that the hydrogen vehicle is still a "dream" for a long time and it has to give way to the hybrid electric vehicle as realistic solution. The study by Demirdoven & Deutch (2004) indicated that fuel cell vehicles using hydrogen from fossil fuels offer no significant energy advantage over hybrid vehicles operating in an urban drive cycle. They suggested the industry and government to give priority to develop hybrid vehicles, as reduction in imported oil and carbon dioxide emissions can be achieved more quickly by the hybrid car rather than fuel cell hydrogen car: "Hybrid cars now, fuel cell cars later".

Hydrogen and fuel cell technologies promise considerable benefits in terms of energy security and CO₂ emission, but they require significant technical breakthroughs, cost reduction and appropriate policies to enter the energy market (OECD, 2005). Fuel cell and hydrogen energy is highly fragmented (RNCOS group, 2008). The deployment of

hydrogen fuel cell vehicles faces a “chicken-or –egg” problem. No demand without infrastructure investment and no investment in expensive infrastructure without demand (OECD, 2005). Deployment of hydrogen infrastructure needs international co-operation, supportive policies and large-scale practice. The application of hydrogen in public service fleets (i.e. bus) is vital step towards the hydrogen economy in the future. Hydrogen is likely to conquer a significant market share only if effective policies for CO₂ mitigation and energy security are in place and with considerable reductions of hydrogen and fuel cell cost.

Larger scale electrification in conjunction with plug-in hybrid vehicles and li-ion batteries will lead to re-consideration of the role of electricity in transport (OECD, 2005). The global electric car battery market is growing as cars near production. A global recession depressed oil prices to around \$40 per barrel in December, 2008 causing some to question the plans of automakers investing significant time and money in the hybrid and electric car market. But small signs of an upturn in 2009 from an economic trough have boosted prices back above \$70 per barrel and have given battery makers and their suppliers hope. The achievement of good performance in terms of long range and good acceleration depends on the availability of high energy and high power batteries. The current battery technology is still not powerful enough to allow the widespread diffusion of electric cars. Recently, hybrid electric cars are emerging as a more realistic vehicle. It appears as a compromise in the transit from polluting combustion engine cars to controlled emission hybrid vehicles.

Governments across the world are enthusiastic about green innovation, not only developed countries but also the developing countries. LG Chem of South Korea is becoming one of the world’s key producers of Li-ion batteries for automotive use. REVA, the Bangalore-based Indian electric-car maker entered global electric car market after it announced its plan to build new manufacturing plants in the US. The E6 is a maker that China expects to dominate in energy storage technologies. It could become much more important if the world makes a significant shift towards green vehicles. The Chinese manufacturers have the opportunity to leapfrog traditional technologies and to gain a leading position in terms of new energy cars. These emerging flagship companies have attracted global attention on various occasions and rang a warning bell “Who is the next winner in the race of green economy, US, EU or China?” This is the challenge namely how government support could help to combat global climate change and boost regional economic growth via green innovation.

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