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Configuration of solar-hydrogen mild hybrid fuel cell power systems for electric vehicles

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ABSTRACT

This paper considers the evaluation of a configuration of solar-hydrogen mild hybrid fuel cell power systems for electric vehicles. The primary objectives are to relieve the prerequisite need on the infrastructure for hydrogen supply and reduce the cost of fuel cell module compared to the conventional fuel cell electric vehicles. The advantage of the proposed vehicle power system configuration is addressed in terms of the criteria of availability and affordability. Availability considers issues of energy resource and engineering technology. Affordability considers issues of operational cost and environmental cost. With regard to issues of implementation, a cost-benefit ratio is defined and used to evaluate the feasibility of the proposed mild hybrid power systems. A demonstration is conducted based on four exemplary vehicles. The value of the computed cost-benefit ratio can be used to determine the suitability of implementation of the proposed configuration of a hybrid power system for electric vehicles. The presented costs are based on per/unit prices as cited by manufacturers on the Internet and are useable guidelines for further development. In actual practice, substantial further efforts would be needed to facilitate safe, reliable cost-efficient operation of the proposed system.

1. Introduction

Due to limited fossil fuel reserves and the detrimental ecological effects of burning fossil fuel to produce power on a global scale, the development of sustainable energy sources has become a critical issue for the global community and a common concern of enterprises and governments all over the world. Hydrogen possesses the merits of non-toxic and contains most energy per unit mass. Regardless of whether used to produce power by conventional burning processes or fuel cell devices, production of power by use of hydrogen does not produce the notorious greenhouse gasses carbon dioxide and methane, nor air pollutants such as carbon monoxide.

Motivated by increasingly rigorous emission standards, vehicle manufactures are attempting to improve the efficiency of the traditional internal combustion engine (ICE) and are also striving to develop electrically driven vehicles, including various hybrid electric vehicles (HEV), pure battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). However, the charging energy needed for electric vehicles is typically provided from large urban or national power plants, which typically burn conventional fossil fuels. A large number of electric vehicles recharging by such means would dramatically increase the loading of electric transmission lines and tax the generating capacities of the power plants. Currently, advanced vehicles using alternative fuels are costly and the resulting gasoline savings generally cannot offset the high development and implementation expenditures. However, costs are expected to decrease dramatically with production volume and technological progress [1].

The usage of hydrogen and fuel cell technologies as alternative energy sources or vehicle-carried power systems is still not popular, largely because of the high cost of fuel cells and problems regarding the availability, storage and transportation of hydrogen. Though substantial research and investment have been directed toward exploration and demonstration programs for hydrogen and fuel cell applications, commercialization of fuel cell electric vehicles will not be realized before 2020, as estimated in Ref. [2]. If the threshold for utilization of hydrogen and fuel cell technologies can be lowered such that production and proliferation of the technologies can be increased, then unit cost can be reduced, techniques improved and mass commercial implementation can be achieved sooner. Serious international research is focused on this goal. For example, a demonstration program featuring a fuel cell hybrid bus featuring a battery-heavy hybrid design was shown recently to offer multiple advantages in terms of cost, performance and durability [3].

Because of global concern regarding control of greenhouse gas emissions and the urgency of development of clean energy technologies, the government of Taiwan has endeavored to promote electric vehicle development. For example, according to the

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"Development Strategies and Action Plans for Intelligent Electric Vehicles" announced on April 15, 2010, by the Taiwan Ministry of Economic Affairs, Taiwan, will have ten electric vehicle demonstration areas established, each with at least 3000 electric vehicles, by the end of the year 2013. The conducted projects will include related infrastructure, charging stations and operational model appraisal.

As pointed out in Ref. [4], hydrogen from renewable energy provides an elegant and complementary solution to the hydrogen energy system. As stated in Ref. [5], renewable energy utilization in hydrogen production can provide environmentally responsible alternatives to conventional energy system, as well as more flexibility and decentralization. As in the investigation of Ref. [6], a FCEV with rooftop photovoltaics can provide nearly 40% less in hydrogen consumption, as compared to a simple FCEV.

This paper proposes a solar-hydrogen mild hybrid fuel cell power system configuration for the electric vehicles. If electricity is acquired photovoltaically from solar panels mounted on the roof of the electric vehicle and then transformed into hydrogen via an electrolyzer, the prerequisite of establishing an infrastructure of hydrogen supply facilities can be removed. In terms of the usage of a mild hybrid fuel cell configuration for power systems, the installation cost for the required fuel cell devices can be substantially reduced. On the other hand, the hydrogen storage produced from the solar power via the electrolyzer is expected to be fully utilized by the fuel cell with a comparatively smaller power rating than the fuel cell that would be needed to provide full rating power for the vehicle. Therefore, through this operation strategy for hydrogen and fuel cell related technologies, the usage threshold can be reduced and the objectives of application promotion and cost reduction can be achieved.

The rest of this work is organized as follows. Section 2 describes the various types of power system structures for hybrid electric vehicles. The proposed solar-hydrogen mild hybrid fuel cell power system for electric vehicles is introduced in Section 3. In Section 4, analysis and comparison of the power systems including the proposed hybrid configuration are performed in terms of the criteria of availability and affordability. Section 5 presents a cost-benefit evaluation of four commercial exemplary vehicle models, which manifest the implementation issues of the proposed power configurations. Final conclusions are summarized in Section 6.

2. The various power system configurations of hybrid electric vehicle

In ICE-battery hybrid electric vehicles, the mechanical energy from the ICE is used as the main power source and electrical energy supplied from the battery serves as auxiliary power. According to the scale of the electrical energy extracted from battery and the functions executed by this energy, hybrid electric vehicles can be categorized as micro hybrid, mild hybrid and full hybrid.

In micro HEVs, the engine is turned off when the vehicle brakes to a complete stop. The vehicles are designed to restart the engine automatically when the brake pedal is released. Therefore, the battery needs to support the energy used for the starter's intermittent operation. As shown in Table 1, the typical battery capacity is about 0.5 kWh, which is only moderate larger than that used in a conventional ICE sedan vehicle.

In a mild HEV, the battery not only functions for the engine restart operation but also for extra auxiliary power provision to improve driving performance. Moreover, the battery is used as an energy storage device during the process of recharging from regenerative braking to raise the efficiency of fuel usage.

In full HEVs, the battery capacity and electric motor power rating are designed to be able to serve as the sole power source for the vehicle's cruising. In order to the increase vehicle's battery-powered driving range, the battery is allowed to be recharged from external electrical sources. This type of vehicle is designated a plug-in hybrid electric vehicle (PHEV). According to the definitions of the Energy Independence and Security Act issued by the United States in 2007, the battery capacity of a PHEV needs to be at least 4 kWh. Based on the definitions of the Institute of Electrical and Electronic Engineers (IEEE), a PHEV-10 type is required to drive for at least 10 miles = 16 Km under pure electric operation. Similarly, a PHEV-40 type has the capability of driving 40 miles = 64 Km using only the battery. The various types are summarized in Table 1, with the battery price estimates based on a figure of 1333 US$ kWh^{-1}.

Table 1
The battery capacity and price estimate of various types of hybrid electric vehicles [7].

Types of hybrid EVs	Capacity of Li-iron battery (kWh)	Prices estimation of advanced battery (US$)	Typical models
Micro hybrid	0.5	667	SMART, Fortwo
Mild hybrid	1	1333	HONDA, Insight
Full hybrid	1.5	2000	TOYOTA, Prius
PHEV-10	5	6665	TOYOTA, Prius
PHEV-40	16	21,328	GM, Chevrolet Volt

The considered capacity efficiency of a battery, η_{bat}, is defined as the driving distance per unit kilowatt-hour, i.e. Km kWh^{-1}. For the PHEV-10 listed in Table 1, the battery capacity efficiency is computed as 10 mile/5 kWh = 2 mile Wh^{-1} = 3.2 Km kWh^{-1}. For the PHEV-40 in Table 1, the battery capacity efficiency is 40 mile/16 kWh = 2.5 mile kWh^{-1} = 4 Km kWh^{-1}. The reasonable range of the battery capacity efficiency for a sedan vehicle can be estimated as 3.2–4 Km kWh^{-1}. For vehicle models different than the typical sedan vehicle, the actual battery capacity efficiency varies depending on the vehicle's size and power rating. It is expected that battery capacity efficiency will improve with progress in vehicle design and battery manufacture. In addition, it is expected that battery prices will be reduced due to the increasing usage of electric vehicles.

The FCEV type is mainly powered by a fuel cell. In such vehicles, an ICE is not equipped but a battery for buffering and storing of electric energy is still required. In the FCEV scheme, the fuel cell provides the main power source while the battery is only for power assistance in compensation for the fuel cell's reaction speed. The battery also serves as a steady power source for other electric instrumentation on board. The hydrogen consumed by the fuel cell must be supplied from outside. The battery can be optionally charged from external electrical facilities. Currently, the drawbacks of this power system structure include the high cost of the fuel cell and insufficient infrastructure for hydrogen supply.

3. Solar-hydrogen mild hybrid fuel cell power systems for electric vehicle

The proposed power system configuration for electric vehicles with solar-hydrogen mild hybrid fuel cell (SHMHFC) is illustrated in Fig. 1, where the red lines denote electric circuits and the boldfaced green lines denote hydrogen routes. The power system is composed of a main power source, i.e. a battery that can be recharged from an external charging station. There are two auxiliary power sources. In one case, electricity is provided directly from solar panels. In the other case, electricity from the solar panels is used to produce hydrogen via electrolysis. The hydrogen gas can then produce electric power in a fuel cell. The operation strategy is that, when the battery is in a low state of charge (SOC) status, the solar panels provide direct electric energy for battery charging. This maintains a higher efficiency for the photo voltaics (PV) system. However,

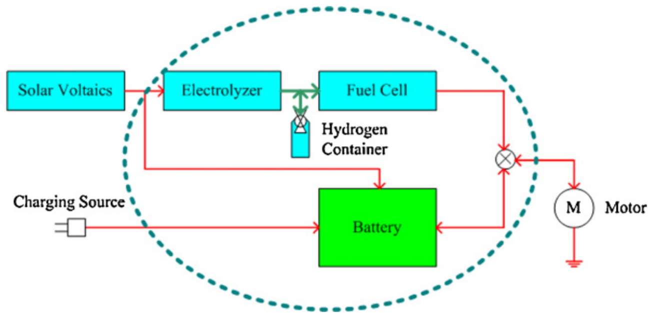

Fig. 1. Solar-hydrogen fuel cell mild hybrid power system structure for electric vehicles.

when the battery is near its full charge status, the electric energy from solar panel is switched to the electrolyzer, which produces hydrogen from water and stores it for later use as auxiliary power via a fuel cell for driving the electric motor.

The power system structure of the current FCEV systems is shown in Fig. 2a. The power system structure of current solar mild hybrid electric vehicle (SMHEV) systems is shown in Fig. 2b. Together, these can be considered as a simplified version of the investigated scheme. The structure in Fig. 2b possesses the merits of easy implementation and low cost. A limitation is that the solar panel can be used only for direct charge of the battery or to provide direct electric energy to the motor for usage while the motor is hard-wired to the solar panel. Typically, for daily commutating between home and work place, the vehicle might be used for only one hour per day and exposed to sunlight for more than ten hours per day. The extra energy produced by the solar panel can be stored as hydrogen gas and used by utilization of the proposed solar-hydrogen mild/micro hybrid fuel cell power system configuration. If the surplus energy collected from the solar cell can be properly transformed and stored, the fuel cell can serve as a separate electric power source independent of the battery,

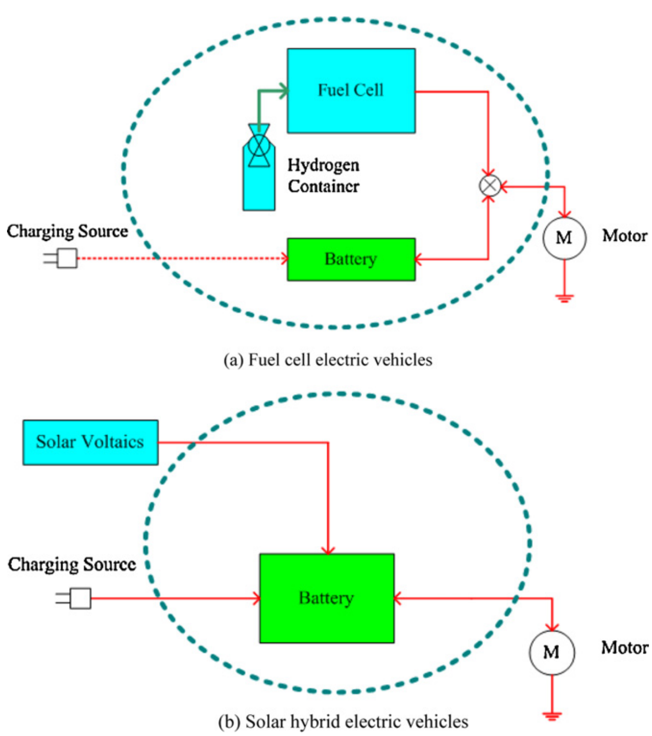

Fig. 2. Simplified schemes of the proposed power systems for electric vehicles.

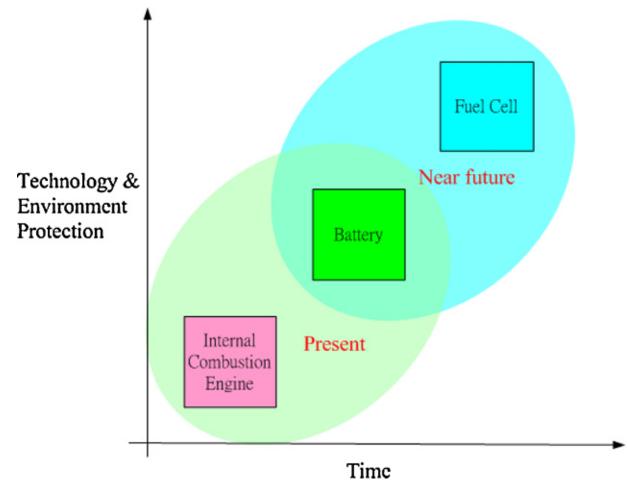

Fig. 3. Development trends of vehicles power sources.

extending driving range and providing supplemental power for additional speed and acceleration.

Fig. 3 shows the evolutionary trend of vehicular development in terms of technology and environmental protection. At present, vehicle power configurations involve mostly the ICE, ICE-battery hybrid or battery-only configurations. Use of the ICE-battery hybrid structure allows the fuel efficiency of an ICE to be improved via suitable charging and discharging operation of the battery. The opportunity to coordinate batteries of small capacity with the well-practiced ICE technology would tend to advance battery technological development, encourage the evolution of electric vehicle technology and lower the cost of installation and operation electric-based vehicular systems. Similarly, a hybrid configuration with the battery as main power source but assisted by a solar-hydrogen fuel cell can improve battery capability and also facilitate the progress of hydrogen and fuel cell technologies. Finally, solar panel technology has been making significant progress in terms of energy, cost efficiency and commercial availability. For example, flexible thin film solar panels have become available as customizable roof solar panels to fit the curvature and shape of specific vehicle models [8].

4. The analysis and comparison of the vehicle power system configurations

The composition of power sources in various types of vehicles is outlined in Table 2. The considered types include the fossil fuel vehicle (FFV) powered by ICE, the BEV driven solely by battery, the FCEV using fuel cell module as main power drive, the HEV and PHEV operated with hybrid power from ICE and battery as described in Section 2, and the proposed solar-hydrogen fuel cell electric vehicle (SHFCEV) mentioned in Section 3.

Table 2
The composition of power sources for various vehicle types.

Vehicle types	Main power	Auxiliary power	Remarks
FFV	ICE	(not equipped)	
BEV	Battery	(not equipped)	
FCEV	Fuel cell	Battery	
HEV	ICE	Battery	All the micro, mild, and full hybrid
PHEV	Either ICE or battery		Depending on the operation mode
SHFCEV	Battery	Fuel cell	Both the micro and mild hybrid

The various types of electric vehicles are evaluated according to the properties of availability and affordability. The aspect of availability is addressed in terms of availability of the consumed energy resource and the maturity of engineering technology. Affordability is characterized by the operational cost of the system, for both initial installation and ongoing maintenance, and also by the environmental cost that needs to be paid for use of the system, though perhaps not directly by the manufacturers or users.

As shown in Table 3, a scale of 5, ranging from −2 to +2, is used to rate each of the four considered criteria. According to the considered types of power system configurations, the scores for each level are comparatively set from the favorite 2 down to the least desirable −2. The score 0 denotes a neutral or medium condition for the considered power source on the specific criterion.

The conventional vehicular power configurations often rate contrastingly for criteria in the categories of availability and affordability. For example, a highly mature and long-term used engineering technology might also be excessively demanding of a given energy resource. Similarly, a power system with low operational costs may have excessively detrimental effects on the natural environment. Some of the criteria, on the other hand, may synergize. For example, the maturity of a technology tends to enhance the both the availability and affordability of the technology. Another synergistic effect can be seen for power systems that consume less of a given energy resource, which in turn tend to be less harmful to the ecological environment. The exploration and exploitation of advanced technologies so as to obtain affordable, available, efficient and environmentally friendly transportation is the ultimate goal of the vehicular industry.

According to the rating criteria in Table 3, the resulting scores for the ICE, battery and fuel cell vehicle types are outlined in Table 4. Currently, the historically highly profitable FFV has clear advantage with regard to maturity of technique and operational costs, but is also the most energy consuming and environmentally malignant. In contrast, the FCEV is still not mature and affordable enough, though it is the most promising with regard to energy resource requirements and environmental issues. Comparatively, the BEV pure battery vehicle is rated neutrally in all the four considered criteria. Though numerous BEV models are currently produced and promoted commercially, battery capacity remains an issue for desirable traveling distance and thus is not so desirable from the consumer standpoint. This makes it less desirable to manufacturers. With regard to affordability, the total cost of ownership of future battery powered cars is considered to be at least 25% higher than hybrid or regular cars [9].

Presently, the comparative shares of vehicles utilizing the three basic power sources are approaching a dynamic equilibrium. Therefore, based on the four criteria considered in Table 4, the sums of the rating scores for the three basic vehicles are reasonably normalized as zero. Thus, although a specific type of vehicle may have advantages with regard to certain criteria, then that same type of vehicle certainly possesses some drawback with regard to other criteria. The relative equality of the sum of various advantages and disadvantages is what gives rise to the current dynamically balanced utilization of the three basic power systems.

As seen in Table 2, the hybrid power system configurations, i.e. the HEV, PHEV and SHFCEV configurations, are derivatives of the three base power sources. Their evaluation according to the four criteria can be conducted according to the configuration's utilization of the three base power sources. Let the rated scores in Table 2 for the three base power sources be denoted as ξ_j^i with $i = 1, 2, 3, 4$ for the four criteria and $j = 1, 2, 3$ for the three base power sources. Also, let the power source composition ratio be represented as the weightings w_k^j with $k = 1, 2, 3, 4, 5, 6$ for the evaluated six power system configurations in Table 2. For example, the weightings of the FFV are $w_1^1 = 1$, $w_1^2 = 0$, $w_1^3 = 0$. Then, for the six derivatives of the three base power system configurations in Table 4, their rating scores for the four criteria in Table 3 can be obtained as

$$\xi_k^i = \sum_{j=1}^{3} w_k^j \xi_j^i \qquad (1)$$

With the ICE as main power source for the HEV and PHEV operated individually with 10% and 20% of energy from battery, the respectively corresponding weightings are $w_4^1 = 0.9$, $w_4^2 = 0.1$, $w_4^3 = 0$ and $w_5^1 = 0.8$, $w_5^2 = 0.2$, $w_5^3 = 0$. The computed ratings are obtained from Eq. (1) are shown in Fig. 4, denoted by $\xi_{\rm hev}$ and $\xi_{\rm phev}$. For the proposed SHFCEV, assuming that the fuel cell module is designed to provide 10% of driving energy, the weightings are $w_6^1 = 0$, $w_6^2 = 0.9$, $w_6^3 = 0.1$. Its rating scores can be computed according to Eq. (1), with the result shown in Fig. 4 and denoted as $\xi_{\rm shfcev}$. As demonstrated in Fig. 4, the HEV and PHEV can reduces the drawbacks of the FFV with regard to the aspects of energy consumption and environment cost. The proposed SHFCEV substantially improves on the developing FCEV with regard to the weaknesses of engineering technology and operating cost.

The proposed power configuration of the SHFCEV can be considered as integration of the mild hybrid FCEV with the solar-hydrogen (SH) technique. Using the fuel cell device only for auxiliary power source lowers the utilization barriers with regard to engineering maturity and operational cost in the present time window. Further, by use of on board solar-hydrogen production, reliance on external facilities for hydrogen supply is reduced. Therefore, use of the proposed SHFCEV improves the energy efficiency of vehicular travel and the utilization threshold of fuel cell related technology.

Table 3
The four criteria and ratings for evaluation of various power sources.

Availability		Affordability		Rating
Energy resource	Engineering technology	Operational cost	Environmental cost	
Plentiful	Extensively mature used	Low	Beneficial	2
Not to worry about quantity and price	Popular used	Medium to low	Partly beneficial	1
Not shortage in the foreseeable future	Becoming popular usage	Medium	Neutral	0
Likely shortage in the foreseeable future	Likely popular in the foreseeable future	Medium to high	Partly harmful	−1
With limited resource	Key technique still under development	High	Harmful	−2

Table 4
The rated scores considering four criteria for three base power sources.

Types of base power sources	Energy source	Engineering technique	Operational cost	Environmental cost	Sum of scores
FFV	−2	2	2	−2	0
BEV	0	0	0	0	0
FCEV	2	−2	−2	2	0

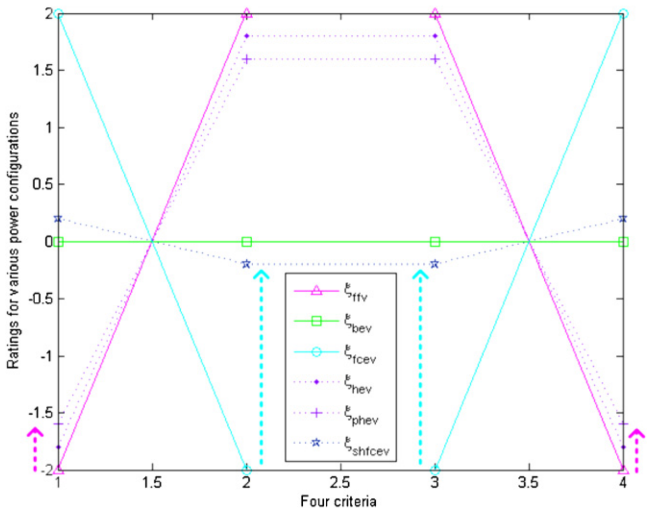

Fig. 4. Ratings of the various vehicles power configurations.

5. The cost-benefit evaluation for four exemplary vehicles

To demonstrate the system design and utility of the proposed SHMHFC power configuration, the issues related to component selection, cost estimation and benefit evaluation are investigated further. Four exemplary vehicle models (VM) are considered, namely the VM #1 TOYOTA fuel cell electric vehicle FCEV-5, VM #2 TOTOTA hybrid electric vehicle Prius-ZVW30, VM #3 NISSAN electric vehicle LEAF and VM #4 YINGTON ENERGY electric bus EV-Bus.

Specifications related to the power systems of the discussed vehicles include the battery capacity (kWh), travel distance (Km) and capacity efficiency (Km kWh^{-1}); the motor's rated power (kW) and cruise power (kW); the vehicle's physical characteristics in terms of the distance between the wheel axels, i.e. the wheelbase (m), and the distance between the wheels on an axel, i.e. the track (m), as shown in Table 5. The battery capacity efficiency η_{bat} (Km kWh^{-1}) can be estimated approximately from the data in Table 1. The actual battery capacity value depends on the vehicle's exterior volume and the battery system design.

According to the specifications provided by the manufactures, the compact NISSAN LEAF can achieve a battery capacity efficiency of 6.67 Km kWh^{-1}. The YINGTON ENERGY electric bus EV-Bus exhibited at the 25th World Electric Vehicle Symposium (EVS-25), Shenzhen City, China, 2010, has the largest exterior size and therefore the lowest battery capacity efficiency, 1.2 Km kWh^{-1}. The TOYOTA fuel cell hybrid electric vehicle FCHV-5 is a sports utility vehicle (SUV) with a battery capacity efficiency of 2.38 Km kWh^{-1}, which is lower than the average. The TOYOTA Prius is an ICE-battery hybrid electric vehicle that uses no external charging. The battery capacity is given as 1.31 kWh but no accurate travel distance under pure battery driving is provided. The battery capacity efficiency is assumed as 3.2 Km kWh^{-1} from the general data in Table 1, and the travel distance is estimated accordingly. In Table 5, the underlined information denotes that the data is obtained from reasonable estimation instead of from the specifications provided by the manufactures.

The considered motor power includes the rated power and cruise power. The rated power is a specification provided by the manufactures, whereas the cruise power is computed as the ratio between the evaluation speed (Km h^{-1}) for travel distance and the battery capacity efficiency (Km kWh^{-1}). In Table 5, the NISSAN LEAF's travel distance is 169 Km as evaluated for city traffic conditions at a speed of 39 Km h^{-1}. This value is used to estimate the cruise power. For the other three exemplary vehicles, the manufactures have not provided the vehicle speeds used for testing travel distance, so a nominal vehicle speed is assumed for estimation of cruise power. The cruise speed of the FCEV-5 is assumed equal to its driving distance 50 Km for duration of 1 h under pure battery operation. For the Prius, a cruise speed of 60 Km h^{-1} is used. For the case of the EV-Bus, the cruise speed is assumed simply as half of its travel distance in 1 h, i.e. 52 Km h^{-1}, as noted in Table 5.

5.1. The cost of the SHMHFC power systems

5.1.1. The required additional components

The specifications in Table 5 will be used to determine the appropriate capacities of the power system components used in the investigated SHMHFC power system configuration, after which a reasonable cost-benefit evaluation of the demonstrated vehicles will be obtained. As shown in Fig. 1, the required additional components include PV, PEM based electrolyzer, fuel cell and hydrogen container. The power rating of the PV depends on the available installation area of the vehicle roof. In this study, the effective area A_p is estimated as the average of 50% and 75% of the vehicle's of track W_c multiplied by the wheelbase L_c,

$$A_p = W_c L_c \frac{(0.5+0.75)}{2} = 0.625 W_c L_c (m^2) \quad (2)$$

Assuming that under standard operating conditions with solar radiation of 800 W m^{-2} [10] and a solar panel efficiency of 10% [11], the power available from the PV is computed as

$$P_p = W_c L_c \frac{(0.5+0.75)}{2} \times 800 \times 10\% = 50 W_c L_c = 80 A_p (W) \quad (3)$$

The power rating of the electrolyzer can be adopted as slightly larger than the available power from the PV, as shown in Eq. (3). If an electrolyzer with a much larger rating is used, it can produce hydrogen when the battery is being recharged from an external electrical source. This allows storage of more energy via hydrogen content, thereby increasing the vehicle's travel distance or lowering the battery capacity requirements. As for the power rating of the fuel cell, it can be designed according to a certain percentage of the motor's rated power or cruise power. In this study of the mild hybrid power scheme, the rating of the fuel cell module is specified to be approximately 10% of the motor cruise power.The unit prices of solar panels as cited from PV Insights [12] on July 11, 2011 are shown in Table 6. The prices differ among the manufactures and allow a flexible range for business operation. In terms of the average of the six major producers of Table 6, the average solar panel unit

Table 5
The electric power rating and appearance specifications of the exemplary vehicles.

Vehicle models	Battery			Motor		Appearance size	
	Capacity (kWh)	Driving distance (Km)	Capacity efficiency (Km kWh^{-1})	Rated power (kW)	Cruise power (kW)	Wheelbase (m)	Track (m)
VM #1: FCHV-5	21	50	2.38	60	21 kW @50 Km h^{-1}	2.715	1.815
VM #2: Prius	1.31	4.2 @3.2 Km kWh^{-1}	3.2	60	18.7 kW @60 Km h^{-1}	2.700	1.745
VM #3: LEAF	24	169	7.0417	80	5.5385 kW @39 Km h^{-1}	2.700	1.700
VM #4: EV-Bus	86.5	104	1.2	65	43.3 kW @52 Km h^{-1}	11.480	2.495

Table 6
Unit prices of solar panels [12] (US$ W^{-1}).

Items	High	Low	Average
ALL Brands	4.040	1.240	1.931
BPSolar	2.220	2.120	2.194
Evergreen	1.890	1.890	1.890
Kyocera	2.500	1.990	2.202
REC	2.300	1.720	1.960
Sharp	2.470	2.090	2.253
Average	2.570	1.842	2.0717

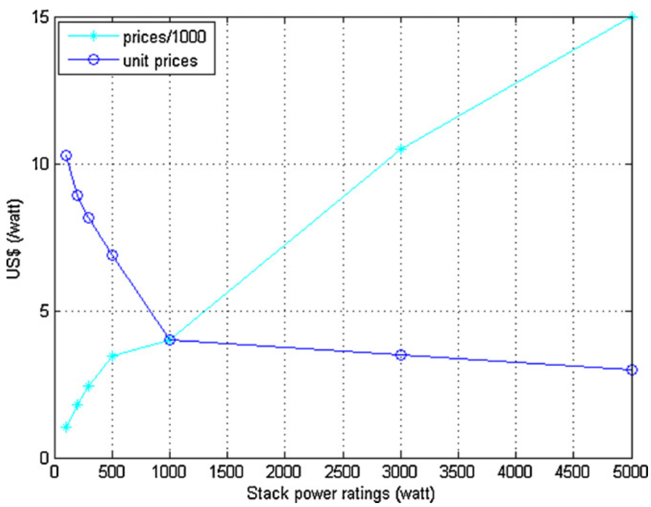

Fig. 5. Unit prices of PEM fuel cell power systems.

price used to evaluate the installation cost is 2.0717 US$ W^{-1}. For the PEM fuel cell module, the cost is cited from Fuel Cell Store [13] and Horizon Fuel Cell Technologies [14]. The price (US$) and per unit price (US$ W^{-1}) in the power ranges of 100–5000 W are as shown in Table 7. The unit price falls from 10.29 US$ W^{-1} to 3.0 US$ W^{-1} as the power rating increases from 100 to 5000 W. For the considered fuel cell modules, the price divided by 1000 and the unit price are depicted in Fig. 5. As the power rating increases, the price tends to be linearly proportional to the module capacity. The trend of unit price becomes flat, which means that the unit price does not decrease significantly with increasing fuel cell rating.Although the space of unit price reduction exists for fuel cell modules of ratings larger than the considered 5000 W, the complexity of the required monitor and control to assure efficient and safe operation is also increased. In this study, the unit price for fuel cell modules with ratings larger than 5000 W is estimated by using the value of 3.0 US$ W^{-1} obtained from the 5000 W module.It is noted that for the fuel cell module to be successfully applied in automotive applications, additional study and consideration of safety and durability issues must be accomplished. Therefore, although mass production would lower certain costs, other additional cost can be expected. Thus, prices cited in [13,14], which are intended for back-up power or portable usage, can be considered only as contemporary guidelines for further research and development.It is also noted that from the report in [15] that the unit price of an 80 kW fuel cell system for transportation is projected as 0.228 US$ W^{-1} at a volume of 1000 units per year, based on 2010 technology. This cost is only about one tenth of the estimated 3.0 US$ W^{-1} mentioned above, but the per/1000 price is not a price available to the average user. This fact underscores the importance of relieving the barricades that inhibit the average user's easy access to fuel cell related products. With regard to electrolyzer devices, the same unit price as the fuel cell system will be used in this study since the same PEM material and technology is used.

5.1.2. The considered four exemplary vehicles

The required cost of setting up a SHMHFC power system for the four exemplary vehicles is shown in Table 8. The estimated Li-ion battery price of 1,000 US$ kWh^{-1} is a projection of about 75% of the current price 1,333 US$ kWh^{-1} shown in Table 1. The unit prices for the solar panel and PEM devices are as shown in Tables 6 and 7, respectively. In Table 8, for each of the considered models, the first row R #1 is the cost estimation for vehicle fully powered by fuel cell modules denoted by σ_{fc}, the second row R #2 is for the vehicle equipped as pure battery driving denoted by σ_{bat}, and the third row R #3 is for the vehicle as installed with the proposed SHMHFC power module denoted by σ_{shfc}.

For the VM #1 TOYOTA fuel cell hybrid FCHV-5, the cost estimation in terms of the original equipped 21 kWh battery and a 60 kW fuel cell is 201,000 US$. The high cost is mainly due to the fuel cell device with price estimation 3.0 US$ W^{-1} as shown in Table 7. On the other hand, if the cost estimation of 0.228 US$ W^{-1} according to [15] is used, the required investment for the 60 kW fuel cell is only 13,680 US$, which is even cheaper than the 21 kWh battery and does not agree with the current market status. Therefore, the

Table 7
Unit prices of PEM fuel cell energy systems [13,14].

Watt (W)	100	200	300	500	1000	3000	5000
Price (US$)	1029	1780	2450	3435	4000	10,500	15,000
Unit Price (US$ W^{-1})	10.29	8.90	8.17	6.87	4.00	3.50	3.00

Table 8
The cost analysis of the exemplary vehicles' power systems.

Vehicle models		Battery		Solar panel		Electrolyzer, fuel cell		Total cost of components (US$)
		Capacity (kWh)	Cost (US$)	Effective area (m^2)	Cost (US$)	Rated power (kW)	Cost (US$)	
VM #1: FCHV-5	R #1	21	21,000			60	180,000	201,000
	R #2	67.2	67,200					67,200
	R #3	67.2	67,200	3	500	2	15,000	82,700
VM #2: Prius	R #1	1.31	1,310			60	180,000	181,310
	R #2	50	50,000					50,000
	R #3	1.31	1,310	3	500	2	15,000	16,810
VM #3: LEAF	R #1					20	60,000	60,000
	R #2	24	24,000					24,000
	R #3	24	24,000	3	500	1	8,000	32,500
VM #4: EV-Bus	R #1					65	195,000	195,000
	R #2	86.5	86,500					86,500
	R #3	86.5	86,500	14	2,320	5	30,000	118,820

price estimation for the fuel cell modules is conducted according to the market available prices from Table 8 instead of the ideal manufacturing cost from [15].

According to the manufacture‘s data, the equipped 21 kWh battery can support a travel distance of 50 Km. For a pure battery EV to be capable of cruise driving for two hours or traveling distance around 160 Km, the required battery capacity for the FCHV-5 is 67.2 kWh. For a unit cost 1,000 US$ kWh^{-1}, the battery cost to support the vehicle to operate as a pure electric vehicle is σ_{bat} = 67,200 US$, as shown in Table 8.

Moreover, the required cost to implement the proposed SHMHFC power system, including the solar panel, electrolyzer and fuel cell modules, is estimated as σ_{shfc} = 15,500 US$. The cost of solar panels according to Eq. (2) and Table 6 is computed as 80A_p (W) × 2.07 (US$ W^{-1}) = 500 (US$). For the fuel cell module, the power rating is selected as 2 kW, which is about 10% of the 21 kW motor cruise power as mentioned in Table 5. The cost estimation following Table 7 is obtained as 7500 US$. The cost for the PEM fuel cell and electrolyzer is computed as 15,000 US$ if the same rating is chosen for the electrolyzer.

It is noted that if the capacity of electrolyzer is chosen in accordance with the power of installed solar panel as shown in (3), then an electrolyzer rating of 80A_p = 240 (W) would be suitable, with the cost estimated as 240 (W) × 8.5 (US$ W^{-1}, Table 7) = 2040 US$. In this case, the cost for both fuel cell and electrolyzer would be 9540 US$, instead of 15,000 US$ as summarized in Table 8. Such a configuration would allow the system to produce a limited amount of hydrogen when the solar panels were illuminated, and a limited amount of hydrogen when the system was plugged into a power grid. If, however, the rating of electrolyzer is the same as the fuel cell, i.e. if the electrolyzer rating is significantly greater than the rating of the solar cell, then hydrogen in considerably greater quantity can be produced while the vehicle is plugged in. In this study, an electrolyzer is chosen with the same rating as the fuel cell, but this should be considered a design option. If, on the other hand, an electrolyzer is chosen with capacity only just matching the rating of solar panel, then a minimum installation cost would be achieved.

Let the estimated cost for the vehicle functioning under pure battery drive, 67,200 US$, be chosen as the nominal basis of cost. The required additional investment for the proposed mild hybrid solar-hydrogen fuel cell power systems is about $\sigma_{shfc}/\sigma_{bat}$ = 15, 500/67, 200 = 23.07%. However, for the fuel cell module to be able to provide full power operation for the vehicle, i.e. 60 kW, the required cost ratio is σ_{fc}/σ_{bat} = 180, 000/67, 200 = 267.86%. The required cost of the proposed SHMHFC power structure is only about $\sigma_{shfc}/\sigma_{fc}$ = 8.6% of the full rating fuel cell system. Using the proposed mild hybrid approach, the installation cost for the required power modules can be reduced relative to the currently commercially available products.

For the VM #2 TOYOTA‘s Prius-ZVW30, only the electric energy rated for battery operation is evaluated, while the mechanical energy from the ICE is not. For a fuel cell with a capacity equaling the rated power of motor 60 kW, the price is estimated as σ_{fc} = 180,000 US$. The battery capacity efficiency for this vehicle is obtained as 3.2 Km kWh^{-1} as shown in Table 5. For the vehicle to be driven solely by the battery for the desired distance of 160 Km, the required battery capacity is 50 kWh and the price estimate is σ_{bat} = 50,000 US$. For the vehicle to be equipped with the investigated SHMHFC power system scheme, according to the solar panel area and cruise power of the vehicle, the total cost for the solar panel, fuel cell and electrolyzer modules is about σ_{shfc} = 15,500 US$, as shown in Table 8.

The next, consider the VM #3 NISSAN electric vehicle LEAF. From Table 5, although the equipped motor is 80 kW, the cruise power is only 5.5385 kW in the evaluated city traffic conditions with a speed 39 Kmh^{-1}. We consider that the motor in this case is overpowered relative to the requirements of normal city driving. Consider that the rated motor powers of VM #1 and VM #2 are equal (60 kW), which in both cases is about three times the approximately 20 kW cruise power. Accordingly, the capacity of the fuel cell for VM #3 is chosen as 20 kW, i.e. approximately three times the 5.5385 kW cruise power, with an estimated cost σ_{fc} = 60,000 US$. The cost of the battery based on the nominal estimate of 1000 US$ kWh^{-1} is σ_{bat} = 24,000 US$. It is noted that the price of the designed 24 kW battery module can be obtained for 10,000 US$, as claimed by the manufacturer. However, this projected unit cost of battery, 416.67 US$ kWh^{-1}, is based on a volume of 200,000 units per year.

In the investigated SHMHFC power system structure, the fuel cell module for VM #3 is chosen as 1 kW, which is about 18% of the cruise power. According to Table 7, the cost estimation for the electrolyzer and fuel cell devices is 4000 × 2 = 8000 US$. The effective solar panel area and cruise power of the LEAF is approximately the same as the VM #1 FCHV-5 and VM #2 Prius-ZVW30. It is noted that the effective area A_p = 3 M^2 for VM #1, VM #2 and VM #3 is exactly the same as the estimate in [6] for medium-size automobiles. Therefore, the specified capacity and cost for the investigated power system structures is σ_{shfc} = 8500 US$, as shown in Table 8.

For the VM #4 EV-Bus by YINGTON ENERGY, due to the vehicle's larger exterior size and the larger cruise power, a larger effective area for the solar panel and a larger capacity rating for the fuel cell are required. According to the specifications in Table 5, cost of the fuel cell module with full power rating is σ_{fc} = 195,000 US$. The cost of the battery is σ_{bat} = 86,500 US$. The cost estimation of the additional power components for the addressed SHMHFC scheme is computed as σ_{shfc} = 32,320 US$, as shown in Table 8.

Vehicles powered by an ICE, possibly hybrid with battery, are considered currently as the market mainstream. Electric vehicles without an ICE device are not well accepted by the mass consumers because of battery charging and price issues. When appraising potential commercialization of the hydrogen and fuel cell technologies for vehicular application, analysis of installation costs is critical. Herein, such evaluation is conducted with the battery price used as the basis. The motor power rating ratio between the cost of fuel cell module σ_{fc} to the cost of battery σ_{bat} with an energy capacity supporting the nominal 160 Km is used to quantify the comparative installation costs between fuel cell vehicles and pure battery vehicles. If the cost ratio is lowered to a reasonable level, then a possible market transition from battery to fuel cell powered vehicles can happen. For the four exemplary vehicles, based on the σ_{fc} verses σ_{bat} price estimates as shown in Table 8, the cost ratio $\rho_{bat}^{fc} = \sigma_{fc}/\sigma_{bat}$ can be obtained as in the first data row of Table 9. The average cost ratio is computed as 4.6332. VM #4 possesses the lowest ratio, i.e. 2.2543, which indicates the opportunity for a fuel cell module to compete with a battery in this type of EV-Bus.

Moreover, the comparative ratio between the cost of the various power modules used in the SHMHFC structure σ_{shfc} to the nominal battery cost σ_{bat} represents the extra cost required to implement the SHMHFC structure beyond that of the vehicle‘s existing battery power system. If the cost ratio is low enough and the benefit is proved to be fruitful, as will be discussed in the following Section 5.2, implementation of the SHMHFC power configuration will be encouraged. From the price estimates σ_{shfc} and σ_{bat} shown in Table 8, the cost ratio $\rho_{bat}^{shfc} = \sigma_{shfc}/\sigma_{bat}$ can be obtained and is presented in the second data row of Table 9. It is found that the average additional cost ratio is 0.3171.

Also, the comparative cost ratio $\rho_{bat}^{shfc}/\rho_{bat}^{fc} = \sigma_{shfc}/\sigma_{fc}$ can be computed as shown in Table 9. The average cost ratio between the SHMHFC configuration and full rating fuel cell is just 0.1199. The cost analysis data of the four exemplary vehicles in Table 9 is also illustrated in Fig. 6 for visual quantitative comparison.

Table 9
Cost analysis of the exemplary vehicle power systems.

Vehicle models	VM #1: FCHV-5	VM #2: Prius	VM #3: LEAF	VM #4: EV-Bus	Average cost ratio
Cost ratios of rated fuel cell to battery, ρ_{bat}^{fc}	2.6786	3.6000	2.5000	2.2543	4.6332
Cost ratios of SHFC components to battery, ρ_{bat}^{shfc}	0.2307	0.3100	0.3542	0.3736	0.3171
Comparative cost ratio, $\rho_{bat}^{shfc}/\rho_{bat}^{fc}$	0.0861	0.0861	0.1417	0.1657	0.1199

Table 10
The benefit evaluation of the proposed hybrid power systems for the exemplary vehicles.

Vehicle models	Acquired energy from solar panel (kWh day^{-1})	Supplied energy from electrolyzer, fuel cell (kWh day^{-1})	Full load operation of fuel cell (h day^{-1}@rate kW)	Provision of driving distance (Km day^{-1})	Percentage of daily driving distance (% day^{-1})
VM #1: FCHV-5	2	1	0.5	2.4	12.63
VM #2: Prius	2	1	0.5	3.2	16.84
VM #3: LEAF	2	1	1	7.0416	37.06
VM #4: EV-Bus	9.2	4.6	1	5.5	(not evaluated for a bus)

5.2. The benefit of the SHMHFC power systems

Based on the effective area of the solar panel A_p in Eq. (2) and the produced electric power P_p in Eq. (3), the acquired PV electric energy under a nominal eight hours solar radiation per day is computed as

$$50W_cL_c \times 8 = 400W_cL_c = 640A_p\,(\text{Wh}). \tag{4}$$

The reasonable integrated efficiency of the PV electric power, after factoring in the processes of the electrolyzer, the hydrogen container and the electric energy output from the fuel cell, is around 50%; therefore, the usable electric energy via the SHMHFC configuration is

$$E_{shfc}\left(A_p\right) = 400W_cL_c \times 0.5 = 200W_cL_c = 320A_p(\text{WH}). \tag{5}$$

For the four exemplary vehicles under consideration, the related data regarding the effective solar panel area, the obtainable PV electric energy per day (kWh day^{-1}) and the electric energy provided by fuel cell are shown in Table 10. Based on the specified fuel cell capacity, the available full load operation hours for the fuel cell (h day^{-1}@rate kW) using the solar generated hydrogen can be computed. According to the analysis of the battery capacity efficiency η_{bat} (Km kWh^{-1}) for the four considered exemplary vehicles as given in Table 5, the corresponding driving distance per day (Km day^{-1}) based on the electric energy provided by the fuel cell (kWh day^{-1}) can be obtained.

According to the statistical data of [16], the daily average driving distance for private vehicles in Taiwan, is 19 Km day^{-1}. Based on this, the percentage of daily travel distance supported by the electric energy from the SHMHFC power systems for the four exemplary vehicles is as shown in Table 10. The Model #3, NISSAN LEAF can support the highest driving distance percentage, more than one third of the vehicles' daily driving distance, which is due to its superior battery capacity efficiency, as shown in Table 5. VM #4, the YINGTON ENERGY EV-Bus, is used for public transportation, so the estimated percentage of supported daily driving distance is not evaluated. From the data in Table 10, the average percentage of the daily driving distance of VMs #1, #2 and #3 is obtained as 22.1767%.

According to the National Household Travel Survey in United States [17], the average annual vehicle travel distance (VTD) per household and vehicles per household for the years 1969, 1977, 1983, 1990, 1995 and 2001 are given in Table 11. Then, the average annual VTD and daily driving distance per vehicle can be obtained as shown in Table 11. The average daily vehicle driving distance over the surveyed years is computed as T_{day} = 42.7222 Km day^{-1}. Based on Table 11, the percentage of the daily driving distance that can be supported by the SHMHFC power systems for VMs #1, #2 and #3 is depicted in Fig. 7. The annual average of the three models and the total average over the considered years, computed as 10.26%, are displayed with square-solid line and dotted line, respectively.

5.3. Cost-benefit evaluation of the SHMHFC power systems

To analytically investigate the cost-benefit characteristics of the SHMHFC power systems, let the installation cost ratio $\gamma_{cost} = \rho_{bat}^{shfc}$

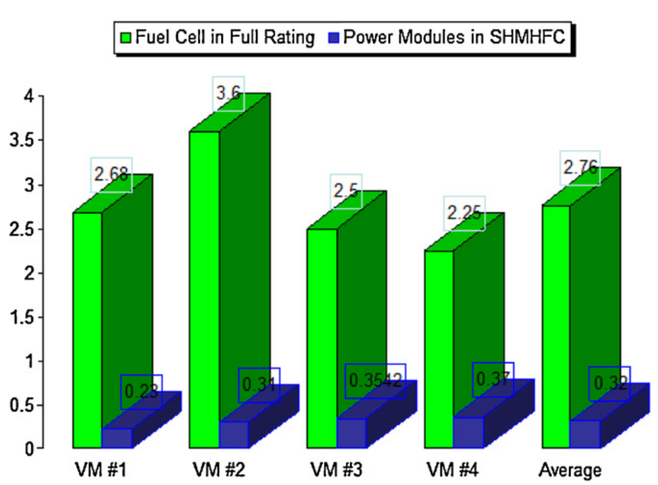

Fig. 6. Installation cost normalized by the full rating battery capacity.

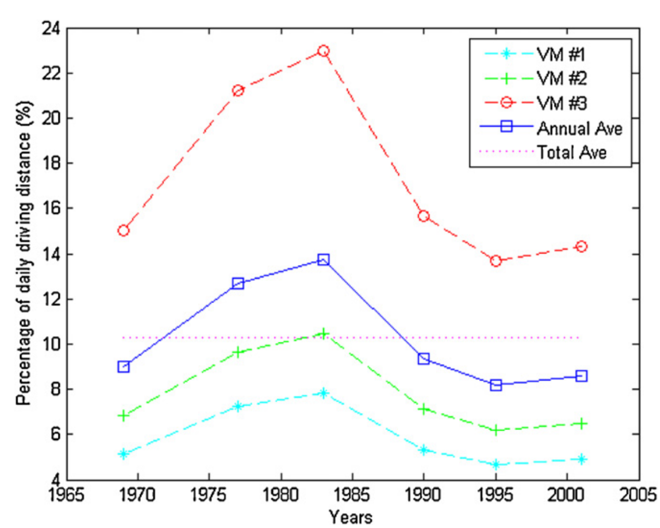

Fig. 7. Supported average daily driving distance by SHMHFC modules.

Table 11
The average vehicle travel distance (Km) [17].

	1969	1977	1983	1990	1995	2001	Average
Average annual VTD per household (Km)	19,877	19,258	18,782	29,058	33,432	33,899	25,718
Vehicles per household	1.16	1.59	1.68	1.77	1.78	1.89	1.6450
Average annual VTD per vehicle (Km)	17,134	12,112	11,179	16,416	18,782	17,936	15,594
Average daily driving distance per vehicle (Km)	46.9457	33.1827	30.6301	44.9773	51.4576	49.1400	42.7222

based on the nominal battery capacity as described in Section 5.1 and the daily driving distance ratio γ_{bene} supported by the SHMHFC module as mentioned in Section 5.2 be represented respectively as

$$\gamma_{\text{cost}} = \rho_{\text{bat}}^{\text{shfc}} = \frac{\sigma_{\text{shfc}}}{\sigma_{\text{bat}}} = \frac{\sigma_{\text{shfc}}\left(p_{\text{pem}}, A_{\text{p}}\right)}{R_{\text{bat}} C_{\text{bat}}} \tag{6}$$

$$\gamma_{\text{bene}} = \frac{T_{\text{shfc}}}{T_{\text{daily}}} = \frac{E_{\text{shfc}}\left(A_{\text{p}}\right)\eta_{\text{bat}}}{T_{\text{daily}}} \tag{7}$$

The notation $\sigma_{\text{shfc}}\left(p_{\text{pem}}, A_{\text{p}}\right)$ was introduced in Section 5.1.1 and represents the cost of the various power modules to construct the SHMHFC power systems as functions of the power rating of the PEM devices p_{pem} and the solar panel effective area A_{p}, which is also explained in (2). The cost of the nominal battery system $\sigma_{\text{bat}} = R_{\text{bat}}C_{\text{bat}}$ capable of supporting a driving distance of 160 Km is the product of the battery capacity R_{bat} and the per unit cost C_{bat} = 1000 US\$ kW^{-1} as adopted in this work. In Eq. (7), $E_{\text{shfc}}\left(A_{\text{p}}\right)$ represents the energy that is collected from the solar panel under nominal solar radiation for eight hours and can be transformed and provided by the SHMHFC power system, as described in Eq. (5). As defined in Section 2, η_{bat} is the battery capacity efficiency depending on the vehicle's design and is shown in Table 5 for the exemplary vehicles. $T_{\text{shfc}} = E_{\text{shfc}}\left(A_{\text{p}}\right)\eta_{\text{bat}}$ is the vehicle daily driving distance supported by the SHMHFC power system. T_{daily} is the vehicle average daily driving distance cited from [17] as shown in the bottom row of Table 11.

From Eqs. (6) and (7), the cost-benefit ratio of the SHMHFC power systems is written as

$$\zeta_{\text{shfc}} = \frac{\gamma_{\text{cost}}}{\gamma_{\text{bene}}} = \frac{\sigma_{\text{shfc}}\left(p_{\text{pem}}, A_{\text{p}}\right) T_{\text{daily}}}{E_{\text{shfc}}\left(A_{\text{p}}\right) R_{\text{bat}} C_{\text{bat}} \eta_{\text{bat}}} \tag{8}$$

By definition, the product of the battery rating capacity R_{bat} (kWh) and the capacity efficiency η_{bat} (Km kWh^{-1}) equals 160 Km. The same per unit cost for battery C_{bat} = 1000 US\$ kW^{-1} is used for the evaluated vehicles. The discussed vehicles have the same effective area $A_{\text{p}} = 3\,\text{m}^2$, as mentioned in Table 8. Therefore, the cost-benefit ratio of the SHMHFC power systems depends on only the average daily driving distance T_{daily} and the power rating of PEM devices p_{pem}, which is also illustrated in Fig. 8 for the discussed exemplary vehicles, VM #1, VM #2 and VM #3.

According to Table 9, the average installation cost ratio of the VM #1, VM #2 and VM #3 is γ_{cost} = (0.2307 + 0.3100 + 0.3542)/3 = 29.83%. As shown in Table 10, for the VM #1, VM #2 and VM #3, the average daily driving distance supported by the SHMHFC power system is T_{shfc} = (2.4 + 3.2 + 7.0416)/3 = 4.2139 (Km day^{-1}). As shown in Table 11, the year 1983 has a shortest average daily driving distance T_{daily} = 30.6301 (Km), which corresponds to the largest daily driving distance ratio $\gamma_{\text{bene}} = 4.2139/30.6301 = 13.76\%$. Therefore, as shown in Fig. 8, the cost-benefit ratio ζ_{shfc} has a minimum of $\zeta_{\text{shfc}} = \gamma_{\text{cost}}/\gamma_{\text{bene}} = 29.83/13.76 = 2.1679$ in 1983. The average cost-benefit ratio for the sample years is computed as 3.0240, which is also displayed with dotted lines in Fig. 8.

The cost-benefit ratio ζ_{shfc} for the proposed SHMHFC power systems in Eq. (8) is also characterized by the price competition between the PEM devices represented by the fuel cell power rating p_{pem} and the battery unit cost C_{bat}. A reasonable low level of the cost-benefit ratio ζ_{shfc} can be used to signify the suitability of implementation of the SHMHFC power systems based on the considered electric vehicles.

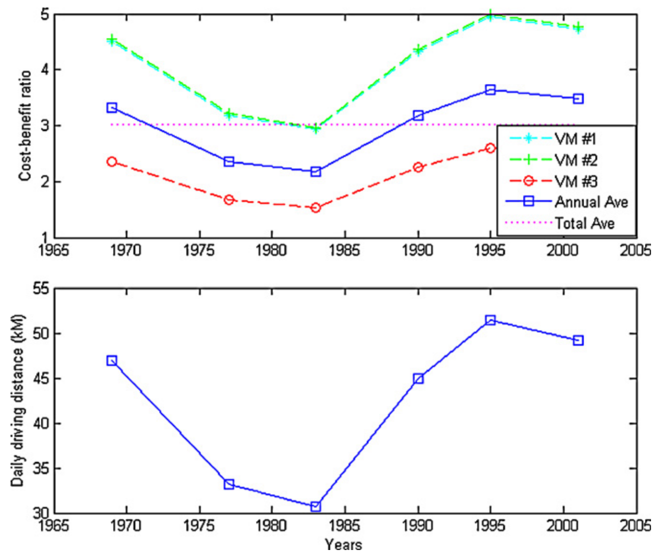

Fig. 8. Cost-benefit ratio and surveyed daily driving distance.

6. Conclusion

This paper has investigated a solar-hydrogen mild hybrid fuel cell (SHMHFC) power system configuration for electric vehicle. Electric energy acquired from photovoltaic cells on the roofs of vehicles can be accumulated as hydrogen gas via an electrolyzer. Thus the prerequisite need for infrastructure for hydrogen refilling can be alleviated via the solar-hydrogen approach. The cost for development and installation of fuel cell modules of the required capacity can be reduced significantly by this mild hybrid fuel cell structure. Analysis and comparison of various power systems including the proposed hybrid configuration were performed in terms of the criteria of availability and affordability. Cost-benefit evaluation regarding implementation issues was conducted and demonstrated for four exemplary vehicle models. The cost is defined as the comparative ratio between the cost of the proposed SHMHFC and the cost of the battery necessary for driving 160 Km. The benefit is defined as the percentage of daily vehicle traveling mileages supported by the SHMHFC power system. For the considered exemplary vehicle models, the average comparative cost ratio is 0.3171 and the benefit percentage is 10.26% based on a daily vehicle travel mileage of 42.7222, as quoted from the National Household Travel Survey of the United States.

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