PLUG-IN HYBRID ELECTRIC VEHICLES FOR JAPAN
OPPORTUNITIES, EFFECTS, EFFICIENCIES AND BARRIERS

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This evaluation is based on recent publications by the author. [Hori 2005A, 2005B, 2006A, 2006B, 2006C, 2007A and 2007B]. Data from the Ministry of Land Infrastructure and Transport, Japan (MLIT) are used to define an average behavior of target motor vehicles (personal-use passenger vehicles, called 'Registered' vehicles and 'Light' vehicles). The methodology used for the analysis is similar to the one used by Uhrig [Uhrig 2005A and 2006B] in his evaluation for the United States.

1. OPPORTUNITIES IN JAPAN

Situation of Automotive Fuels and Electric Power in Japan

Japan imports about 96% of its energy from abroad, including 99.7% of its petroleum, of which 89.5% is from the Middle East, 96.5% of its natural gas, and 99.2% of its coal (FY2003-2004).

The transportation sector consumes about a quarter of the final energy in Japan. Most of the consumption is petroleum fuels (98% in FY2000) such as gasoline or kerosene used for automobiles which consume 87% of the transportation sector energy.

In Japan, electricity, similarly to the transportation sector, makes up a quarter of final energy. Electricity in Japan, however, is generated from nuclear 31.5%, coal 25.4%, natural gas 24.0%, petroleum 10.3%, and hydro 8.4% (2005 statistics). Thus, in the power generation sector, the dependence on fossil fuels has decreased to about 60%. Hence, the security of the energy supply and the reduction of CO2 emission are being improved by decreasing the petroleum and carbon fuel consumption.

Therefore, if automobiles are powered by electricity by using plug-in type vehicles, the energy supply to the transportation sector can be diversified to become less dependent on petroleum. Along with the increase of plug-in vehicles in the future, the new electric demand for charging the batteries would hopefully be supplied by nuclear power, thus making the energy supply more secure and reducing CO2 emission in Japan.

Driving Patterns of Japanese Passenger Vehicles

There are about 77.4 million vehicle altogether in Japan. From the size and the driving pattern of vehicles, the categories suitable for the plug-in hybrid electric vehicles are the personal-use, passenger vehicles, of which number are 54.4 million vehicles as of 2003. They are classified into the 'registered' vehicle, which are ordinary sized cars, and the 'light' vehicles, which are smaller sized cars with engine under 660 cm^3 and have some benefits in tax and in other costs.

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The average daily travel distances of these categories of vehicle are estimated from the statistical survey data by the MLIT on the relationship of passengers carried with distance band.[2]

From the figure on the driving pattern of Japanese passenger vehicles (Fig. 1), it is presumed that the 50% of Japanese vehicles are driven less than about 20 Km (18 Km for the light vehicles and 22 Km for the registered vehicles). The average daily travel distance of Japanese vehicles is about 1/1.6 of that of US light vehicles, which is about 20 miles or 32 Km.

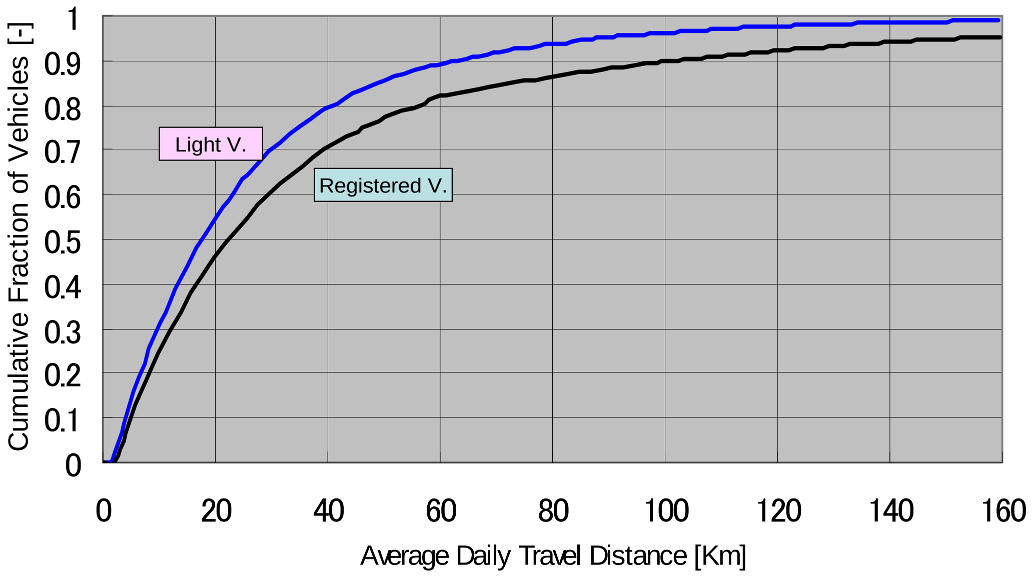

Fig.1 Driving Pattern of Japanese Passenger Vehicles
Registered and Light Vehicles for Personal Use

Expectation for Plug-in Hybrid Electric Vehicles in Japan

As the self-sufficient ratio of energy is very low currently in Japan, shifting the energy for transportation sector into nuclear energy, though it takes long time, would be indispensable for her energy security. To realize the nuclear energy supply for transportation, there may be ways such as by plug-in type vehicles, hydrogen fuel cell /combustion engines, or synthetic fuels. Among them, introduction of plug-in hybrid vehicles into market is expected to be the most realistic and lead-off way for this purpose.

As the weight of vehicle is lighter and the daily travel distance of vehicle is shorter in Japan as compared to the U.S., especially for the category of 'light vehicle', it would be easier to introduce plug-in hybrid vehicles in Japan because a small battery could give a larger electric run fraction.

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[2] As the data on the relationship of fraction of vehicles with average daily travel distance are not available from the MLIT at present, the derived relationship should be confirmed or corrected, if necessary, by more direct data when available.

2. EFFECT OF ‘PHEV’ INTRODUCTION IN JAPAN

Effect of introducing the plug-in hybrid electric vehicles (PHEV) in Japan is evaluated for the category of personal use passenger vehicle.

Target Vehicles for Evaluation

The passenger cars are classified into two categories in Japan: the ‘registered’ vehicle and the ‘light’ vehicle. Typical statistical data of these vehicles are shown in Table 1, which are derived from the 2003 Report by the Ministry of Land Infrastructure and Transport, Japan (MLIT).

Table 1 Data Used for Evaluation of PHEV

	Registered Vehicles	Light Vehicles
Number of cars	42,620,000	11,820,000
Average distance traveled per day worked per car, km	40.7	27.9
Working ratio *	66.9	72.7
Average distance traveled per day per car, km	27.2	20.3
Average distance traveled per year per car, km	9,900	7,400
Fuel consumption per car per Km **, liter/km	0.12	0.09

* Working ratio＝(Working days x cars / Existing days x cars) x 100

** Gasoline engine

Methodology and Input Data

The methodology and most of the parameters used are similar to the U.S. analysis. (Uhrig, 2005A and 2005B)

Following are different points from the U.S. analysis;

- The average electric run fraction is estimated from the statistical data by the MLIT.
- The tank-to-wheel efficiency for ICEV is based on the information from Toyota Motor Company.

Input data used for the evaluation are as follows[1];

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[1] Abbreviations

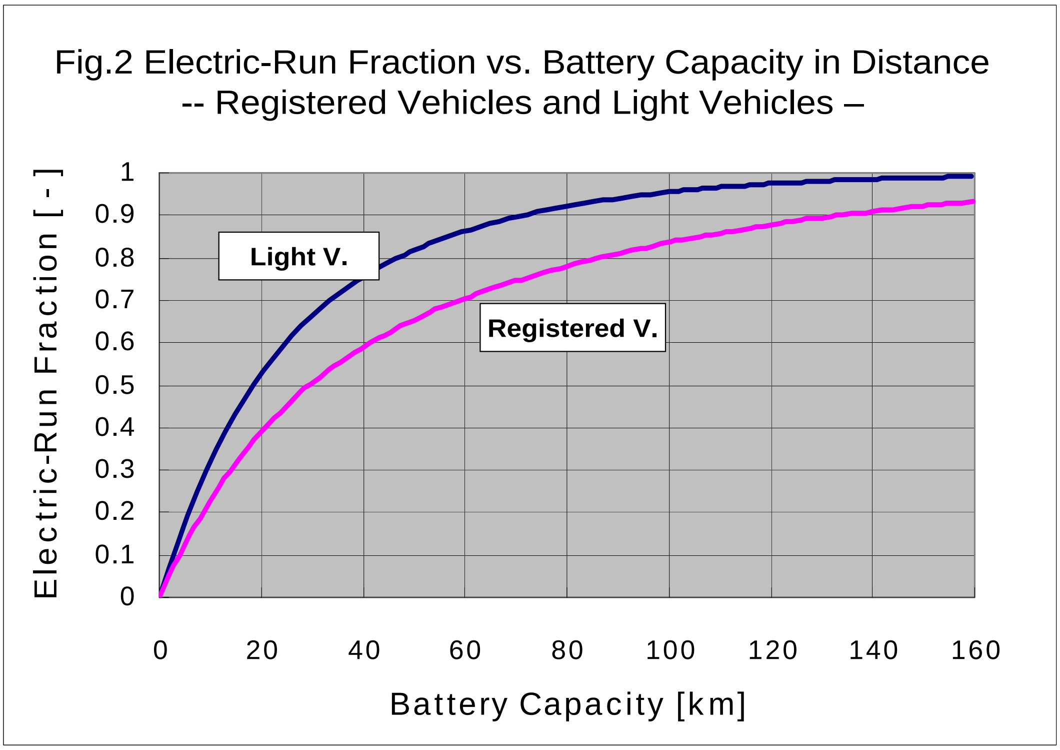
ICEV: Internal Combustion Engine Vehicle
PHEV: Plug-in Hybrid Electric Vehicle
HEV: Hybrid Electric Vehicle or Gas Electric Vehicle
BEV: Battery Electric Vehicle
FCV: Hydrogen Fuel Cell Vehicle

- Tank-to-wheel efficiency for ICEV: 16%
- Battery-to-wheel efficiency for PHEV: 70% (Adding 15% to the required energy due to the extra weight for PHEV)
- Gasoline price: 122 Yen/liter including the gasoline tax of 53.8 Yen/liter.
- Electricity price: 10 Yen/kWh (Typical price of the midnight special fee for 11pm to 7am including the basic charge)
- CO_2 Emission for gasoline: 2.32 Kg-CO_2/liter gasoline (Guideline by Ministry of Environment)
- CO_2 Emission for electric power: 0.381 Kg-CO_2/KWh (Performance data of Tokyo Electric Power Company in 2004)

Electric Run Fraction

In this evaluation, the average daily travel distance is estimated from the statistical survey data by the MLIT on the relationship of passengers carried with distance band for these categories of vehicle as described in Chapter 1, and in Fig. 1 is shown the cumulative fraction of vehicles with average daily travel distance for the two categories of vehicles.

Average fraction, by distance, of traveling in the electric vehicle mode (electric-run) relative to capacity of equipped battery can be estimated from the relation of Fig. 1. The obtained relation on average electricity-run fractions is shown in Fig.2 for the registered vehicles and the light vehicles. From the figure, it is estimated that 70% of electric-run fraction by distance can be obtained by installing a battery of traveling capacity of about 60km for the registered vehicles and about 35 km for the light vehicles.



Running Cost

The running costs of ICEV, PHEV in the electric-run mode, and PHEV in the mixed electric-run/hybrid-electric mode are evaluated and compared as follows;

The running costs for registered vehicles are;
- ICEV: 14.6 Yen/km
- PHEV in the electric-run mode: 3.0 Yen/km
- PHEV in the 70% electric-run mode and 30% hybrid-electric mode: 4.3 Yen/km

The running costs for the light vehicles are;
- ICEV: 11.0 Yen/km
- PHEV in the electric-run mode: 2.3 Yen/km
- PHEV in the 70% electric-run mode and 30% hybrid-electric mode: 3.2 Yen/km

The running cost of PHEV in the electric-run mode is about 1/5 of gasoline ICEV, and the running cost of PHEV in the 70% electric-run mode and 30% hybrid-electric mode is 1/3.4. If the gasoline tax is excluded, this ratio becomes about 1/2.7.

CO_2 Emission Reduction

The CO_2 emissions of ICEV, PHEV in the electric-run mode, and PHEV in the mixed electric-run/hybrid-electric mode are evaluated and compared as follows;

The CO_2 emissions for registered vehicles are;
- ICEV: 0.278 Kg-CO_2/Km
- PHEV in the electric-run mode: 0.115 Kg-CO_2/Km
- PHEV in the 70% electric-run mode and 30% hybrid-electric mode: 0.122 Kg-CO_2/Km

The CO_2 emissions for the light vehicles are;
- ICEV: 0.209 Kg-CO_2/Km
- PHEV in the electric-run mode: 0.087 Kg-CO_2/Km
- PHEV in the 70% electric-run mode and 30% hybrid-electric mode: 0.092 Kg-CO_2/Km

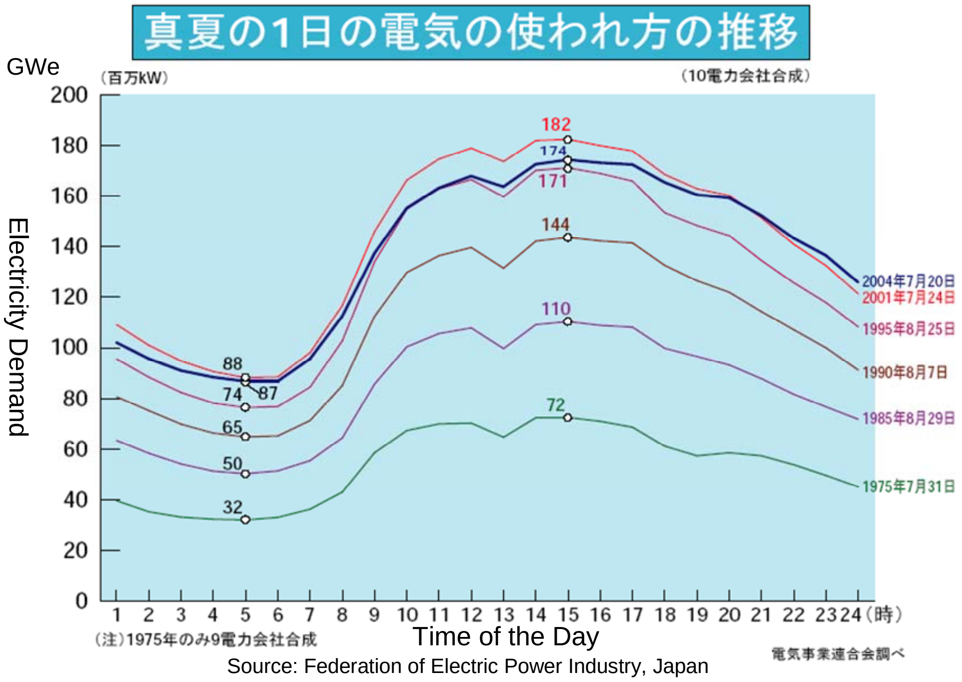
The CO_2 emission of both PHEV in the electric-run mode and PHEV in the 70% electric-run mode and 30% hybrid-electric mode is about 1/2.4 of gasoline ICEV.

Electric Power Requirement

If all the vehicles (both registered vehicles and light vehicles, total 54 million vehicles) become PHEV in the 70% electric-run mode, the total electricity requirement for 8 hr charging is about 35 GW (35 units of 1,000 MW plant). Since there is about 50 GW difference between the peak hours and the midnight hours currently in Japan, the power for all PHEV could be supplied by the spare power (Fig.3).

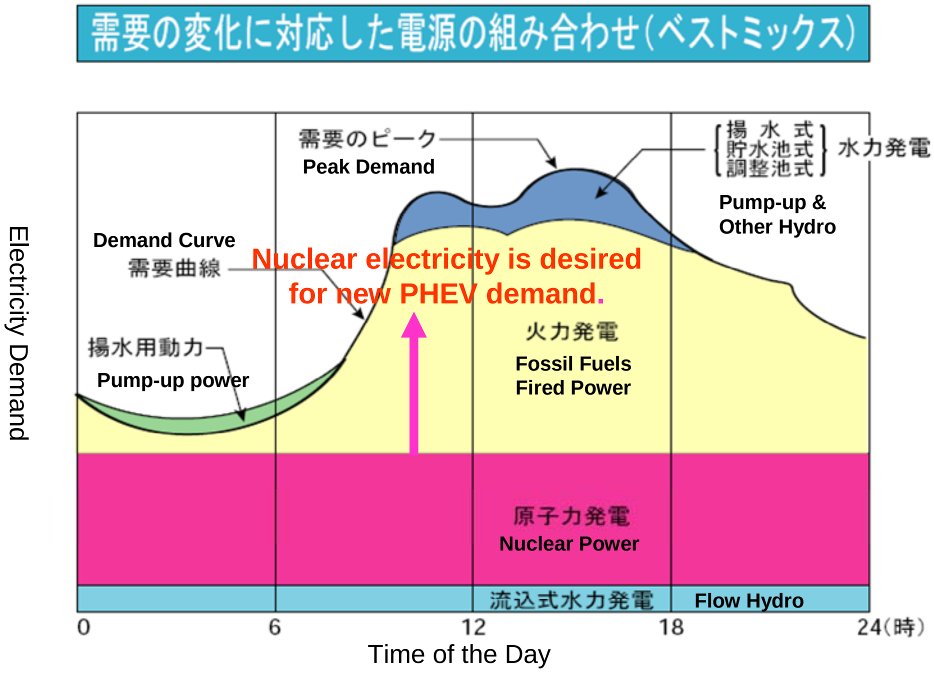
Since nuclear power is presently used as the base load in Japan, the additional power requirements would have to be supplied by operating the fossil fuel plants at night. For energy security and global environment, it is better to shift the power supply structure, in the course of introducing PHEV, to more nuclear share by replacing the fossil fuels plants by new nuclear plants (Fig.4).

Fig.3 Trend of Electricity Demand by the Time in a Midsummer Day
Sum of 10 Utility Companies in Japan (1975~2004)



Source: Federation of Electric Power Industry, Japan

Fig.4 Best Supply Structure to Match the Change of Demand is Necessary

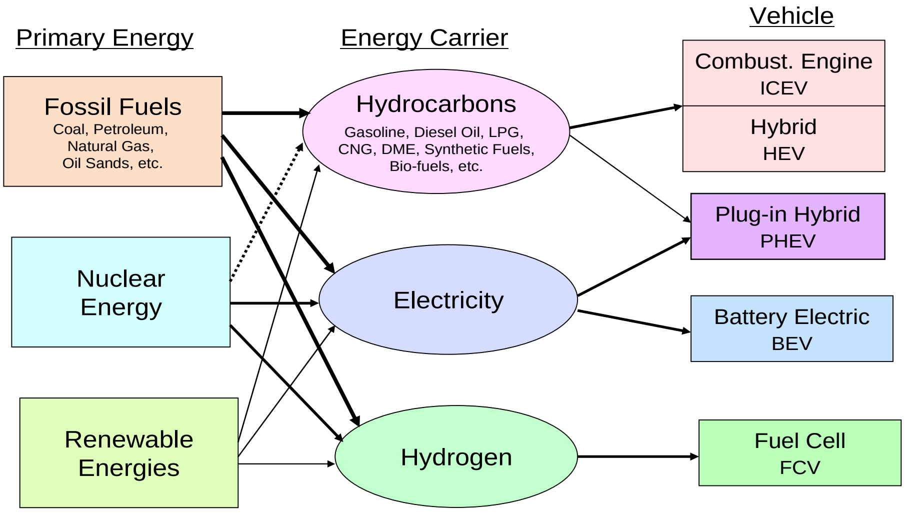


Source of original figure: Federation of Electric Power Industry, Japan. Modified by Masao Hori

3. ENERGY UTILIZATION EFFICIENCIES OF VARIOUS POWER TRAINS

Energy flow to the vehicles with various power trains, such as internal combustion engine vehicle (ICEV), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV) and hydrogen fuel cell vehicle (FCV) is shown in Fig. 5.

Fig.5 Energy Flows to Vehicles with Various Drive Trains



The ‘energy carriers’ such as hydrocarbons (gasoline, kerosene, etc.), electricity and hydrogen are produced from primary energies, such as fossil fuels, nuclear energy and renewable energies.

The energy utilization efficiencies of vehicles are usually expressed by the ‘Well-to Wheel’ (WTW) efficiencies, of which typical values are shown in Table 2.

Table 2 Energy Utilization Efficiency for Various Power Train Vehicles
‘Well to Wheel’ Efficiency -- Fossil Fuels

	Well to Tank Efficiency		Tank to Wheel Efficiency		Well To Wheel Efficiency	
Gasoline Engine Vehicle ICEV	Oil Field	88 %	Tank	16 %	Wheel	14 %
Gasoline Hybrid Vehicle HEV		88 %		32~37 %		28~32 %
Plug-in Hybrid Vehicle PHEV	Natural Gas Field	50 %	Battery	70 %		(29~30 %)
Battery Electric Vehicle BEV						35 %
H_2 Fuel Cell Vehicle FCV		58~70 %	Tank	50~60 %		29~42 %

- The values for ICE-V, HEV, FCV are from a Toyota Motors's 2003 presentation. The values for FCV are for the hybrid specification.
- Electric Power for B-EV is based on the natural gas ACC power generation of 55% thermal efficiency (LHV), 5% loss from well to station, and 5% loss for electricity transmission and distribution.
- EV battery-to-wheel efficiency is based on Uhrig (ANS, 2005).
- P-HEV adds 15% to the energy required by weight increase. P-HEV well to wheel efficiency is estimated for 75% EV run.

In this table, for gasoline engine driven vehicles the ‘well’ means the oil wells producing crude oils, and for battery powered electric vehicles and hydrogen fuel cell vehicles the ‘well’ means the gas fields producing natural gas.

From Table 2, the FCV has the highest efficiency and the BEV is the second highest. The PHEV efficiency would be somewhere between BEV and HEV.

The energy utilization efficiencies of nuclear energy base by the BEV and the FCV are shown in Table 3. (Hori 2006B) Here, the efficiencies from three kind of nuclear reactors are examined, namely LWR (Light Water Reactor, typical of low temperature reactors), SFR /SCWR (Sodium-cooled Fast Reactor / Super Critical Water Reactor, typical of medium temperature reactor), and VHTR (Very High Temperature Gas-cooled Reactor, typical of high temperature reactor).

As for the LWR based energy flow paths to vehicles, one path is the electricity from steam turbine generator of LWR being supplied to BEV, and the other is hydrogen from water electrolysis by the LWR electricity being supplied to FCV. As for the SFR/SCWR based energy flow paths to vehicles, one path is electricity from steam turbine generator of SFR/SCWR being supplied to BEV, and the other path is hydrogen from SFR/SCWR heated steam reforming of natural gas being supplied to FCV. As for the VHTR based energy flow paths to vehicles, one path is electricity from gas turbine generator of VHTR being supplied to BEV, and the other path is hydrogen from thermochemical splitting of water by VHTR heat being supplied to FCV.

Table 3 Energy Utilization Efficiency for Electric and Fuel Cell Vehicles
‘Nuclear Reactor to Wheel’ Efficiency

	Electricity / Hydrogen Vehicle Power Train	Efficiency Reactor → Battery/Tank	Efficiency Battery/Tank → Wheel	Overall Efficiency Reactor → Wheel
LWR	Steam Turbine BEV	30%	70%	21%
	Electrolysis FCV	23%	50~60%	12~14%
SFR, SCWR	Steam Turbine BEV	39%	70%	27%
	Nuclear-Heated Steam Methane Reforming FCV	77%*	50~60%	38~46%*
VHTR	Gas Turbine BEV	45%	70%	31%
	Thermochemical FCV	45%	50~60%	23~27%

- Thermal efficiency: For LWR steam turbine 32%, for SFR or SCWR 41% and for VHTR gas turbine 47%
- Efficiency of H_2 production: By electrolysis 80% (from electricity) and by thermochemical 50% (LHV)
- Efficiency of H_2 production by reforming 85% (* Based on the sum of both primary energies)
- Transmission & distribution loss for electricity: 5%, Compression & transportation loss for H_2: 10%

As shown in Table 3, in either the LWR or the VHTR case, the path to BEV is more efficient than the path to FCV. This is due to the following two reasons (Hori 2005B);

1. Both the electricity generation by turbine generator and the hydrogen production by electrolysis or thermochemical splitting of water have to go through the ‘heat engine’ cycle, where conversion efficiency is limited by thermodynamics law (the Carnot-cycle efficiency at the highest).
2. The drive train efficiency is higher in BEV (70%) than in FCV (50~60%).

Contrary to the above, in the SFR/SCWR case, the path to FCV becomes higher efficiency than the path to BEV, where hydrogen is produced by the process of nuclear-heated steam reforming of natural gas (methane). In this hydrogen production process, chemical energy of methane and nuclear heat is converted to chemical energy of hydrogen regardless of limitation of thermodynamic cycle efficiency. This is the same as in the case of hydrogen production from natural gas shown in Table 2.

In the case of nuclear-heated steam reforming of methane, it is inevitable that the process produces CO_2 though its amount is reduced about 30% as compared to the case of conventional methane-combusted steam reforming of methane.

A medium temperature reactor with outlet temperature 500 ~ 600 ºC, such as SCWR or SFR is the best suited for the membrane reformer hydrogen production method using Palladium (Pd) as membrane material. The Pd-membrane reformer has been developed by Tokyo Gas as a production method for hydrogen station (Shirasaki 2002 and Yasuda 2004). The nuclear-heated membrane reformer, combining the membrane reformer with nuclear reactor has been designed by Mitsubishi Heavy Industries, Ltd. and others and evaluated to be economically competitive or advantageous to the conventional methane-combusted steam reforming of methane (Tashimo 2003).

It can be concluded that, in the nuclear energy based energy flow to vehicles, the path to electric vehicle is more efficient than the path to hydrogen fuel cell vehicle, except the case of using hydrogen produced by nuclear-heated steam reforming of methane.

4. BARRIERS TO OVERCOME; THE BATTERY TECHNOLOGY

The battery technology, especially cost, durability and performance, is the most important barrier to be overcome for the commercialization of PHEVs.

In August, 2006, the Study Group on Next Generation Vehicle Batteries in the Ministry of Economy, Trade and Industry (METI), issued a report “Recommendations for the Future of Next-Generation Vehicle Batteries”. (The main text is written in Japanese. English summary is available.) [METI Study Group, 2006]

In the appendix of this report, the battery cost and the competitiveness of PHEV with ICEV and HEV are evaluated for setting the R&D goals of battery development. In Tables 4 and 5 are shown the battery cost and the competitiveness of PHEV with ICEV and HEV evaluated by the METI Study Group for setting the above R&D goals of battery development. The comparison was made on the sum of vehicle purchase cost and fuel/electricity cost for 10 year period of using a vehicle. One example on Prius-class vehicles shows that, for the PHEV to become comparable with ICEV and HEV, it is necessary to reduce the cost of lithium-ion battery from the present cost (200 K Yen/kWh) by a factor of about 7 (30 KYen/kWh).

This example shows that intensive efforts toward development of battery technology are necessary for the introduction of economically competitive PHEVs into the market. The report recommends that, for introducing PHEVs around 2015, it is necessary to conduct a battery development project that is completed by about 2010.

Table 4 Action Plan for Next Generation Battery Technology Development
Approximation for Setup of Cost Target for Light Vehicles [METI Study Group, 2006]

	ICEV Gasoline Engine Light Vehicle *(Reference)*	BEV Limited Purpose Commuter Battery Range 80Km Year 2010	ICEV Gasoline Engine Light Vehicle *(Reference)*	BEV Personal Commuter Battery Range 150Km Year 2015
	For Business 18,000Km/Year		For Personal 7,000Km/Year	
10 Year Total Cost	2,260 KYen	2,380 KYen	1,490 KYen	1,710 KYen
Vehicle Cost	1,000 KYen	2,200 KYen	1,000 KYen	1,650 KYen
Battery Cost		*Cost 1/2* 800 KYen		*Cost 1/7* 450 KYen
Base Vehicle Cost		1,000 KYen		1,000 KYen
Other Cost		400 KYen		200 KYen
10 Year Gasoline/Electricity Cost	1,260 KYen	180 KYen	490 KYen	70 KYen

Gasoline:	Gasoline Consumption 20Km/L	Gasoline Price 140 Yen/L
Electricity:	Electricity Consumption 10Km/KWh	Electricity Rate 10 Yen/KWh

Table 5 Action Plan for Next Generation Battery Technology Development Approximation for Setup of Cost Target for Registered Vehicles [METI Study Group, 2006]

	ICEV Gasoline Engine Passenger Vehicle *(Reference)*	HEV High Performance Hybrid Year 2010	PHEV 40 Km Battery Cruising Range Plug-in Hybrid Year 2015	BEV 480Km* Battery Cruising Range Full-fledged Electric Vehicle Year 2030
	10,000Km/Year			
10 Year Total Cost	2,630 KYen *	2,650 KYen	2,650 KYen	2,580 KYen
Vehicle Cost	1,700 KYen *	2,300 KYen *	2,400 KYen	2,500 KYen
Battery Cost		*Cost 1/2* 100 KYen	*Cost 1/7* 120 KYen	*Cost 1/40* 200 KYen
Base Vehicle Cost		1,700 KYen	2,000 KYen	2,000 KYen
Other Cost		500 KYen	280 KYen	300 KYen
10 Year Gasoline/Electricity Cost	930 KYen	350 KYen	Electricity 40 KYen Gasoline 210 KYen	83 KYen

* Revised from the original figure for consistency

Gasoline: Gasoline Consumption ICEV 15 Km/L Gasoline Price 140 Yen/L
Gasoline Consumption HEV 40 Km/L Gasoline Price140 Yen/L

Electricity: Electricity Consumption PHEV 10 Km/kWh Electricity Rate 10 Yen/L
Electricity Consumption EV 12 Km/kWh** Electricity Rate 10 Yen/L
(** As of Year 2030)

Battery Capacity: HEV 1 kWh
PHEV 4 kWh
(Gasoline Running 60%, Electricity Running 40% by Distance)
EV 40kWh

Based on these evaluations, the METI Study Group recommended two action plans for the future of next-generation vehicle batteries, namely the R&D Strategies and the Infrastructure Building Strategies.

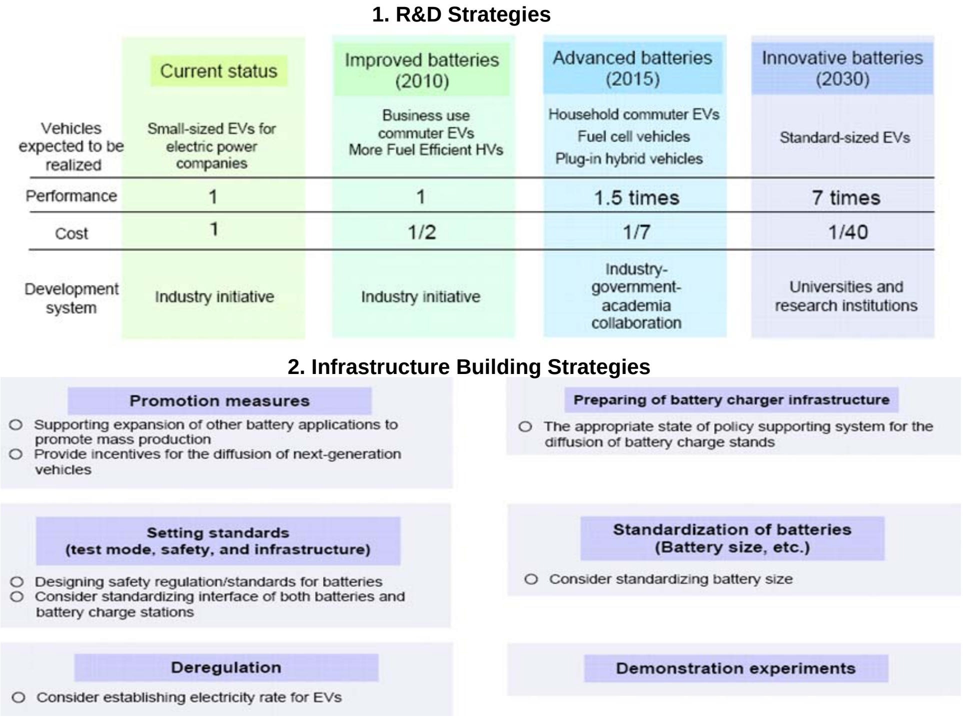
(1) Action Plan – R&D Strategies

The action plan of R&D Strategies is composed of three phases – (i) Improvement phase, (ii) Advanced phase, (iii) Innovation phase. At each phase specified are the types of vehicles expected to be developed, performance and cost target of batteries, and role of industry, government and academia.

As shown in Table 6 and 7, the PHEV is supposed to be introduced around 2015 with a battery of 1.5 times performance and 1/7 cost of current battery.

To implement this action plan, budget for FY2006 is about 2 BYen and budget for FY2007 will be about 5 BYen. New Energy and Industrial Technology Development Organization (NEDO) will be the secretariat for coordinating universities, research institutes, automobile manufacturers, battery manufacturers, material manufacturers, and electric power companies.

Table 6 Japan's battery development action plan [METI Study Group, 2006]



1. R&D Strategies

	Current status	Improved batteries (2010)	Advanced batteries (2015)	Innovative batteries (2030)
Vehicles expected to be realized	Small-sized EVs for electric power companies	Business use commuter EVs More Fuel Efficient HVs	Household commuter EVs Fuel cell vehicles Plug-in hybrid vehicles	Standard-sized EVs
Performance	1	1	1.5 times	7 times
Cost	1	1/2	1/7	1/40
Development system	Industry initiative	Industry initiative	Industry-government-academia collaboration	Universities and research institutions

2. Infrastructure Building Strategies

Promotion measures

○ Supporting expansion of other battery applications to promote mass production

○ Provide incentives for the diffusion of next-generation vehicles

Preparing of battery charger infrastructure

○ The appropriate state of policy supporting system for the diffusion of battery charge stands

Setting standards (test mode, safety, and infrastructure)

○ Designing safety regulation/standards for batteries

○ Consider standardizing interface of both batteries and battery charge stations

Standardization of batteries (Battery size, etc.)

○ Consider standardizing battery size

Deregulation

○ Consider establishing electricity rate for EVs

Demonstration experiments

(2) Action plan – infrastructure building strategies

This action plan is to be implemented along with the battery R&D plan, and is composed of building software and hardware infrastructures such as incentive measures for vehicle popularization, regulatory framework, standardization, safety standard and battery charge stations, as shown in Table 6. The Secretariat of this action plan will be the Japan Automobile Research Institute (JARI) and METI.

Table 7 Research and Development, Action Plan for Next Generation Battery Technology Development [METI Study Group, 2006]

	Phase	Time	Target Vehicle Type	Goals of Battery		
				Performance	Cost	Required R&D Items
１	Improvement	ca. 2010	Limited Purpose Commuter BEV Battery Range 80Km, 2 Seater	Same as Present 100Wh/Kg 1000W/Kg	1/2 of Present	Li-ion Battery Carrier: N.R. Material: P.R. Design: R.
			High Performance Hybrid HEV Fuel Economy 30% Up	Same as Present 70Wh/Kg 2000W/Kg	1/2 of Present	
２	Advanced	ca. 2015	Commuter BEV Battery Range 150Km, 4 Seater	1.5 Times of Present 150Wh/Kg 1200W/Kg	1/7 of Present	Li-ion Battery Carrier: N.R. Material: R. Design: R.
			Plug-in Hybrid Electric PHEV Battery Range 40Km	1.5 Times of Present 100Wh/Kg 2000W/Kg	1/7 of Present	
３	Innovative	2030~	Full-fledged Electric BEV Battery Range 480Km	7 Times of Present 700Wh/Kg 1000W/Kg	1/40 of Present	New Principle Battery Carrier, Material and Design: All Required

N.R.= Not Required, P.R.= Partly Required, R.= Require

Present Status：Li-ion battery for EV 100Wh/Kg
400W/Kg
Present Status：Li-ion battery for HV 70Wh/Kg
1800W/Kg

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