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Renewable Energy Technologies and Hybrid Electric Vehicle Challenges

***Abstract**. This paper introduces the utilization of selected renewable energy technologies such as solar cell, battery, proton exchange membrane (PEM) fuel cell (FC) and super-capacitors (SCs) in the electrical vehicle industry. Combination of multiple energy resources is imperative to balance the different characteristic of each resource. Concomitantly, the need of an efficient energy management system arises within the industry. Thus, existing system from past and present undergoing research papers are summarized to give a compact overview on the technology and know-how technique to readers.*

***Streszczenie.** W artykule zaprezentowano wykorzystanie różnych źródeł energii odnawialnej – baterii słonecznych, baterii z protonową membraną i superkondensatorów w przemyśle motoryzacyjnym. Rozważano możliwość stosowania równocześnie różnych źródeł w celu zrównoważenia ich charakterystyk. (**Technologie energii odnawialnej w przemyśle motoryzacyjnym**)*

Keywords: Hybrid electric vehicle, solar cell, battery, fuel cell, super-capacitors.
Słowa kluczowe: pojazdy hybrydowe, źródła energii odnawialnej

Introduction

Renewable energy technologies such as fuel cell and solar are gaining popularity for vehicle application. Not only these energy sources reduce gas in the cities but they also reduce dependability on the fossil energy [1]. As a platform to exchange ideas and research findings related to solar vehicles, North American Solar Challenge [2]. One of the highlights of the event is the solar racecar. This initiative ignites interests of many researchers to develop high efficiency power generated solar, improve aerodynamic and reduce losses in mechanical and electrical in the car. As solar power depends on the sunlight, such vehicle needs secondary sources to drive at night or in cloudy conditions. Alternatively, fuel cell can work all day long as long as hydrogen is available in the tank. Unfortunately, fuel cell has slow response in high power condition and it also needs SCs to overcome its low start-up time [3]. As a result, SCs are a mandatory part in every fuel cell powered system in hybrid electrical vehicle (HEV) [4]. In order to minimize the usage of energy and fulfill different stage of power condition, an innovative energy management system is required to coordinate these multi energy sources.

This review paper handles novel research paper focusing on solar cell, fuel cell and SCs for vehicle. For a better understanding, topic related to these energy sources will be basically explained and then, the handled research papers are discussed in details.

Solar cell technology

Solar cells or photovoltaic (PV) solar cells are electronic devices that convert sunlight energy into electricity. The physic of solar cell is derived from the principles of semiconductor known as diodes and transistors. The advantage of solar cell is their ability to convert free solar energy from the sun into electricity without producing any pollution that could affect the ecology. This kind of energy sources is classified as a renewable and sustainable energy.

The photovoltaic effect was first studied in 1839 by Alexander-Edmund Becquerel. He observed that electric current is produced when certain light – induced from chemical reactions. After a few decades, it was Charles Fritz who invented the first solar cell. The material that was used is made of a thin layer of gold coated with semiconductor selenium. The device was found to have efficiency of 1% only. In year 1954, Chapin, Fuller and Pearson announced the first silicon solar cell with 6% efficiency [5]. Since then, technology continues to evolve and becoming more significant as years passes by.

Solar cell technology is divided into three main categories [6]: mono-crystalline (single-crystal construction), polycrystalline (semi-crystalline), and amorphous silicon. Mono-crystalline cells have the highest efficiency but the most expensive cost in production. The cells are produced from pure silicon through Czochralsky process or floating zone technique. The technique is done by slowly pulling mono-crystalline seed from melting silicon. The silicon grows on a seed and forms silicone rod. Then, they are sliced into thick wafer disks. Polycrystalline cell is manufactured by slowly cooling down the melting silicon in a controlled environment. This process produces silicon ingot that has crystalline region. This manufacturing process is cheaper but it comes with a price - lower efficiency when compared to the mono-crystalline. Amorphous silicon cells production's cost is the lowest among the three. Thin wafer silicon is deposited on carrier material, followed by several doping process. Compared to the other two, amorphous silicon cell has the lowest efficiency [7].

Advancement in the solar cell technology has produced other type of solar cells too such as the thin-film cell, gallium-arsenide cell and tandem cell technology [8]. These technologies improve efficiency and flexibility of solar cell as well as reduce its production cost.

The equivalent circuit of solar cell can be expressed as a current source in parallel with a diode. The I-V characteristic of solar cell can be derived from the Shockley equation and the output current I, which can be expressed as [9];

$$I = I_L - I_0\left[\exp\left(\frac{qV}{KT}\right) - 1\right] \tag{1}$$

where: I_L – light generate current, I_o – initial current, V – voltage, K – Boltzman constant, q – electron charge, T – absolute temperature.

Solar cells are influenced by two parameters: temperature and irradiance. Temperature has an important effect on the power output of solar cell. Increasing the temperature will decreased the voltage value of solar cell typically by 2.3mV per °C [10]. The temperature variation of the current shows minimum effect and can be neglected. Irradiance is total power from a radiant source falling on a unit area. Increasing the irradiance will increase the photon flux, which in turn generates proportionally higher current. Thus, the short circuit current of a solar cell is directly proportional to the irradiance [11].

Solar-powered vehicle is getting attention many researchers to involve in this area. Auto rickshaw or known as Bajaj auto are widely used in many Asian countries. The idea to apply solar energy to the vehicle is technically reasonable because of power capacity factor. For example, the power consume for this vehicle is around 5-6 kW and the solar module that will be used is 250 Watt. Roughly estimation; solar energy that can support the vehicle powered is between 5-8 %. However, if the vehicle is not extensively used, the percentage will be increased. Another factor to introduce renewable energy in this vehicle is to reduce pollution in the city as this vehicle for instance in India growing 250,000 new auto rickshaws each year [12].

Fuel cell technology

Fuel cell energy is considered as renewable energy as it uses hydrogen as fuel system and emits water. By definition, it is an electrochemical device that produces DC electrical energy through chemical reaction. Fuel cell is built of several parts such as anode, anode catalyst layer, electrolyte, cathode and cathode catalyst layer [13]. A multiple fuel cell can be arranged in series or parallel in a stack to produce the desired voltage and current. The anode and cathode are made of thin layer of porous graphite. These parts are known as porous gas diffusion layer. Its catalyst layer determines type of fuel cell. For example, catalyst layer platinum is used for low temperature whereas catalyst layer nickel is used for high temperature fuel cells. Additionally another factor that determines fuel cell type is the type of the charge carriers whether it's flowing from anode to cathode or vice versa. The names of different types of fuel cell for instance are proton exchange membrane fuel cells (PEMFC), direct methanol fuel cells (DMFC) and alkaline electrolyte fuel cells (APC) [14].

The PEMFC is a solid polymer fuel cell that uses special plastic membrane as an electrolyte. The primary fuel source of energy comes from hydrogen. The hydrogen will be fed into the cathode layer and oxygen will be derived from air feeds into the anode layer. The electrochemical reaction will occur between oxygen and hydrogen to produce electricity. The overall chemical reaction between hydrogen and oxygen at the anode and cathode reaction are described by formula (2) and (3) as shown below [15],

$$H_2 \rightarrow 2H \rightarrow 2H^+ + 2e^- \tag{2}$$

$$2H^+ + 2e^- + O \rightarrow H_2O \tag{3}$$

The byproducts of the chemical reaction are heat and water/steam. The theoretical voltage is where (E: [O_2/H_2O] = 1.23V) fuel cell standard condition of 25ºC and 1 atmosphere pressure apply [16].

The voltage produced by fuel cell, V_{cell} is a summation of the polarizations at the electrodes as described below [17]:

$$V_{cell} = \Delta E - \frac{RT}{\alpha nF}\ln\left(\frac{i}{i_o}\right) - iR + \frac{RT}{nF}\ln\left(1-\frac{i}{i_1}\right) \tag{4}$$

where: ΔE – difference between the ideal potential of cathode and anode, i – current flow, i_o – exchange current density, i_1 – current corresponding to zero concentration of reactant at the surface, R – in ohmic term as an area-specific resistance, α – the electrode transfer coefficient, n – constant coefficient, F – Faraday's constant. The term RT/F can be valued at 25.7 mV at T = 298 K.

According to Chao et al. [18], FC empirical model can be derived from Nernst equation in standard state entropy change as

$$\begin{aligned} E_{nernst} &= 1.229 - (8.5x10^{-4})(T - 298.15) + \\ &(4.308x10^{-5}T)(\ln P_{H_2} + \frac{1}{2}\ln P_{O_2}) \end{aligned} \tag{5}$$

where, T is the absolute temperature and P_{H_2}, P_{O_2} are the partial pressure of hydrogen and oxygen at the cathode.

In the general, PEMFC fuel cell shows good promise to replace combustion engine. It has high specific energy and with a single tank of hydrogen, a vehicle can travel long enough just like a normal practice today. However, fuel cell requires times in high demand load situation and this characteristic is known as low power density.

Super-capacitors technology

An electrochemical capacitor (EC), also widely known as SCs or ultra-capacitors, offers high specific power compared to other storage devices. Thus, SCs are the perfect choice to assist fuel cell in supporting high output current when fuel cell slowly increases its output capacity. SCs contain electrical double layer in the inside and separator that separated electrical charges and hold the charges. While separating the charges, it provides a small potential energy of as low as 2 to 3V [19].

The electrical characteristics of SCs are similar to capacitors. This means that electrical charge of SCs can be derived from capacitors too. The charge of a capacitor, which is measured in capacitance, can be calculated from the area of the two parallel conductors, A by a distance d. A dielectric material is placed between the parallel-plate to enhance the capacitance. Thus, the capacitance of an electrostatic capacitor is known as [20]

$$C = \frac{\varepsilon_r \varepsilon_o A}{d} \tag{6}$$

where: ε_r – the relative dielectric constant of material between plates, ε_o – the permittivity of vacuum.

The energy, E stored in the SCs is given by [21]:

$$E = \frac{1}{2}CV^2 \tag{7}$$

Apply the basic capacitor model for SCs, voltage $V_C(t)$ can be defined in the following equation where $i_c(t)$ is the charging capacitor current and $V_o(t_0)$ is the initial voltage of capacitor [22]:

$$V_C(t) = \frac{1}{C}\int_{t_0}^{t} i_c(t)dt + V_O(t_0) \tag{8}$$

SCs can be arranged in series and parallel which form a module. The total capacitor charge, C_{total} is [23],

$$C_{total} = n_p \frac{C}{n_s} \tag{9}$$

where, n_p is the number of capacitors arrangement in parallel and n_s is number of capacitors arrangement in series.

The double layer inside SCs is made of nano-porous material like activated carbon that can increase density storage. The range values of SCs can be up to hundred thousands of farad with operating application until 1500V. SCs (800-1500F) can be compared to a high power battery but with low capacity. It stores electrical energy by accumulating and separating opposite charges. Battery, on the other hand, stored energy chemically in reversible chemical reactions. One advantage of SCs is that it shows excellent lifecycle. It's lifecycle can reached a range of 10^5 – 10^6 and is expected to last as long as a car's lifecycle. Its high cycle efficiency is estimated to be 90% compared to the battery. SCs and battery have low specific energy at range of 5-10 Wh/kg and 30-40 Wh/kg respectively [24].

Battery Model Technology

Battery technology becomes significant as electric and hybrid vehicles are getting more attention in the recent years. Lead acid batteries have been established for more than 100 years and are thus used extensively as energy and storage device in transportation industry. However, due to its low specific energy of typically 20-30Wh/kg, a nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion) battery is implemented instead. These battery types have between 2-5 times higher specific energy.

A simple model of a battery terminal voltage, V_{bat} is built of an open source voltage, E_{bat} subtracted by battery current, I_{bat}, flowing into the internal resistor, R_{int}. This is described as follows:

$$V_{bat} = E_{bat} - R_{int} I_{bat} \tag{10}$$

The state-of-charge (SOC) represents status of existing battery capacity in percentage. The SOC can be calculated from current drawn from the battery, I_{bat} divided by battery capacity, Q. This is presented below [25] as follows:

$$SOC = 100\left(1 - \frac{\int I_{bat}\,dt}{Q}\right) \tag{11}$$

The opposite of SOC is DOD, which is abbreviated from depth of discharge. The DOD value is simply:

$$SOC = 1 - DOD \tag{12}$$

Hybrid electric vehicle

Research work in the fuel cell-battery hybrid system for transport application is done by Garcia et al. [26]. In this paper, the transport application selected is the tramway. The work done includes designing energy management system (EMS), which has fix references signals for fuel cell (FC) dc/dc boost converter, electrical motor drives and energy dissipation in the braking chopper. This paper focuses on studying the configuration, modeling and control of a FC-battery powered system for a tramway in Metro Centre in Seville, Spain. As part of the simulation test, an actual tramway was used.

The configuration of the tramway is as follows:

i. PEM FC (300 kW, 375V) and the modeling are performed by using Nernst's voltage equation.
ii. Ni-MH battery (240kW, 48kWh, 68 Ah) that is taken from SimPowerSystems toolbox of Simulink.
iii. DC/DC converter with rated power 375V.
iv. Tramways load is represented by four electric motor drives with each has 120 kW, 625V, 50 Hz and was modeled by PWM VSI induction motor using toolbox of SimPowerSystems in Simulink.
v. Braking chopper through modeling parallel current source.

The EMS of the tramway will optimize the generated energy system every time demanded power is provided. It also manages the operation of regenerative braking. The EMS has seven states of control strategy, which covers three level of battery state of charge (SOC) as followed: high SOC (60%-65%), medium SOC (42%-60%) and low SOC (<40%). The simulation of hybrid system and the control strategy in the real drive cycle is conducted for 330 s. The result shows that the tramway followed the real driving cycle properly.

Study of solar application on electric auto rickshaw has been done by Mullhal et al. [12, 27]. Auto rickshaw is a three-wheeled vehicle that can carry two or three passengers for short distance travel. It is heavily used in Asian countries like India, Indonesia and Vietnam. The research's main concern is to design a solar- or battery-powered vehicle that can reduce not only the total power consumption but also to increase efficiency in the motor and inverter. The prototype is designed and the vehicle layout is modeled and simulated by using the Advance Vehicle Simulator (ADVISOR) software. The author also develop model of recharge infrastructure. Investigation is done by using the Hybrid Optimization Model for Electric Renewables (HOMER) software. The software is used to calculate the amount of energy of power produced by renewable energy sources by any given station layout. The result presents three optimized layouts, which use PV, wind and generator as energy sources. For instance, in case 1: the percentage of renewable energy sources is used around 73% of a given station. The objective of the research is to study the efficiency between conventional rickshaw and solar-assisted electric rickshaw. As for the specification of a conventional rickshaw, Auto Rickshaw 1.0 has power capacity of about 6 kW with engine displacement of 175cc. Its weight is about 280kg, top speed of 55 km/h and distance travel is 70-120 km. The electric auto rickshaw, the Auto Rickshaw 2.0, on the other hand, has electric motor of 11 kWh, 48 V. Its batteries have a capacity of 5 kWh and solar cell power is 250 Watt. It is estimated to be able travel up to 120 km per charge and top speed of 70 km/h. There are four types of different drive train available. They are drive train with direct drives, with one electric motor, with parallel hybrid configuration and conventional rickshaw with a solar assist auxiliary power unit. The first two types are identical with the Auto Rickshaw 2.0 and the last two are identical with the Auto Rickshaw 1.0. Based on the simulation results, it had been seen that solar-assisted electric vehicle did not achieved the expected vehicle's travel distance. However, this is actually due to the fact that the simulated vehicle has not yet been optimized and thus has low value of efficiency. Overall, the simulation data provide researchers some important guidelines in terms of performance and range in solar-assisted electric vehicle. The author also did experiment verification through data acquisition from GPS to analysis vehicle speed, battery voltage and motor currents.

Characteristics study of HEV was executed by Lukic et al. [28]. HEV is categorized by their mechanical connections such as series, parallel or series/parallel. For a series HEV, electric motor will be responsible for the propulsion power. Meanwhile, engine is used to recharge the battery. For a parallel HEV, both electric motor and engine support will power the drive train. In a series/parallel HEV, an additional planetary gear set is used [29]. This mechanical device allows the energy flow to the drive train either in series or parallel HEV. However, Lukic introduces the concept of hybridization factor, HF to level hybridization of HEV. The classification of HEVs in HF is categorized between HF=0 (internal combustion engine, ICE vehicle) and HF=1 (electric motor, EM vehicle). The HF is interpreted as

$$HF = \frac{P_{EM}}{P_{EM} + P_{ICE}} \tag{13}$$

where: P_{EM} – the peak power of the EM and P_{ICE} – the peak power of ICE.

In the automobile industry, manufacturer produces different function of HEV to improve vehicle fuel economy and efficiency. These can be classified as [30]:

Micro-HEV (HF < 0.1): Micro-HEVs use limited power of EM as a combination of starter and alternator to provide a fast start/stop operation and then allowed the ICE to propel the vehicle. This means that the ICE can be stopped when the vehicle is in standstill condition. Thus, it saves the vehicle's fuel consumption by about 10% especially when traveling in the urban city.

Mild-HEV (HF<0.25): Mild-HEVs have additional function, which is to use EM to boost ICE during acceleration and to perform regenerative braking as well. However, the electric machine alone is not capable to drive the vehicle. It can save roughly about 10 – 20 % fuel consumption.

Power-assist HEV (0.25<HF<0.5): Power-assist HEV can provide substantial electric propulsion to support ICE. In a short distance, the vehicle can be turned into fully electric system or becomes zero-emission vehicle, ZEV. ICE alone can also insure the propulsion of the vehicle. This will allow fuel economical advantage to rise to up to 50%.

Plug-In HEV or Battery EV (HF>0.5): PHEV can also be considered as BEV as it uses battery as its storage device. The battery is recharged from residential power grid. Some of the vehicles are fully electric vehicles and some of them are accommodated with a generator for extended distance travel.

Hybrid fuel cell vehicle, HFCV (HF=1): HFCVs are electric vehicle as FC is considered as green emissions. A hydrogen tank is placed in the vehicle, and a reformer is used to extract the gas. The electricity gained by FC will drive the electrical machine. Additionally SC will also be used to improve its low power response. The FC development has been significantly researched but the major obstacles for the commercialization are cost, hydrogen storage and refueling infrastructures. Since the oil price is still affordable, HFCV is not yet preferred.

Another interesting overview paper is about open-road solar car racing written by Wisniewski [31]. It is a platform for the researchers to develop solar electric-drive vehicle. A solar car is an electric drive vehicle with battery as its primary power source. The solar cells will charge the battery for extended driving distance. The basic electrical components that of an electric vehicle are rechargeable energy storage system, electric drive motor and distribution, electronic control, lightning and mechanical parts like body, chassis and etc. For the combination of solar source, the essential components are photovoltaic cell and maximum power point trackers (MPPT). Some optional accessories that are a must for the top team are controller area network data communication bus, radio communication bus and telemetry.

Past 100 years ago, battery has faced tremendous development to improve its weight, durability, lifecycle, cost and effectiveness [32]. A new generation of battery, lithium-iron-phosphate (LIP), improves battery stability (safety), reduces toxicity and has better battery life. Today, battery safety is an important issue and battery protection system (BPS) is mandatory in a solar car race. For instance, battery specific energy allowed for LIP is 90 Wh/kg whereas for lead acid is at 40 Wh/kg.

Another important feature of solar controller is the MPPT [33], which has high efficiency of dc-to-dc converter. A photovoltaic cell shows exponential characteristics between voltage and current. A MPPT will select the best point of the curve and the optimum solar power will be delivered to the load. The MPPT also can store excess energy to battery or demand additional power from the battery. A MPPT can determine the suitable power of solar array even in changes weather.

Chao [18] performed simulation study on a fuel cell scooter in Taiwan. The study includes non-linearity form of power electronics and electrical machine. Factors like loss of conduction and switching as well as temperature stress on the semiconductors are simulated. Attention is also given on the influence of saturation and reluctance of electrical machine that have impact on performance of the overall system.

The study begins with performing cost analysis between a gasoline 50cc scooter and a 3.6 kW PEM fuel cell scooter. The first scooter is priced at approximately $1400 and the latter at $2045. However, the price of fuel cell scooter studied is actually a prototype price and it will certainly be lower in mass production. The author also did a cost comparison study on the fuel consumption of both scooters in Taiwan. The findings of the study showed that cost per distance for gasoline scooter is ¢1.5/km and it is ¢0.65 /km for the fuel cell scooter. As a summary, for long-term usage, the whole cost is actually the same for both scooters.

The simulation model of a fuel cell scooter is built of analysis of battery, electrical machine, power electronics, inverter, permanent magnet synchronous motor (PMSM) and field oriented control (FOC) model [34]. This model is using a dq model to study reluctance torque in PMSM and also d- and q- axis inductance to analyse influence of high loads. A hardware test is done to verify all simulation data. Some of the test items result differs from the simulation value. As an example: Mileage value in simulation model can reach only to 80km but in actual test it reaches even until 100.8 km and in fuel consumption, simulation value recorded was 1.6g hydrogen/km but in actual test the value is better at 1.34g hydrogen/km.

All results from these studies are essential in designing fuel cell scooter. The cost analysis gives an idea of the estimated selling price that people are willing to pay. The evaluation of simulation and real test results is also acceptable, as it didn't vary too far away from the expected value. The difference exists due to the fact that simulation model wasn't executed in ideal cases but with some aspect of losses and other decisive factor. In order to progress continuously, future study should be taken in the infrastructure of fuel cell station [35].

Research for energy management in a solar race car design and application was done by Ustun et al. [36]. Energy management model (EMS) is concerned in computing energy consumption from virtual vehicle including virtual racetrack. A model of the solar race car is set by the Scientific and Technical Research Council of Turkey (TUBITAK). The rules stated that battery power is 1000Wh and solar cell surface are 9 m^2. The design strategy is based on the design of electric-electronic, electro mechanic and energy management system. Thus, it will fulfill the objective to have high acceleration, speed and efficiency vehicle with less energy. Some of the decisions made in order to reduce losses are to do direct coupling of the electric machine with the wheel, high voltage in the dc bus eliminates transmission losses and the dc bus voltage of solar cell is attuned through MPPT [37].

There are four major components for the vehicle simulation and modeling. The modeling are in designing of energy sources like solar cells, battery and SOC, the body and mechanical loads, drive and transmission systems and data acquisition and measurements system. For the first model, total force of the load calculated is based on wheel friction, slope force, acceleration force and other motion and mechanical forces [38]. The second part focuses in optimization of MPPT of solar cell and calculation of power demand and supplied power through battery and solar. Regenerative braking is also taken into account and in this case, battery will turn into charge mode. An algorithm is developed to model the SOC of the battery. Designing of vehicle drive system involves power and control electronics. This system will drive brushless dc motor through mathematical model that includes variables of motor speed and currents. For data acquisition, Visual Basic 6 is developed to display data into main computer and the vehicle display. While the design of the solar race car is according to race track, a road race track of Istanbul is created and the vehicle runs virtually on the modeled track. The main objective of the study is to develop energy management software. This can be done by obtaining the best driving scenario with focus in calculating energy balance principles. The principle used is as following equation: (battery + solar cell) power = driving load power + losses. At the end, varieties of drive track cycle are tested and finest drive condition is developed.

The author of this paper gives an overall idea in technical aspects of solar car race. The solar car race is a platform for young researchers, who are interested to be involved in the technical development or project management of a solar car.

Renewable energy technologies challenges on hybrid electric vehicle

The most important challenge for hybrid electric vehicle to overcome is to demonstrate the same capability in speed, acceleration and power as the commercial ICE vehicle. This cannot be achieved with a single renewable energy, since it offers between low to medium specific power and energy only. Following sections will describe this in more details.

Battery Challenge

The effectiveness of fuel consumption in today's hybrid vehicle depends on the efficiency of the batteries. Hybrid vehicle is designed to allow battery powered driving for short distance travel and traffic-jam condition. This short distance drive is also known as the all-electric range (AER) [39]. This kind of driving is usually observed when driving in the cities and resulted in a significant decrease of fuel consumption. Once the battery reaches depleting mode or low SOC threshold, combustion engine started and charged batteries. The depth discharge cycle of the HEV is suggested at above 50% of SOC depth. Any value beyond this will reduce life cycle of the battery dramatically. This is demonstrated in Fig. 1, where depth of discharge and number of life cycle of Ni-MH and Li-ion batteries are presented.

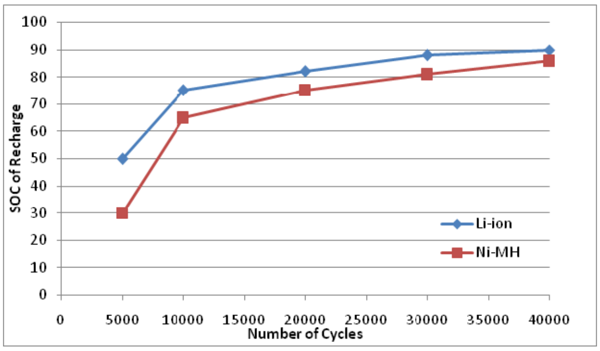

Fig. 1. The reduction of life cycle through SOC of recharge [39]

In order to increase AER and maximize storage capacity of the battery, its capability is measured in specific energy against weight (Wh/kg). Various battery types have different specific energy ranging from 20-40 Wh/kg for lead acid battery to 70-140 Wh/kg for Li-ion battery. This range is way too small when compared to about 12,000 Wh/kg of a gasoline. Nevertheless, the optimum battery capability for HEV lies in the range of 500 to 1000 Wh/kg. If this is achieved, other technical challenges that still to be considered are cost, higher life cycle, short recharge time, performance, durability and overall weight and volume [40].

Judging from the overall characteristics of the different battery types, Li-Ion is the best candidate that can offer good performance, and high durability with less weight and volume. Nonetheless, price and long recharge time are still two factors to contemplate. In term of cost, Li-ion price today is 35 Euro for 100Wh compared to 14 Euro of lead-acid of the same capacity. The best margin price is <5 Euro for every 100Wh. A light electric vehicle powered by 5kW electric motor, with distance travelled of 240km at constant speed of 80km/h, will need energy storage capacity of about 15kWh. This means that the cost of a battery electric vehicle (BEV) using Li-ion battery will achieve 5,250 Euro. Full recharge time will take about 5 hours to complete with the assumption that the energy capacity is 15kWh and recharge system is 3kW per hour. This is impractical for long distance travelling. A workaround for this is to charge to only 50% capacity, which will take less than half an hour.

Fuel Cell Challenge

Fuel-cell vehicle (FCV) is another candidate that shows high potential in HEV. Prototype FCVs from Honda, Mercedes and General Motors have shown that the vehicle is exceptional in terms of performance but are not yet market ready for commercialization. FC is pricey and has short durability of about 10 years only. Moreover, a designated refuelling station is also required. This is a major hurdle in the commercialization of FCV. Additionally, the cost to produce hydrogen, storage tank and fuel cell stack is also high.

Today, there are three methods used to yield hydrogen. Firstly and the highest producing method is by steam reforming by using natural gas. Chemical reaction between natural gas and steam will produce hydrogen and carbon monoxide. However, since natural gas is treated as fossil fuel, it has high price. Besides, the by-product is not free from greenhouse gas (GHG). Secondly, electrolysis method is used. Hydrogen will be accumulated from two electrodes that are submerged into water. This method does not produce any GHG emissions but it requires substantial electricity to flow current between the electrodes. Thirdly, the method used is called waste stream hydrogen, where hydrogen is the by-product from manufacturing sodium chlorate. Hydrogen will be the sole side product.

If mass production of hydrogen can be achieved, another challenge faced would be the storage tank. A standard storage tank for vehicle to travel distance of 200-350km needed to fill 5kg of hydrogen. This tank costs between 2000-2500 Euro and weights about 110kg. An ideal storage tank should cost less than 500 Euro and weight less than 50kg. The FC stack is also expensive due to the use of platinum (Pt) and Pt group metals (PGM) as catalyst. This PGM is a precious metal and it can improve performance and durability of fuel cell. Thus, it is challenging to find a non-precious metal replacement for it. For vehicular applications, FC stack should last for at least 10 years or more with 10,000 operating hours. It can also hold dynamic load variation which can cause hydrogen starvation, differential pressure imbalance and mechanical stress.

Super-capacitor Challenge

Super-capacitor is an assisting storage for electric vehicle. It is used as back-up storage or as uninterrupted power supply (UPS) for electric transportation. It also helps FC for low start and sudden high load in the vehicle. If the low energy capacity of SC is increased to more than 100

Wh, it can be useful to combine with battery as SC recharges faster, is lighter in weight, has longer lifecycle and higher specific power. Thus, in order to improve SC storage capacity, many scientist focus in the three basic SC design which are to increase the electrode surface, to decrease the electrode separation and to improve insulating layer. It would be very beneficial if SC can store energy as much as battery because then all the lead, cadmium, nickels and mercury found in battery can be omitted.

Solar Challenge

Energy from solar is still not adequate and inconsistent to be utilized for commercialization of electric vehicle. Although solar energy per meter area is considered intensively high at about 1500-2500 Wh, but after converting through PV panel, the energy produced is left to between 200-300 Wh only. If the energy amount is compared to light electric vehicle, it serves about 5-20% of energy consumption. If solar cell efficiency can be improved up to 40%, the idea of solar harvesting on the surface of vehicle would be better received by customers. Besides, the price of the solar panel needs to be kept reasonable too. Today, solar energy is priced at 1 Euro per Watt and if it can be reduced to less than 0.50 Euro, it would be attractive not only to transportation industry but also for stationary application.

Conclusion

Battery, FC, SCs and solar energy have potentials in the development of an electric vehicle. Many researches are trying to combine various energy sources including internal combustion engine. These combination techniques required an innovative energy management system. This technology has improved the efficiency of the vehicle, minimize the usage of energy and exhaust less polluted emission. For congested big cities where small size vehicle is a preferable, this kind of vehicle gives certainly huge benefit. A vast study has been done in fuel cell and solar array in transport application. Various kind of energy management has been designed with positive feedback. Thus, there is no doubt that these renewable energies will be our next generation of energy sources in the near future.

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REFERENCES

[1] Mierlo J.V., Maggeto G., Lataire P. Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles. Energy Conversion and Management, 47 (2006), Nr. 17, 2748-2760.

[2] Purvis G. Momentum is a winner, III-Vs Review 18 (2005), 35.

[3] Thounthong P., Chunkag V., Sethakul P., Sikkabut S., Pierfederici S., Davat, B., Energy management of fuel cell/solar cell/supercapacitor hybrid power source, Journal of Power Sources, 196 (2010), Nr. 10, 313-324.

[4] Mierlo J., Bossche P.V.d., Maggeto G. Models of energy sources for EV and HEV: fuel cells, batteries, ultracapacitors, flywheels and engine-generators, Journal of Power Sources, 28 (2004), Nr. 1, 76-89.

[5] Markvart, T. Solar Electricity, West Sussex: John Wiley & Sons. (2010).

[6] Parida B., Iniyan S., Goic R. A review of solar photovoltaic technologies, Renewable and Sustainable Energy Reviews, 15 (2011), Nr. 3, 1625-1636.

[7] Alamgir K., Pervaiz T., Arif S. Characterization of Cadmium Selenide Thin Film for Solar Cell Application, Energy Source Part A, 34 (2011), Nr. 4, 297-305.

[8] Borkowski P., Rakus, J. The concept and mathematical model simulations of light rail vehicle power using photovoltaic panels, Przeglad Elektrotechniczny (Electrical Review),11a (2012), 115-118.

[9] Liu G., Nguang S.K., Partridge A., A general modeling method for I–V characteristics of geometrically and electrically configured photovoltaic arrays, Energy Conversion and Management, 52 (2011), Nr. 12, 3439-3445.

[10] Khatib T., Mohamed A., Sopian K., Mahmoud M. Modeling of Daily Solar Energy on a Horizontal Surface for Five Main Sites in Malaysia, International Journal of Green Energy, 8 (2011), Nr. 8, 795-819.

[11] Khatib T., Mohamed A., Sopian K., Mahmoud, M. 2012. Estimating Ambient Temperature for Malaysia using Generalized Regression Neural Network, International Journal of Green Energy, 9, 195-201.

[12] Mulhall P., Lukic S.M., Wirasingha S.G., Lee Y.-J., Emadi A., Solar-Assited Electric Auto Rickshaw Three-Wheeler, IEEE Transaction on Vehicular Technology, 59 (2010), Nr. 5, 2298-2307.

[13] Wang Y., Chen K.S., Mishler J., Cho S.C., Adroher X.C., A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research, Applied Energy, 88 (2011), Nr. 4, 981–1007.

[14]Stambouli A.B., Fuel cells: The expectations for an environmental-friendly and sustainable source of energy, Renewable and Sustainable Energy Reviews, 15 (2011), Nr. 9, 4507-4520.

[15] Basu, S. Recent Trends in Fuel Cell Science and Technology, New Delhi: Springer, (2007).

[16] Correa J.M., Farret F.A., Canha L.N., Simoes M.G., An Electrochemical-Based Fuel-Cell Model Suitable for Electrical Engineering Automation Approach, IEEE Trans. Industrial Electronics, 51 (2004), Nr. 5, 1103-1112.

[17] Pasricha S., Shaw S.R. A Dynamic PEM Fuel Cell Model, IEEE Trans. Energy Conversion, 21 (2010), Nr.2, 484-490.

[18] Chao D., Duijsen P.J., Hwang J.J., Liao C.-H. Modelling of a Taiwan Fuel Cell Powered Scooter, International Conference on Power Electronics and Drive System, (2009), 913-919.

[19] Thounthong P., Chunkag V., Sethakul P., Davat B., Hinaje M., Comparative Study of Fuel-Cell Vehicle Hybridization with Battery or Supercapacitor Storage Device, IEEE Trans. Vehicular Technology, 58 (2009), Nr. 8, 3892-3904.

[20] Miller J., Introduction to Electrochemical Capacitor Technology, IEEE Electrical Insulation Magazine, 26 (2010), Nr. 4, 40-47.

[21] Hannan M.A., Azidin F.A., Mohamed A. Multi-sources model and control algorithm of an energy management system for light electric vehicles, Energy Conversion and Management, 62 (2012), 123-130.

[22] Hannan M.A., Azidin F.A., Mohamed A., Light Vehicle Energy Management System using Multi-Power Sources, Przeglad Elektrotechniczny (Electrical Review), 3b (2012), 197-204.

[23] Uzunoglu M., Alam M.S. Dynamic modeling, design and simulation of a PEM fuel cell/ ultracapacitor hybrid system for vehicular applications, Energy Conversion and Management, 48 (2007), Nr. 5, 1544-1553.

[24] Michalczuk M., Grzesiak L.M., Ufnalski B. A lithium battery and ultracapacitor hybrid energy source for an urban electric vehicle, Przegląd Elektrotechniczny (Electrical Review), 4b (2012), 158-162.

[25] Fernandez L.M., Garcia P., Garcia C.A., Jurado F. Hybrid electric system based on fuel cell and battery and integrating a single dc/dc converter for a tramway, Energy Conversion and Management, 52 (2011), 2183-2192.

[26] Garcia P., Fernandez L.M., Garcia C.A., Jurado F. Energy Management System of Fuel-Cell-Battery Hybrid Tramway, IEEE on Industrial Electronics, 57 (2010), Nr. 12, 4013-4023.

[27] Mulhall P., Emadi A. Comprehensive Simulations and Comparative Analysis of the Electric Propulsion Motor for a Solar/Battery Electric Auto Rickshaw Three-Wheeler, 35th Annual Conference of IEEE on Industrial Electronics, (2009) 3785-3790.

[28] Lukic S., Cao J., Bansal R.C., Rodriguez F., Emadi A. Energy storage systems for automotive applications, IEEE Trans. on Industrial Electronics, 55 (2008), Nr. 6, 2258-2267.

[29] Chan, C.C., Bouscayrol, A., Chen, K. Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling, IEEE Trans. Vehicular Technology, 59 (2010), Nr. 2, 589-597.

[30] Lukic S.M., Mulhall P., Emadi A. Energy autonomous

solar/battery auto rickshaw, Journal of Asian Electric Vehicles, 6 (2008), Nr. 2, 1135-1143.

[31] Wisniewski D., Solar Flair: An open-road challenge, IEEE POTENTIALS, (2010), 6-9.

[32]Pawłowski M., Borkowski P., Electric Energy Management System in a Building with Energy Storage, Przeglad Elektrotechniczny (Electrical Review),12b (2012), 272-274.

[33] Subiyanto, Mohamed A., Hannan M.A. Photovoltaic Maximum Power Point Tracking Controller Using a new High Performance Boost Converter, International Review of Electrical Engineering, 5 (2010), Nr. 6, 2535-2545.

[34] Yang Y-P., Liu J-J, Hu T-H, An energy management system for a directly-driven electric scooter, Energy Conversion and Management, 52 (2011), Nr. 1, 621-629.

[35]Azidin F.A., Hannan M.A., Mohamed A. An Energy Management of Light Electric Vehicle, International Journal of Smart Grid and Clean Energy, 2 (2013), Nr. 2, 271-276.

[36] Ustun O., Yilmaz M., Gockce C., Karakaya U., Tuncay, R.N., Energy Management Method for Solar Race Car Design and Application, IEEE International on Electric Machines and Drives Conference, (2009), 804-811.

[37] Bogalecka E., Kołodziejek P., Licznerski M. Photovoltaic modules shading effect impact to the Maximum Power Point Tracking algorithms efficiency, Przeglad Elektrotechniczny (Electrical Review),12b (2012), 303-305.

[38] Li Q., Chen W., Li Y., Liu S., Huang J., Energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle based on fuzzy logic, Electrical Power and Energy Systems, 43 (2012), Nr. 1, 514-525.

[39] Amjad S., Neelakrishnan S., Rudramoorthy R. Review of design considerations and technological challenges for successful developement and deployment of plug-in hybrid electric vehicles, Renewable and Sustainable Energy Reviews, 14(2010), 1104-1110.

[40] Daud M.Z., Mohamed A., Hannan M. A. A review of the integration of Energy Storage Systems (ESS) for utility grid support, Przegląd Elektrotechniczny (Electrical Review), 10a (2012), 185-191.

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