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A review of energy sources and energy management system in electric vehicles

Siang Fui Tie, Chee Wei Tan*

Department of Energy Conversion, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

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ABSTRACT

The issues of global warming and depletion of fossil fuels have paved opportunities to electric vehicle (EV). Moreover, the rapid development of power electronics technologies has even realized high energy-efficient vehicles. EV could be the alternative to decrease the global green house gases emission as the energy consumption in the world transportation is high. However, EV faces huge challenges in battery cost since one-third of the EV cost lies on battery. This paper reviews state-of-the-art of the energy sources, storage devices, power converters, low-level control energy management strategies and high supervisor control algorithms used in EV. The comparison on advantages and disadvantages of vehicle technology is highlighted. In addition, the standards and patterns of drive cycles for EV are also outlined. The advancement of power electronics and power processors has enabled sophisticated controls (low-level and high supervisory algorithms) to be implemented in EV to achieve optimum performance as well as the realization of fast-charging stations. The rapid growth of EV has led to the integration of alternative resources to the utility grid and hence smart grid control plays an important role in managing the demand. The awareness of environmental issue and fuel crisis has brought up the sales of EV worldwide.

Contents

* Corresponding author. Tel.: +60 7 5535768; fax: +60 7 5566272.
E-mail address: cheewei@fke.utm.my (C.W. Tan).

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1. Introduction

Electric vehicle (EV) has gained tremendous attention from the past decade as one of the promising greenhouse gasses (GHG) solution. In the late 20th century, the world energy crisis had brought up the interest in automobile field due to the continuous rising of global warming consciousness. Transportation sector has been one of the top contributors in the GHG emission globally. The conventional vehicle operates through internal combustion engine (ICE) from fossil fuels (*i.e.* gasoline or diesel) emits gases such as carbon dioxide, hydrocarbons, carbon monoxide, nitrogen oxides, water *etc.* From statistical database of U.S. Energy Information Administration (EIA), the world total energy consumption by end-use sector is shown in Fig. 1 and carbon dioxide emissions by end-use sector is shown in Fig. 2 [1]. Transportation sector stands almost 27% of total energy consumption in of the world and 33.7% GHG emission in 2012 [2].

The EV is one of the solutions to decrease the global GHG emission. By using electricity-empowered cars, we are not only providing cleaner and quieter ambiance but are also reducing the operating cost drastically compared to gas-powered cars. Electric vehicle spends 2 cents per mile, roughly, while ICE vehicle spends 12 cents per mile. For an example, \$3/gal can operate at 30 mpg, thus \$0.10/mile but for EV, 3 mile/kWh if \$0.12/kWh = \$0.04/mile. The Envisioneering Group Consumer Metrics, SAE state that using a conventional ICE vehicle, the average consumer spends 41 h and 40 min/yr at a gas station. People could save almost 15 h/yr at gas stations by owning an electric vehicle and charging their car at night. Besides that, EV has an integration flexibility advantage that promises a better performance in transportation area. Energy generators such as fuel cell, solar panel, regenerative braking and any other suitable generators can be integrated into EV.

According to the U.S. Department of Energy (USDE), about 15% of the total fuel energy is consumed to run a car and its other accessories. Most of the energy are transformed into heat during combustion which consequently and directly contribute towards global warming [3]. The typical energy flow for an ICE vehicle is shown in Fig. 3. In general, ICE vehicles lose their energy through friction on a moving part and heat loss from total energy in fuel. Therefore, frequent maintenance is needed for an ICE vehicle. However, EV consumes more than 75% of energy only to run the car. Today EV has an average 4–8 miles range per kWh of stored electricity [4].

However, EV and HEV face a huge challenge in battery cost since one-third of the EV cost lies on battery. A recent analytical report titled "*Global Autos*: *Don't Believe the Hype – Analyzing the Costs & Potential of Fuel-Efficient Technology*" by Bernstein Research and Ricardo PLC has concluded that 45.3% of the EV cost is battery's cost [5]. Because of this, the major challenge in auto-industry is to develop state-of-the-art battery system that complements the technology the most. Table 1 shows the annual fuel cost for BEV, HEV, PHEV and ICEV. Then, the next challenge coming up will be vehicle efficiency improvements. There are two major areas: First is the reduction in parasitic losses in constant and variable-speed electric drive units through the diminution of belts, gears and multiple motor drives, and the second area would be in electric mechanical drive including transmission, direct drive motors and remote controller "cable connected" power electronics.

On the other hand, EV, especially PHEV and BEV, require energy storage charging that poses a new challenge to the utility grid interconnection. Having acknowledged that the energy consumed in transportation is now switched from the conventional internal combustion engine into electricity charging energy storage devices. This has directly affected the electricity consumption of the utility grid. In recent years, many countries invest much in renewable energies (such as wind and solar) to meet the need of increased demand and avoid full dependence on conventional fossil fuels. Furthermore, the renewable energy can also help to reduce the peak load during peak hours of power consumption, as well as favor the supply-side management due to EV charging requirement. From the other perspective of view, the idea of vehicle-to-grid (V2G) system, which is the reverse activity of charging the vehicle, has been proposed recently. Around 95% of vehicles are parked, and the vehicle is connected to the grid as reported in literature [6]. Therefore, it shows that there is a high potential of exporting energy back to the grid during peak power demand or reserve as backup energy. The researchers in [7,8] have also suggested few strategies and business models for the implementation of V2G.

The aim of this paper is to review the state-of-the-art of the available energy source, energy generator for electric vehicle, power converter, low-level control energy management strategy and high supervisor control algorithm use in vehicles. The comparison on advantages and disadvantages of vehicle technology will be discussed next. All the current technologies related to EV will be discussed. This paper is organized as follows: Section 1 explains the environmental impact of current vehicle and future vehicles. Section 2 describes the overview of all types of vehicle configurations. It is followed by the state-of-the-art of the energy storage and energy generation device available for an electric vehicle in Section 3. Then, the overview of energy management topologies and control algorithm strategies will be explained in Section 4. Finally, Section 5 highlights the driving test standards and is followed by conclusions in Section 6.

2. System overview

2.1. Introduction

Vehicles can be classified into three groups: internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV) and all-electric vehicles (AEV). Fig. 4 shows all available vehicle types. All the detailed definitions of vehicles will be discussed next.

The hybridization factor (HF) was derived to calculate the ratio of hybrid or electric vehicle [9,10] as expressed in Eq. (1), where power from electric motor (EM) is divided by total power from EM (P_{EM}) and ICE (P_{ICE}). Assuming that the vehicle is not assisted by an auxiliary energy source (AES), HEV usually can be divided into mild or medium hybrid electric vehicles (mild-HEV) and full

Nomenclature

AC	Alternative current
AES	Auxiliary energy source
AEV	All-electric vehicles
AFC	Solid oxide fuel cells
a-Si	Amorphous silicon
ATEG	Automotive thermoelectric generator
BEV	Battery electric vehicle
BTU	British thermal unit
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Copper, indium or gallium
CSG	Crystalline silicon on glass
DC	Direct current
DIP	Driver's intention predictor
DMFC	Direct methanol fuel cell
DP	Dynamic programming
DSC	Dye sensitised cell
DSI	Driving situation identifier
ECE	Economic Commission of Europe drive cycle
ECMS	Equivalent fuel consumption minimization strategy
EDLC	Electric double-layer capacitors
EFG	Film-fed growth
EIA	Energy information administration
EM	Electric motor
EMI	Electromagnetic interference
EPA	Environment protection agency
EREV	Extended range electric vehicle
ESS	Energy storage system
EV	Electric vehicle
EWT	Emitter wrap through
FC	Fuel cell
FES	Flywheel energy system
FTD	Fuzzy torque distributor
FTP	Federal test procedure
GA	Genetic algorithm
GHG	Green house gasses
GPS	Global positioning system
HEV	Hybrid electric vehicle
HE-VESIM	Hybrid vehicle system simulation
HESS	Hybrid energy storage system
HF	Hybridization factor
HCPV	High concentrator photovoltaic
ICEV	Internal combustion engine vehicle
IEC	International Electrotechnical Commission
LA92	"Unified" dynamometer driving schedule
LCPV	Low concentrator photovoltaic
LED	Light-emitting device
MCFC	Molten carbonate fuel cell
mpg	Mile per gallon
NEDC	New European Driving Cycle
PAFC	Phosphoric acid fuel cells
PBC	Power balance controller
P_{EM}	Power of electric motor
P_{ICE}	Power of internal combustion engine
PEMFC	Proton exchange membrane fuel cells
PHEV	Plug-in hybrid electric vehicle
PSO	Particle swarm optimization
PV	Photovoltaic cell
RB	Rule-based
RTO	Real-time optimization
SC	Switched-capacitor
SC03	Air-conditioning drive cycle
SDP	Stochastic dynamic programming
SFTP	Supplemental federal test procedure
SOC	State of the charge
SOFC	Solid oxide fuel cells
SPHEV	Series plug-in hybrid electric vehicle
SR	String ribbon
TAGS	Alloys containing Te, Ag, Ge, Sb
TEG	Thermoelectric generator
TPV	Thermophotovoltaic
UC	Ultracapacitor
UDDS	Urban dynamometer driving schedule
USDE	U.S. Department of Energy
US06	Aggressive drive cycle in United States
VRLA	Valve regulated lead acid
V2G	Vehicle-to-grid
ZEBRA	Zero emissions batteries research activity
ZT	Dimensionless figure of thermodynamic efficiency
ZVS	Zero-voltage switching

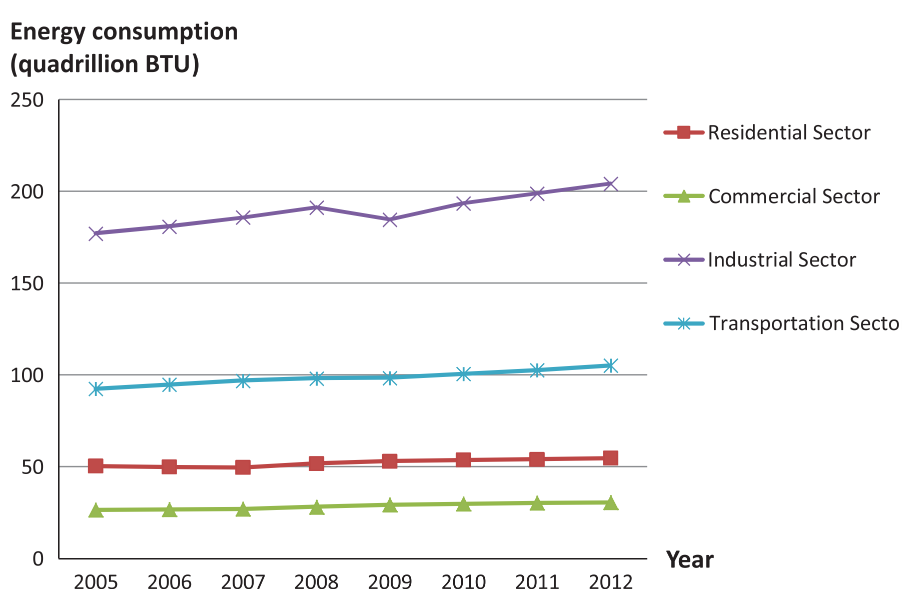

Fig. 1. The delivered energy consumption (Quadrillion BTU) based on different end-users.

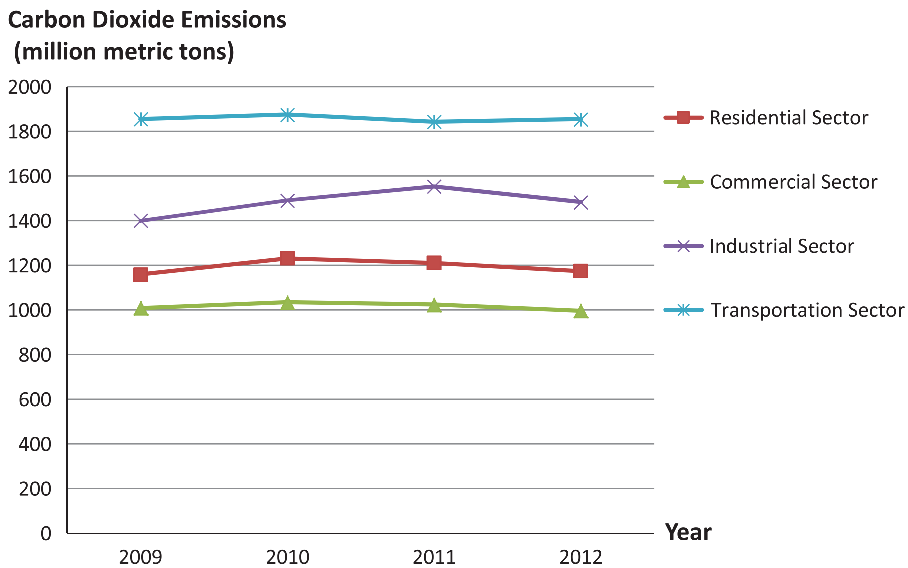

Fig. 2. The energy-related carbon dioxide emissions (million metric tons CO_2 equivalent) based on different end-users.

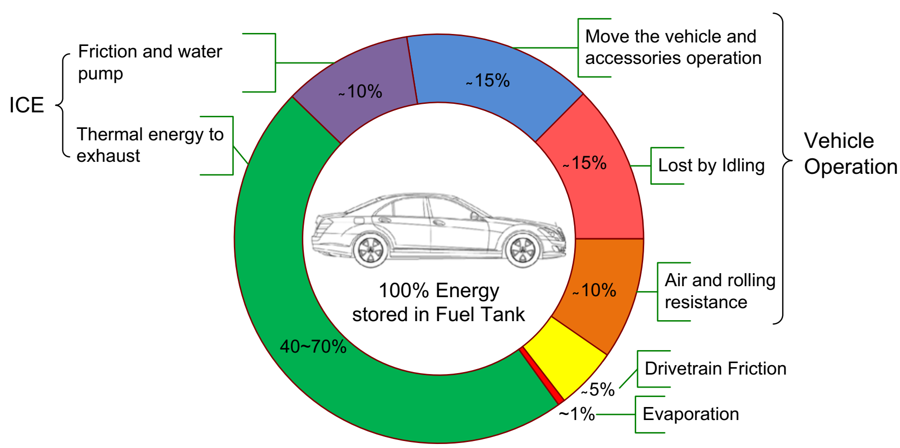

Fig. 3. The typical energy flow of conventional internal combustion engine vehicle.

hybrid electric vehicles (full-HEV).

$$HF = P_{EM}/(P_{EM}+P_{ICE}). \tag{1}$$

Currently, there are two ways to cascade the EM to ICE. One is by sharing the same shaft with ICE and EM. The second one is by a power split path. The difference in fuel efficiency calculated by mile per gallon (mpg) can be seen in every stage of vehicle hybridizing. Fuel efficiency is kept increasing from a conventional ICE vehicle to an AEV, which is shown in Table 2. A footnote on the Environment Protection Agency (EPA) site explains, "MPGe is miles per gallon of gasoline-equivalent and represents the miles per amount of energy of a non-gasoline fuel that is equivalent to the amount of energy in a gallon of gasoline. For an EV or PHEV, 33.7 kWh of electricity represents the same amount of energy as one gallon of gasoline" [11,12].

2.2. Internal combustion engine vehicle (ICEV)

ICEV has a combustion chamber to transform chemical energy to heat energy and kinetic energy to propel a vehicle. It has two types of vehicles: conventional ICEV which have no EM to assist and acquire lowest fuel economy and micro-hybrid electric vehicles (micro-HEV), which have EM with low operating voltage 14 V (12 V) and power not more than 5 kW only to restart ICE from off state without contributing any power to propel the vehicle. During coasting, braking or stopping the ICE turns off in order to improve fuel economy by 5–15 % (in city/urban driving environments). The Citroën C3, currently being sold in Europe, is a micro-HEV .

2.3. Hybrid electric vehicle (HEV)

The hybrid electric vehicle or HEV is a vehicle using both ICE and electric motor as power sources to move the vehicle. Nowadays, there are six types of drive trains architectures for HEV which are shown in Fig. 5. Mild-HEV has the same advantage with micro-HEV but electric motor in mild-HEV has an electric power of 7–12 kW with 150 V (140 V) operating voltage and can run the car together with ICE. It cannot, however, run without ICE (primary power) because they share the same shaft as shown in Fig. 5(a). This type of configuration normally gains fuel efficiency up to 30% and can reduce the size of ICE [13]. The GMC Sierra pickup, Honda Civic/Accord and Saturn Vue are examples for mild-HEV . Today, most of the car makers have the same pace to produce full-HEV due to its use of split power path either running on just ICE or the EM, or both. Without compromising the driving performance, full-HEV can save as much as 40% of fuel. Normally, this type of HEV has high capacity energy storage system (ESS)

with operating voltage 330 V (288 V). Full-HEV can be divided into extended range electric vehicle (EREV) or series full-HEV as shown in Fig. 5(b), hybrid electric vehicle (HEV) or parallel full-HEV, series-parallel full-HEV, complex full-HEV as shown in Fig. 5(c)–(e), respectively, and plug-in hybrid electric vehicle (PHEV) as shown in Fig. 5(f). EREV uses EM as the sole propulsion power as a battery electric vehicle (BEV) but the difference is that they still have a high efficiency (ICE) generator built-in to recharge when the batteries are low. Chevrolet volt is one of the EREVs currently available in the market. Such a vehicle is recognized as series full-HEV or series plug-in HEV. The advantage of this configuration is vehicle's battery that can be reduced depending on the generator power and fuel capacity. This reduces the overall vehicle efficiency to around 25.7% which is the lowest among all other full-HEVs . But it is suitable in stop-and-run driving pattern, *i.e.* city driving pattern. It reserves and stores most of the energy from regenerative braking to the ESS [14–16].

Referring to typical configuration in Fig. 5(c)–(e), parallel full-HEV has two propulsion powers (ICE and EM) in mechanical coupler, and is capable of improving the overall HEV efficiency to 43.4%. Parallel full-HEV, on the other hand, has a weaker battery capacity. One of the advantages of parallel full-HEV is that the EM and ICE complement each other during driving. This makes the parallel full-HEV a more desirable vehicle under both highway-driving and city-driving conditions. As compared to series full-HEV, parallel full-HEV has higher efficiency due to smaller EM and battery size. The series–parallel full-HEV drive train employs two power couplers that are mechanically powered and electrically powered. Although it possesses the advantage of series full-HEV and parallel full-HEV, it is relatively more complicated and costly. Complex hybrid seems to be a similar configuration with series–parallel hybrid. However, the key difference is that the power converter is added to the motor/generator and motor. This makes complex full-HEV more controllable and reliable than series–parallel full-HEV . For series–parallel full-HEV and complex full-HEV, they are more flexible on their control strategies than the other two configurations. Nonetheless, the major challenge is that they need precise control strategy. Furthermore, full-HEV configuration offers the lowest cost and the option of using existing manufacturer methods for engine, batteries and motors [14–16]. Toyota Prius, ToyotaAuris, Lexus LS 600h, Lexus CT 200h and Nissan Tino are commercially available series–parallel full-HEV while Honda Insight, Honda Civic Hybrid and Ford Escape are commercially available parallel full-HEV .

However, the plug-in hybrid electric vehicle (PHEV) is similar to full-HEV but the battery can be plugged-in to grid. Actually, PHEV is directly transformed from any type of HEV. For instance, Fig. 5(f) shows series–parallel HEV transforming into PHEV by adding charger beside the battery. So during running, the driver can set the power draw from battery pack more instead of ICE where it is one of the strategies to further improve the vehicle performance. For instance, in urban drive or a short distance drive, the driver could select the electric motor mode in order to achieve fuel efficiency as compared to the use of ICE engine. This strategy makes PHEV suitable both in city driving and highway driving pattern.

2.4. All-electric vehicles (AEV)

All-electric vehicles or AEV is a vehicle using electric power as only sources to move the vehicle. Currently, AEV have six types of power transfer configurations as shown in Fig. 6 but only three types are famous for use by an auto-maker . The configuration of the drive train designs in BEV and FCEV is similar. Fuel cell is either one of the main energy suppliers or secondary energy suppliers depending on requirement and current technology. Fig. 6(a) is directly converted from a conventional ICE vehicle. The gear box and clutch still remain in the vehicle. Fig. 6(b) uses single-gear transmission without clutch to reduce the size and weight of mechanical transmission. Both configurations have the lowest efficiency compared to other four configurations. To simplify the driveline configuration further, an integrated fixed gearing and differential is used as shown in Fig. 6(c) and (d) using two separate motors and fixed gearing with their driveshafts to operate at different speeds during cornering. However, the Fig.6(e) configuration is a direct drive (without driveshaft) from fixed gearing and motor. In Fig. 6(f), the traction motor is placed inside a wheel (in-wheel drive) which becomes more compact. Therefore, the size of the BEV can be reduced as in Mitsubishi's Colt EV (2005). This type of configuration is most suitable in city driving due to its overall low weight. However, this configuration requires a higher torque traction motor to start the acceleration. Therefore, the efficiency is low due to higher losses in the form of Joule heating by high current in motor windings. Nevertheless,

Table 1
The annual fuel cost of BEV, HEV, PHEV and conventional ICE vehicles.

Type of vehicle	Operating mode	Fuel cost (per 25 miles)	Annual fuel cost (per 15,000 miles)
Honda Fit EV 2012	Electric mode	RM 2.25	RM 1330
Nissan Leaf 2012	Electric mode	RM 2.90	RM 1740
Chevrolet Volt 2012	Electric mode	RM 3.00	RM 1800
	Gasoline mode	RM 8.35	RM 5010
Toyota Prius 1.8	Gasoline-electric mode	RM 5.80	RM 3480
Ptoton Inpsira 1.8	Gasoline mode	RM 6.86	RM 4115

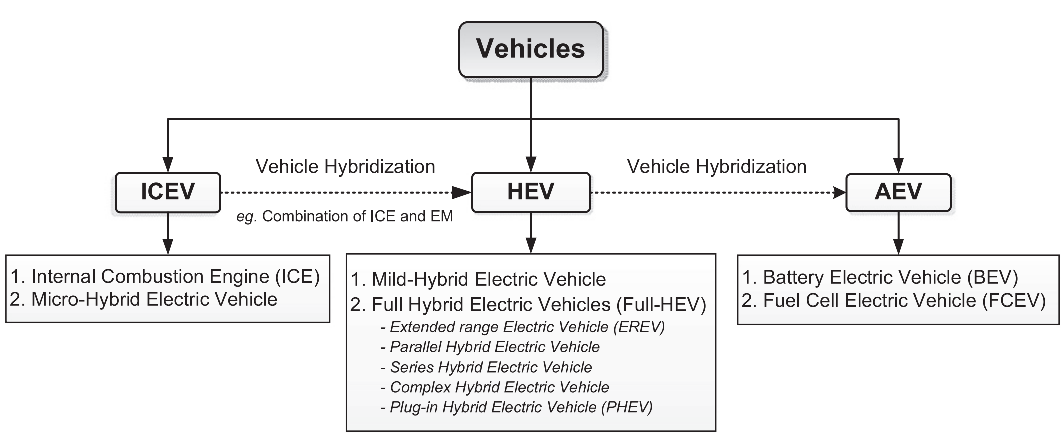

Fig. 4. The classification of the vehicle.

Table 2
The hybridization factor of various vehicles with its fuel economy.

Hybridization ratio (hp) (P_{EM}/ P_{total})	Hybridization factor (HF)	Name of the vehicle	EPA fuel economy (mpg)	
			Hybrid mode	Electric mode
15/455	0.03	BMW ActiveHybrid 7 2012	20	–
49/438	0.11	Lexus LS 600h L 2012	20	–
13/111	0.12	Honda Insight 2012	42	–
47/380	0.12	PorchePanamera S Hybrid 2012	25	–
40/196	0.20	Ford Fusion Hybrid 2012	39	–
23/110	0.21	Honda Civic Hybrid 2012	44	–
36/134	0.27	Toyota Prius 2012	50	–
36/134	0.27	Toyota Prius Plug-in Hybrid 2012	50	95
66/200	0.33	Toyota Camry Hybrid 2012	41	–
149/232	0.64	Chevrolet Volt 2012	37	94
170/170	1	BMW ActiveE 2011	–	102
123/123	1	Ford Focus BEV FWD 2012	–	105
63/63	1	Mitsubishi i-MiEV 2012	–	112
110/110	1	Nissan Leaf 2012	–	99
100/100	1	Honda Fit EV 2012	–	118

this configuration has the lowest mechanical drive train which reduces the losses from energy transfer between mechanical and electrical [14–18].

To sum up, the main disadvantage of BEV is that it can only travel a short distance. BEV is suitable in stop-and-run driving such as city driving. To extend the distance range of BEV so that it becomes suitable in city and highway load profiles, the gearbox is fixed inside the vehicle. By doing so, the ability of the traction system is extended in every range. However, the BEV without gears (motor-to-wheel configuration) can increase the efficiency due to the deduction of the quantity of the moving part (rotational inertia). Hence, no energy is lost in gear and differential mechanism. This configuration reduces the vehicle's central gravity. Housing of the motor in the wheel increases the unsprung weight of the wheel, which exhibits an adverse effect on the handling of the vehicle [18].

3. Energy sources in electric vehicles

3.1. Energy storage unit

In practical, the most commonly used energy storage is a battery. Other energy storage devices include ultracapacitor (UC), flywheel, hydrogen tank *etc*. These storage devices could be utilized as an auxiliary energy source (AES) or hybrid energy source. Below is the state-of-the-art of energy storage unit used in a vehicle.

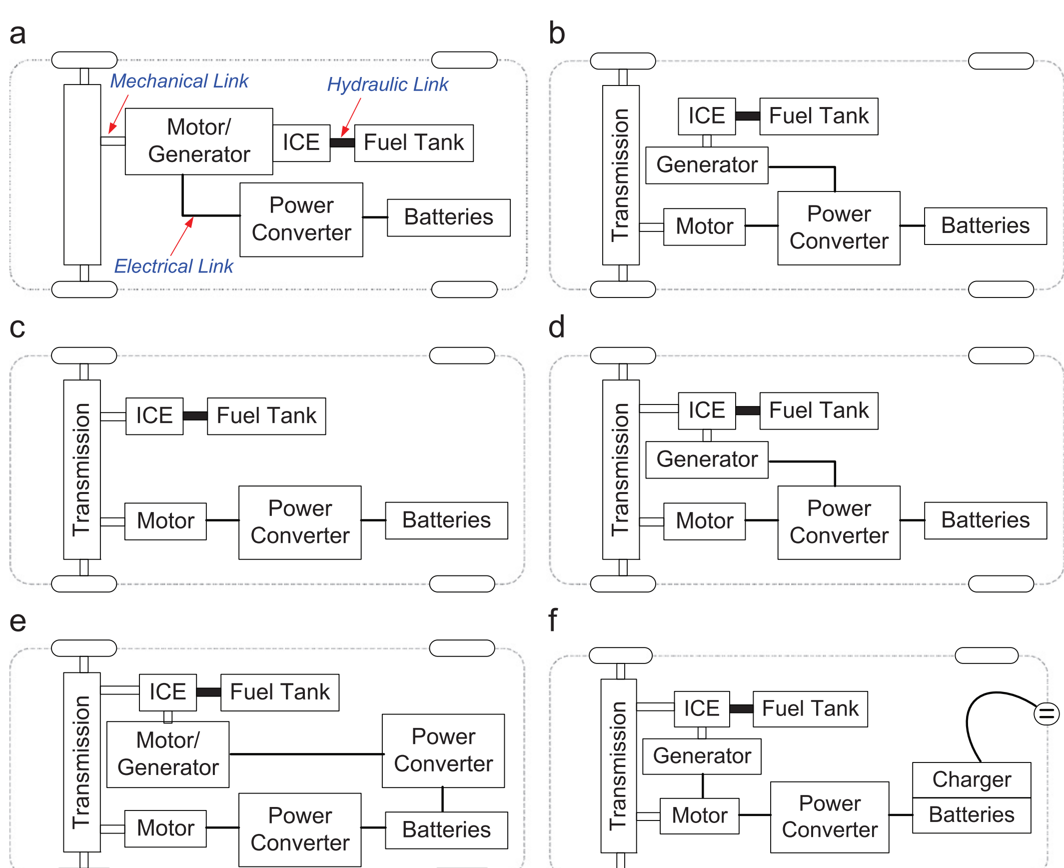

Fig. 5. The drive trains architectures on HEV: (a) mild-HEV, (b) series full-HEV, (c) parallel full-HEV, (d) series–parallel full-HEV, (e) complex full-HEV, (f) series–parallel PHEV.

3.1.1. Battery

Battery is a storage device which consists of one or more electrochemical cells that convert the stored chemical energy into electrical energy. There are several characteristics that one should take into account in selecting the most appropriate battery for EV. The most significant characteristic is the battery capacity, which is measured in ampere–hours (Ah). Besides that, the energy stored in battery (capacity $\times$ average voltage during discharge) which is measured in watt-hours (Wh) should be carefully calculated. The useable state-of-charge (SOC) of the battery which is represented in percentage is equally important as it indicates the current status of charge available in the battery.

The battery has to be managed well to operate in the window of SOC or SOC swing in order to prolong the life-cycle of the battery. The capacity is proportional to the maximum discharge current. The maximum discharge current is typically represented by the index of C. For example, a discharge rate of 1C indicates that the battery is depleted in 1 h while 2C indicates that the battery is depleted in only half an hour. This maximum current is affected by battery's chemical reactions itself and heat generated. Table 3 shows the ESS specifications required for various types of vehicles [3,13,19–22].

Today, five groups of battery are available in the market which is suitable for road transportation application. Table 4 shows all the battery technologies and characteristics. A lead–acid battery is the most common and cheapest battery used by a conventional ICE vehicle. The application of this battery is more preferable when weight is least concern. The lead–acid battery is not an environment-friendly battery. It causes environmental problems either during production or disposal process.

The nickel battery, for example, nickel–zinc is more environment-friendly, comparatively, but has a short life cycle. The major issue of a nickel–iron battery still is its heavy weight, high maintenance cost and high self-discharge rate. The nickel–cadmium (Ni–Cd) battery has a memory effect that is not suitable to use in high charge/discharge rate like automobile application but it performs well under rigorous working conditions. Besides, it contends toxic materials and high maintenance cost. Nickel–metal hydride (Ni–MH) is also one of the environment-friendly batteries. Ni–MH has about 50% higher self-discharge compared to the Ni–Cd . The other drawback of this battery is that it takes longer time to charge than lead–acid and Ni–Cd battery, and it generates a large amount of heat during charging. Consequently, Ni–MH battery requires more complex charge algorithm and expensive chargers despite being most widely used in EV [23].

A zero emissions batteries research activity (ZEBRA) battery is built by sodium nickel chloride (NaNiCl). It has a high temperature characteristic around 300–350 °C. Then high temperature technology has to be used in order to maintain suitable efficient operation. ZEBRA batteries have less life-cycle-cost than those of lead–acid batteries [27]. It has advantages such as higher or equal energy density to lithium battery, lowest cost of any modern EV battery technology, high calendar life, ruggedness, fail-safe to cell failure (overcharging or over discharging), resistant to overcharge and over-discharge . The main drawback of this battery is 90 W energy loss while not in used [28].

A lithium battery is one of the promising energy storage devices due to its light weight, high specific energy, high specific power and high energy density. In addition, lithium batteries have no memory effect and do not have poisonous metals, such as lead, mercury or cadmium. Every lithium battery needs a protection circuit in every pack in order to maintain safe operation. The main disadvantage is that lithium battery requires high production cost than NiCad and Ni–MH battery pack. In a lithium battery, lithium metal is the most expensive among them but less safe than lithium-ion battery. Currently, the lithium–sulfur battery can give

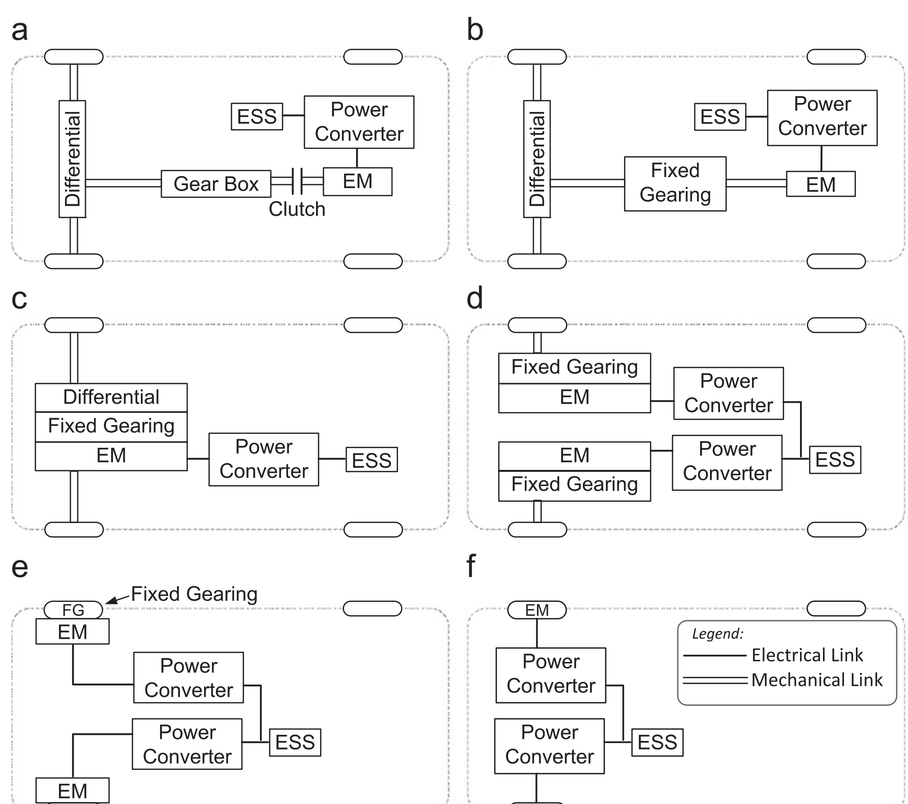

Fig. 6. The drive trains architectures on AEV: (a) conventional driveline with clutch, (b) driveline with single-gear transmission without clutch, (c) driveline with integrated fixed gearing and differential, (d) driveline with two separate motors and fixed gearing, (e) driveline with fixed gearing and motor, (f) in-wheel drive.

a higher energy capacity with low weight among lithium batteries but cycle life is a major drawback. Lithium-ion polymer can adapt to a wide variety of packaging shapes, reliability and ruggedness but it has a poor conductivity and a low power density. For a high power density lithium battery, lithium–iron phosphate is one of selections in other word it has higher discharge current then most of lithium battery. Besides that, lithium–iron phosphate is a superior thermal and chemical stability battery, which provides better safety characteristics than lithium-ion batteries. The lithium–titanate battery has the advantage of being faster to charge than other lithium–ion batteries which are currently used by Mitsubishi's i-MiEV electric vehicles.

The other type of battery such as zinc-air battery is another promising battery. This battery has high specific energy and high energy density than a lithium battery. However, the main drawback is its low specific power, limited cycle life and bulky [23]. Currently, the lithium air battery is still in the research state and has not been commercialized yet. Since the lithium-air battery has a higher energy density than the zinc air battery, it will become the target to all EV.

3.1.2. Ultracapacitor (UC)

Ultracapacitor (UC) or supercapacitor has a similar structure with a normal capacitor, but the difference is that UC have high capacitance (high energy capacity with factor of 20 times) than capacitor. The ultracapacitor characteristic includes maintenance-free operation, longer operation cycle life and insensitive to environment temperature variation. Currently, there are three types UC technologies used in HEV and AEV, that is, electric double-layer capacitors (EDLC)—carbon/carbon, pseudo-capacitors and hybrid capacitors. The difference between those UC is in their energy storage mechanisms and their electrode materials used. The specific power density for these three types UC is almost similar around 1000–2000 kW/kg for 95% efficient pulse but EDLC has a more power density than other types of UC. Specific energy density of EDLC is the lowest (5–7 Wh/kg). However, the other two have almost similar energy density (10–15 Wh/kg). The UC lifetime can reach 40 years, which is the longest among all ESS.

3.1.3. Flywheel energy storage (FES)

Flywheel energy storage or FES is a storage device which stores/maintains kinetic energy through a rotor/flywheel rotation. Flywheel technology has two approaches, *i.e.* kinetic energy (rotational energy) as output and electric energy as output energy. Chris Brockbank, the Business Manager from Torotrak mentioned that the efficiency of energy from braking to FES is 70% which is the double of the efficiency of energy transformed from braking to electric energy and then to FES in [29]. The overall FES mechanical efficiency can hike up to 97% and round-trip efficiency up to 85% if magnetic bearings and vacuum are used. Currently, research agencies (such as Lawrence Livermore National Laboratory (LLNL) in US, Ashman Technology, AVCON, Northrop Grumman, Power R&D, Rocketdyne/Rockwell Trinity Flywheel US Flywheel Systems, Power Center at UT Austin and so on) have developed an ultra-high-speed flywheel system for EV. Typically, the system can achieve 10–150 Wh/kg energy and 2–10 kW/kg power. For instance, LLNL built a prototype which can achieve 60,000 rpm, 1 kWh and 100 kW in a 20 cm diameter and a 30 cm height. Compared to UC, FES has a higher energy density and power density. Unfortunately, the safety issues and gyroscopic force are their disadvantages, if FES fails to manage well in transportation usage [14,30]. However, FES still can be used in transportation due to some characteristic such as long lifetime more than 15 years with less maintenance compared to other energy storage devices. FES has a fast power response time short recharge time which electric vehicles required. Besides, it operates in a wide temperature range which causes less damage to the environment [31,32].

3.1.4. Hydrogen energy

Hydrogen vehicle is the vehicle that uses hydrogen as an onboard energy to power the vehicle. The chemical energy (hydrogen gas) will convert into mechanical energy either by burning hydrogen in an ICE or by reacting hydrogen with oxygen in an FC to produce electricity. Hydrogen contains abundant energy per unit of weight but behave little energy per unit of volume, which is a major drawback for transportation. Dr Ben Lane [33] stated to store an equivalent amount of energy with typical petrol tank, require around 800 times the volume of hydrogen at room temperature and pressure. Table 5 summarizes the comparison of hydrogen storage system in a vehicle which travels the same distance and same type of vehicle. There are three main possible solutions to store hydrogen: compression (7000 times atmospheric pressure), cryogenic system (hydrogen liquefaction at -253 °C), hydrogen absorbing materials (absorb hydrogen when under pressure or temperature). Hydrogen can be absorbed in three methods: first is through metals (pure and alloyed) under pressure to make a metal hydride. Then hydride will release hydrogen when heated. The second methods is hydrogen absorption through charcoal which can achieve an equal amount of storage density of liquid hydrogen, using small glass spheres (microspheres), carbon nanotubes and fullerenes through high pressure and temperature. The third method is that hydrogen is held captive in the solid matrix when the temperature decreases, and can be released by heating the solid again. For safety reason (prevent hydrogen from starting fire), hydrogen tanks come with sealed canalization, ambient well ventilated and minimization of near-ignition sources [33–35]. Today, hydrogen storage technology has already matured and no safety barrier prevents the use of hydrogen for fuel as that with today's gasoline system [36]. However, hydrogen production is still lacking efficient methods to produce hydrogen. Currently it is made through electrolysis on water and alcohol types. Direct production in which water splits by nanophoto catalysis is one of the most promising methods [37]. If hydrogen is produced by electrolysis,

Table 3
Suitable specifications of different vehicle (with mass less than 2000 kg).

Class of HEV[19]	System voltage (V)	Battery (kWh)	UC		Fuel cell		EM or integrated starter-generator (ISG) (kW)
			Energy (W h)	Peak power (kW)	Energy (kWh)	Peak power (kW)	
Conventional ICE	12	–	–	–	–	–	–
Micro-HEV	12–42	0.02–0.05	30	6	–	–	3–5
Mild-HEV[13]	150–200	0.125–1.2	100–150	35	–	–	7–12
Full-HEV [20]	200–350	1.4–4.0	100–200	–	–	–	40
PHEV[21,22]	300–500	6.0–20.0	100–200	28–45	–	–	30–70
AEV[22]	300–500	20.0–40.0	300	28–45	150–200	50–100	50–100

Table 4
The comparison of energy storage specifications based on type of energy storage device [24–26].

Energy storage Type	Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Life cycle	Energy efficiency (%)	Production cost ($/kWh)
Lead acid battery						
Lead acid	35	100	180	1000	> 80	60
Advance lead acid	45	–	250	1500	–	200
Valve regulated lead acid (VRLA)	50	–	150+	700+	–	150
Metal foil lead acid	30	–	900	500+	–	–
Nickel battery [24]						
Nickel–iron [25]	50–60	60	100–150	2000	75	150–200
Nickel–zinc	75	140	170–260	300	76	100–200
Nickel–cadmium (Ni–Cd)	50–80	300	200	2000	75	250–300
Nickel–metal hydride (Ni–MH)	70–95	180–220	200–300	< 3000	70	200–250
ZEBRA battery [24,25]						
Sodium–sulfur	150–240	-	150–230	800+	80	250–450
Sodium–nickel chloride	90–120	160	155	1200+	80	230–345
Lithium battery						
Lithium–iron sulphide (FeS) [24]	150	–	300	1000+	80	110
Lithium–iron phosphate ($LiFePO_4$)	120	220	2000–4500	> 2000	–	350
Lithium-ion polymer (LiPo)	130–225	200–250	260–450	> 1200	–	150
Lithium-ion	118–250	200–400	200–430	2000	> 95	150
Lithium–titanate (LiTiO/$NiMnO_2$)	80–100	-	4000	18000	–	2000
Metal-air battery						
Aluminum-air	220	–	60 [25]	–	–	–
Zinc-air	460	1400	80–140	200	60 [25]	90–120
Zink-refuelable	460	–	–	–	–	–
Lithium-air	1,800	–	–	–	–	–
Ultracapacitor						
Electric double-layer capacitor (EDLC)	5–7	–	1–2M	40 years	> 95	–
Pseudo-capacitors	10–15	–	1–2M	40 years	> 95	–
Hybrid capacitors	10–15	–	1–2M	40 years	> 95	–
Flywheel	10–150	–	2-10k	15 years	80	–
Hydrocarbon [25]						
Hydrocarbon fuel (gasoline/propane)	12,890	9500	–	–	< 30	–
Hydrogen	39,720	1600* 2800**	–	–	ICE: < 25 FC: 50	4**
Natural gas (250bar)	14,890	101	–	–	–	–

***Hydrogen storage cost [26].
* In pressure 700 bar.
** In liquid.

Table5
Summary of weight and volume of different tank types [36].

Vehicles with equal driving distance per fill-up	Mass (kg)	Volume (L)
Gasoline/ICE	50	70
Compressed hydrogen (350bar)/FCs	90	320
Compressed hydrogen (700bar)/FCs	~100	180
Liquid hydrogen/FCs	45	190
Hydrogen in metal hydride/FCs	200–600	180

using under renewable resources the consumption of primary energy of the FCEV is 130% more than that of the BEV; it consumes more than the double [38].

3.2. Energy generation unit

An integrating generator in the vehicle is not a new idea, but it is a promising method to extend the range of a vehicle. After using a battery as an energy storage instead of a fuel tank, more of the electric generator can be built in the vehicle. There are several types of energy generators to be discussed below.

3.2.1. Fuel cell (FC)

A fuel cell or FC is an energy conversion device where chemical energy is converted into electric energy *via* an electrolysis process. The byproduct of an FC is heat and water. Therefore, FC technology was proved to reduce the dependence of oil resources and hazardous CO_2 emissions, which are stated in [27,28]. There are several types of FC, which are direct methanol fuel cells (DMFC), proton exchange membrane fuel cells (PEMFC), alkaline electrolyte fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cells (SOFC). Fig. 7 shows the FC technologies, taken from the U.S. Department of Energy, Energy Efficiency & Renewable Energy (February 2011) [39]. Currently, DMFC is used in portable electronic such as mobile phones, PDAs, tablet, laptop and others due to its low temperature operation, fast recharge and more energy capacity. Energy density of methanol is 4390 Wh/L compared with a Li-ion battery with a density of 620 Wh/L. Among the fuel cells, DMFC, PEMFC, AFC and PAFC are categorized in low operating temperature FC. These FCs are currently used in transportation such as Citaro fuel-cell bus and Honda FCX Clarity (passenger vehicle). The MCFC and SOFC are high operating temperature FC, which are normally used in electric utility and distributed generation due to its high power output. The main advantage of the FC in transportation application is the capability of operating in high efficiency, low emissions, silence, and the FC system is simple [39,40].

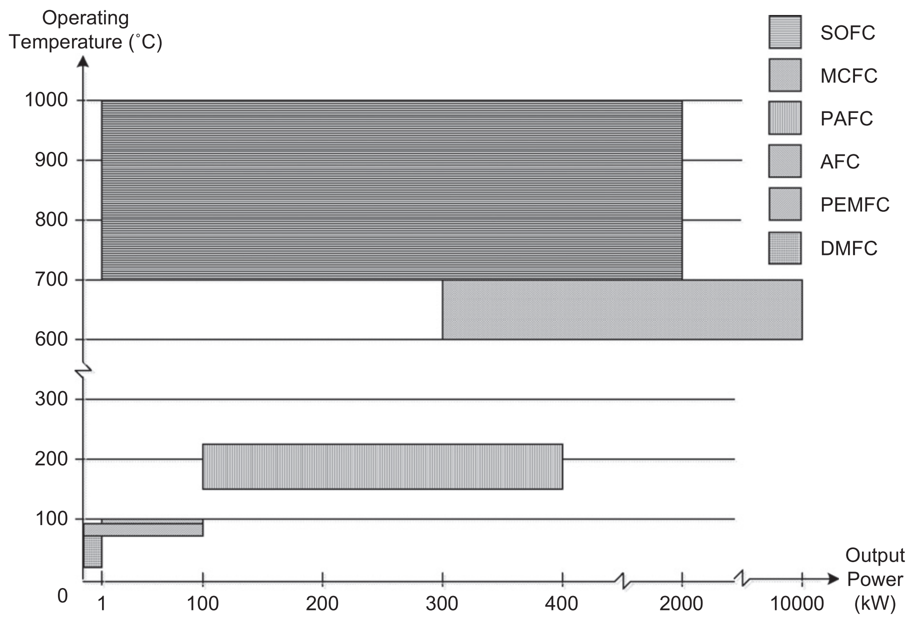

Fig. 7. The temperature–power characteristics of various available fuel cells.

Table 6
The efficiency of existing PV modules based on different PV technologies.

Class of PV[47,50]	Methods/technologies	Cell efficiency (%)
Mono-crystalline Silicon	Thinner Silicon Wafer Technology	–
	Back-Contact SunPower Technology	22.4-23.4
	Sanyo HIT Technology[48]	22.3
	Suntech Pluto Technology (PERL Technology)	20.3
Polycrystalline	Benchmark Silicon Sawn Wafer Technology	14-17
	Edge-defined Film-fed Growth Process (EFG)	15.7-18.2
	String Ribbon (SR)	16-18
	Back-Contact Emitter Wrap Through (EWT) Technology [48]	15
	Light Capturing Ribbon	19.5
Thin film [48,49]	Amorphous silicon (a-Si)	9.5-13.2
	Copper indium diSulphide (CIS or CIGS)	16.7-19.9
	Cadmium telluride (CdTe)	15.0-16.5
	Crystalline silicon on glass (CSG)	8.0-10.4
Very high performance PV cells	Single and double junction (GaAs)	21.0-28.3
	Multi-junction	25.0-41.1
	Indium, gallium, nitrogen (full spectrum)	37.6
	Gallium nitride/silicon tandem solar sell[53]	21-33.8
Concentrator PV technology	Low concentrator PV (LCPV) under five suns	25-30
	High concentrator PV (HCPV) typically 500 suns	40
	Combined CPV electricity and direct heating systems	42.4
Third generation	Dye sensitised cell (DSC)—polycrystalline [45]	8.0-12.3
	Organic polymer	2.0-5.0
	Quantum dot	18.7[55]
	Multi-junction nanowire PV cells	–
	Thermophotovoltaic (TPV)	13.0-22.0
Innovative panel designs	Transparent solar cell	1.7-10%

3.2.2. Photovoltaic cell (PV)

Solar energy or photovoltaic (PV) as the AES for vehicles has been around since 20 years ago [41–43]. During that time, using a solar panel was not applicable and necessary for an idea to be used in a conventional ICE vehicle [44]. However, nowadays the solar panel is drawing attention again and becoming the goal of some automakers for the purpose of increasing passenger's comfort. Vehicles such as the 2010 Prius, Aptera 2, Audi A8 and Mazda 929 have had solar sunroof options for ventilation purposes. There are seven photovoltaic technologies which are shown in Table 6 [45–53]. Currently, the price of solar panel decreases to 40% due to Chinese manufacturers [54].

Currently, the leading manufacturing PV technologies in market are from crystalline silicon PV and thin-film PV. The crystalline silicon PV can be divided into three types: mono-crystalline, polycrystalline

and ribbon silicon. Crystalline silicon PV has an overall efficiency around 15–20 % and can achieve maximum of 30% in rare condition. This PV is very costly in manufacturing, a relatively poor absorber of light and its wafers are thick and bulk if compared to thin-film PV. However, the thin-firm PV has an overall efficiency around 6–11 % and can achieve maximum of 21% in rare condition. This PV technology can have multiple surface options (glass, plastic and steel) with lowest cost per watt (Wp). But the thin-film PV utilizes rare earth elements which is finite quantities globally. Other PV technologies such as shown in Table 6 are the new PV technologies with a small scale in global power production when compared with the crystalline PV.

A solar powered vehicle remains as a challenge due to the limitation of space for PV and moreover the amount of power generated is not high. However, when an airplane took more than 24-h solar-powered flight and landed safely [56], it makes everyone fired up again. Many researchers start to install a solar panel on the vehicle and hope, in the near future, the power is fully generated from PV. They maximize the surface of the vehicle to accommodate the PV panel [57]. Ref. [58] derives control algorithms to increase the power produced by PV. The results indicate that the overall efficiency has improved up to 60%. Literature [59]studies the converter used for PV on rooftop of EV and proves that there are fuel economy improvements. Some automakers also start to include PV on rooftop of vehicle, such as Chevrolet Volt and Prius. These manufactures shave integrated PV on rooftop that gives the power up to 130 W. Toyota Prius uses PV energy to cool the interior of a vehicle. During 2007 to 2008, Palmer Louis had built its own 6 m^2 solar powered vehicle (solar taxi) that traveled a distance of 53,451 km in 534 days [60]. However, these are still incomparable with solar powered vehicle with mass 150 kg, ESS capacity of 5 kWh, power produced at 1.8 kW, surface area covered by PV nearly 12 m^2 and better efficiency as compared to current EVs [61,62].

3.2.3. *Automotive thermoelectric generator (ATEG)*

Thermoelectric generator or TEG is a device that converts heat energy into electricity. Currently, it is very popular in obtaining optimum fuel economy and total efficiency of either ICE vehicle or electric vehicle. This is the highest due to the energy loss in heat energy, as shown in Fig. 3. Therefore, ATEG is a device that can convert waste heat in ICE combustion into electricity. The researcher from [63] builds prototyped ATEG module and has demonstrated that it can achieve 40% to 70% efficiency. The life time of ATEG is around 10 to 20 years without maintenance with low $/watt installed capability. The fuel economy test is also performed to improve fuel economy by 1% to 4% depending on the type of vehicle.

The materials that have a high seebeck effect are semiconductors because of the high electrical conductivity and low thermal conductivity. Most common materials used are Bi_2Te_3, PbTe and SiGe. The other materials such as n-type BiSb, p-type TAGS and $FeSi_2$ have good thermoelectric properties, but are less used. This is because of various practical difficulties such as high sublimation rates, poor mechanical strength and absence of homologous n-type or p-type material. Table 7 shows the characteristic of the TEG materials [64,65]. The symbol, ZT, is the thermoelectric material effectiveness, where a high ZT means that the particular TEG can convert more heat energy into electric energy as ZT. There are some automakers testing TEG with their vehicles such as Nissan, GM Chevy Suburban and 2006 BMW 530i.

Table 7
The characteristic of available thermoelectric generator materials.

Temperature (°C)	Type	TEG material	ZT (maximum)
< 150	p	Bi_2Te_3	0.8
	n	Bi_2Te_3	0.8
150–500	p	Zn_4Sb_3	–
	p, n	PbTe	0.7, 0.8
	p	TeAgGeSb (TAGS)	1.2
500–700	P	$CeFe_4Sb_{12}$	1.1
	n	$CoSb_3$	0.8
700–900	p, n	SiGe	0.6-1.0
	p	LaTe	1.4

3.2.4. *Regenerative braking*

When a vehicle is in coasting and braking modes, the kinetic energy from a moving car generates electricity back to the supply side which is known as regenerative braking. Currently, there are four ways to capture the energy generated by regenerative braking. First, the electricity generated is stored directly into ESS. Second, hydraulic motors could store energy in a small canister through compressed air. Besides that, energy can also be stored in FES as rotating energy. The last way is to store the regenerative braking energy as gravitational energy (potential energy) through spring. Table 8 shows different methods to recover the braking energy [66,67]. Regenerative braking operates together with the friction brake in some ratio when the vehicle starts to slow down. This is because the regenerative braking system has not generated enough energy to physically stop the vehicle. It also serves as a safety purpose of the vehicle. In order to improve the regenerative braking operation, there are some constrains that need to be considered. The consideration factors include the ability or size of electric generator, state-of-charge of battery and UC, electrical circuit design and drive cycles [68].

Today the energy, produced through regenerative braking, is only suitable for vehicles with high ESS capacity, which include HEV and AEV. This is due to the fact that electric generators generate very high power which could be in the range of 15–60 kW during braking. For instance, even though the Mazda's i-ELOOP is for conventional ICE vehicles yet it has the regenerative braking system. This model of vehicles can store the electric energy in capacitor and charges the battery to reduce the use of alternator which is claimed to improve the fuel economy up to 10% [69]. Study shows the conventional ICE vehicles only use less than 20% of total fuel energy to propel [70,71]. Nearly half of the regenerative energy can be recovered back and directly increase the driving range about 10% to 25%; for example, in GM Impact 4 up to 25% [72,73]. Most conventional ICE vehicles use compressed gas energy storage and FES. Compressed gas energy storage converts the kinetic energy into elastic energy in gas. Then the gas comes out through the pump when the vehicle re-accelerates . FES or kinetic energy recovery system (KERS) is currently used only by Formula One [74]. Both compressed gas

Table 8
Methods to recover braking energy [66,67,75].

Energy storage mechanism[66,67]	**Energy converter**	**Recovered energy from braking**	**Example current application**	**Fuel EPA**
Electric energy storage	Electric motor/generator	~50%	HEV, AEV	20%
Compressed gas energy storage[75]	Hydraulic motor	> 70%	Heavy-duty delivery vehicles	40–50% improve
Flywheel energy storage	Rotational kinetic energy	> 70%	F1	43%
Gravitational energy storage	Spring storage system	–	Train	5%

storage and FES are of promising methods to handle regenerative braking due to the advantage of large power density and being small in physical size [67].

3.3. Energy conserving options in EV

Energy consumption in an electric vehicle is another important aspect because it affects the overall efficiency and performance of the vehicle. As shown in Fig. 3, the conventional ICE vehicle only consumes approximately 15% of total energy. In general, most electrical accessory loads in conventional ICE vehicles are comparable with EV. This is because most automakers still focusing on maximizing the vehicles travel a distance as well as the ESS used in EV. The electrical accessory loads in vehicle include electric power steering, electric brakes, air-conditioning systems, head lights, radio system, navigation system, auxiliary battery *etc.* In the past, these electrical loads are only powered by 14 V operating voltage [76]. However, the new technology has led to invention of more advanced electrical load (such as high efficient adjustable speed air-conditioning unit, power electronic controlled steering, electronic brake force distribution (EBD or EBFD) *etc.*) that consumes higher power than the traditional loads. In order to fulfill the increased demand, the electrical power distribution system in EV is operated by 42 V. The advantages of the new technology load include high efficiency and performance, less expensive operational cost and procedures, reduced total installed power due to the integration of the mechanical and hydraulic power into the electrical power system and reduction in overall design complexity [77]. Besides that, high efficiency electrical load can be used to reduce the power consumption which can prolong the per cycle discharge of battery. For example, high intensity light-emitting device (LED) is one high energy efficient product used in modern vehicles. To sum up, the total power consumed by all EV accessories is approximately 1320 W [78] while the total energy consumption by those accessories is roughly 200–600 Wh [26].

3.4. Charging technology for energy storages

Besides the capacity of battery, charging is another challenge in EV, especially PHEV and BEV. The charge duration remains an issue where the large capacity of ESS takes a long time to be fully-charged . Moreover, the charging facility (charging station) has not yet been commonly available and accessible. However, the advancement in power electronic technology has improved the battery charging technology. There are two types of charger, namely inductive coupling and conductive coupling. The former type is a charger without a contacting medium but the power is transferred magnetically. It has the advantage of connection robustness, safer than conductive coupling, power compatibility and durability to the drivers [79]. Although inductive coupling brings convenience to drivers but this method is yet to achieve high efficient level. This technology requires careful considerations which include the range of frequency used, magnetizing inductance, leakage inductance and significant discrete parallel capacitance [80,81]. As for the latter charging method, conductive charging is a conventional charging method which transfers the power through contacting metal to metal between charger and vehicle. In the design of conductive charger, concern has to be stressed on the safety issues and its circuit interface configurations. Currently, the conductive charging method is most widely used and it has two charging methods, namely on-board and off-board methods. For the on-board method, charging activity is done inside the vehicle where the vehicle has its own build-in charger. This is suitable for nighttime charging at residential area and daytime charging at a work place. This is different from the off-board method where an external charger is used to charge the vehicle's ESS. This is similar to a gas station for an ICE vehicle. Table 9 summarizes the classifications and technologies of available EV charging stations [82,83]. Charging infrastructures can be divided into three levels [79]. The first level is the residential charging infrastructure, which is installed at household area. It allows the vehicle to be charged over night time that uses low cost night time energy tariff as well as to avoid the peak hour demand. The residential charging has two modes (Mode 1 and Mode 2), in which the difference is only the protection standard. In the U.S., Mode 1 charging is prohibited due to the national codes and standard. Therefore, the Mode 2 is introduced for safety protection. The second level of charging infrastructure is the public charging infrastructure. This can be found at everyday activity places such as shopping malls, company parking and workplaces throughout city. This charging infrastructure is normally integrated with authentication and payment system. The third charging level is the ultra-fast charging station which is similar to the petrol station that we have now, but this charging station is typically placed at highway/express way [82].

In near future, more charging stations will be installed to stimulate and encourage the use of EV. This will lead to the increase of energy demand, and the power producer has to figure out new supply option to cope with it. For that reason, smart grids with renewable energy sources become the main source for charging station [84]. The development of smart grid control integrated with demand management helps to reduce peak power usage on power distribution system.

4. Energy management review

4.1. Low level component control review

EV re-born is due to the advancement of power electronic technology. Power electronic plays an important role in converting,

Table 9
Classification and technologies of available EV charging station.

Classification	**On-board method Residential/Level 1**				**Public/Level 2**	**Off-board method Fast or ultra-fast/Level 3** [82]
	Mode 1		**Mode 2**		**Mode 3**	**Mode 4**
Electrical characteristic	1-Phase 120/240 V_{ac} 16 A 3.3 kW	3-Phase 400 V_{ac} 16 A 10 kW	1-Phase 240 V_{ac} 32 A 7 kW	3-phase 400 V_{ac} 32 A 24 kW	3-Phase 400 V_{ac} 63 A 43 kW	Direct current 50–700 V_{dc}, 100–125 A, 50–300 kW
Charging period	6-8 h	2-3 hours	3-4 h	1-2 hours	20-30 min	< 20 min
Safety	Circuit breaker to protect against overload		Basic protection * with In-cable protection device		Basic protection* with control system	Basic protection with control system
Standard[83]	local NF-C-15100		IEC 61851-1 IEC 60309		IEC 61851-1	IEC 62196 IEC 61851-1
Socket	Household socket		Domestic socket		Dedicated circuit-socket	DC connection socket

* Such as earthling system, circuit breaker to protect against overload and an earth leakage protection.

transferring, cascading and controlling the energy source and output components. The following review is made on the types of power electronic converter, energy transfer types, type of cascading and controlling method.

4.1.1. Power electronic converter topology

There are four types of converter such as DC–DC converter, AC–AC converter, inverter and rectifier. A lot of DC–DC converters were developed to meet the requirements of certain applications and can be categorized into many groups [85]. This paper focuses only on unidirectional (2-quadrant) and bidirectional (4-quadrant) DC–DC converter. Currently, there are five types of non-isolated converter topologies being used and studied by researchers in EV application [86] as shown in Fig. 8.

Referring to Fig. 8, a cascade buck-boost converter, as shown in Fig. 8(a), has lower electrical and thermal stresses but requires twice the number of active components. This type of converters can be simplified into half-bridge converters as shown in Fig. 8(b), which has the same number of active and passive components as bidirectional buck-boost converters.

Comparing haft-bridge with Fig. 8(c) Cuk and Fig. 8(d) SEPIC/Luo converters, haft-bridge converters require only one small (half of the size) inductor instead of two and low current ratings for active components. This would subsequently lead to lower inductor conduction and lower switching and conduction losses on the active components. Therefore, the efficiency of a half-bridge converter is higher than a Cuk and SEPIC/Luo converter. The main drawback of half-bridge converter is its discontinuous output current during operation in boost mode. The advantage of the Cuk converter is that it has insignificant input and output ripple current. This converter is suitable to be used in fuel cell application because it can be easily isolated. However, the drawback of the Cuk converter is that it has a large inductors size and large voltage ($V_{in}+V_o$) rated on transfer capacitor (C_t). Therefore, a combined SEPIC/Luo converter improves the Cuk converter which has small voltage (V_{in}) rated on a transfer capacitor. However, the main weakness is that it requires two large inductors: discontinuous output current and large output capacitor.

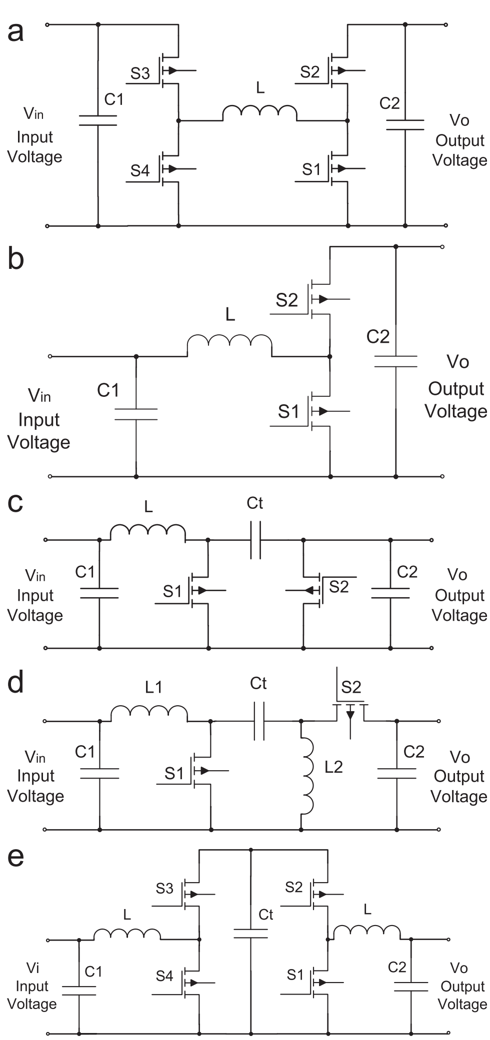

Fig. 8. The configuration of available bidirectional DC–DC converters: (a) cascade buck-boost, (b) half-bridge, (c) Cuk, (d) SEPIC/Luo, (e) split-pi.

Currently, Fig. 8(e) split-pi converter topology as a bidirectional DC–DC converter also applies to various applications including regenerative braking in EVs. The split-pi converter uses smaller passive component sizes with relatively high efficiencies ($>97\%$). The other advantages, such as reducing switching noise and triangular current waveform, contain less harmonics [87]. The other converter topology, such as 4-quadrant switched-capacitor (SC) Luo Converter, is studied by Amjadi [88]. This proposed topology converter promises lower source current ripple, simple dynamics, control simplicity and continuous input current waveform in both modes of operation.

For high performance in automotive application, normally converters require low ripple or tight tolerances. One of the solutions is using three-stage parallel (parallel connection of switching converter) interleaved technique as shown in Fig. 9(a). The interleaved converter topology promised low inductor current ripple due to three inductor currents that are 120° out of phase with each other. This topology can achieve a higher efficiency, compared to the buck-boost converter and full-bridge isolated DC–DC converter. Therefore, it gives a faster transient response to load changes. This technique has improved the total weight and volume of the converter, but it has a serious issue related to charging/discharging on ESS (limited output voltage range) [89,90].

To overcome this problem, the hybrid switched-capacitor (SC) bidirectional converter as shown in Fig. 9(b), which is a combination of switches and capacitor, is used. Different combinations of switches and capacitors give different operations (buck or boost) and polarities of voltage. The advantages of this converter are that it has a lower source current ripple with high power density, cheap topology with simple dynamics (easy to control), produces low electromagnetic interference (EMI) and has continuous input current waveform in both buck mode and boost mode. Therefore, it gives a high efficiency in energy conversion [91,92].

When the vehicle comes to more sources, sources selection strategy can be implemented. There are two methods to do it: by source swapping topology as shown in Fig. 9(c) and by using source selection on half-bridge converter topology as shown in Fig. 9(d). Source swapping topology gives less flexibility compared to using switch selection on half-bridge converter. However, source swapping topology uses fewer switches which are simpler to control compared to topology in Fig. 6(d). The source selection method shown in Fig. 9(d) can be modified into a multi-input converter which is suitable to an electric vehicle [93–95].

The Z-Source network as shown in Fig. 9(e) can be placed in the front of an inverter after the input source to boost the voltage. Z-source converters behave like a voltage source and current source converter, composed of an impedance network to couple converter circuit to the power source or load. This method can also be applied to all types of converters (DC–DC, DC–AC and AC–AC) to increase performance, minimized component count, increase efficiency and reduced cost. The Z-source inverter is suitable used in FC, PV and wind energy sources which are

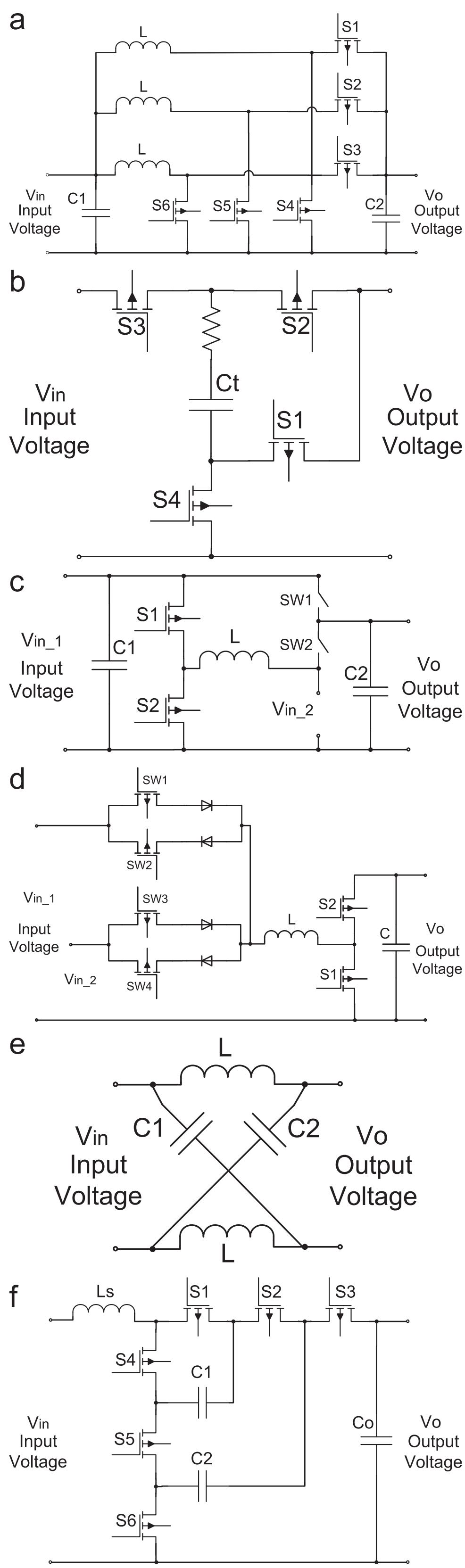

Fig. 9. The available improvement of converter topologies: (a) interleaved converter, (b) hybrid switched-capacitor, (SC) bidirectional DC/DC converter, (c) power swap, (d) source selection on half bridge converter, (e) Z-source network, (f) bidirectional 3× DC–DC multiplier/divider converter (Ls is the parasitic inductance of cable and the equivalent series inductance of battery).

unidirectional power flow. However the Z-source in FC application is recommended by Mitch Olszewski, due to the Z-source inverter with self-voltage boost (self-boost phenomenon) function for faster and more reliable fuel cell startup, especially for freeze startups [96–101].

The bidirectional 3× DC–DC converter as shown in Fig. 9 (f) is another converter having high power DC–DC boost converter. Obviously, the inductor in the traditional converter is bulky, heavy and hottest parts for HEV or EV application. Advantages of 3× DC–DC converter or so-called multilevel DC–DC converter include no or minimal need for magnetic components (inductor), easy to integrate, compact size, lightweight, high efficiency (98%), low EMI and magnetic-less circuit [102]. Compared with traditional DC–DC converter, it has a much higher power density. If compared with the existing switched-capacitor converters, it has the minimum device count, the lowest voltage stress and much higher efficiency [103].

4.1.2. Hybridization of energy storages

Energy management topology refers to power transfer drive train architecture where strategies are on controlling energy and power flow. Hybrid energy storage system or HESS is a combination of more energy storages in the system. The DC-bus system is used due to most of the energy storage system or ESS is done in a DC source. Clearly, the bidirectional DC–DC converter is used to manage two-way energy transfer and cascading HESS to DC-bus system. Some considerations have to tackle such as the peak power of the source and output power requirement. Different power ratings of converters may have different sizes of power semiconductor, inductor and total cost [104].

The study by researchers in [9,104–114] concluded that there are five types of HESS and converter arrangement topology illustrated in Fig. 10. The simplest and inefficient energy management topology is known as passive parallel connection between two sources as shown in Fig. 10(a). Two sources (battery and UC) will be used in the discussion below. Referring to Fig. 10(a), battery's voltage is always the same as the UC voltage. Therefore, the power delivered from the UC is limited, and higher power of the UC's characteristic cannot be fully utilized. In the arrangement shown in Fig. 10(b), a DC/DC converter is placed before one of the energy sources. The efficiency of the inverter in floating DC link arrangement (b)(i) is lower than the fixed DC link (b)(ii) because of the voltage between DC–DC converter and inverter varying with the UC's voltage. However, fixed DC link arrangement (b)(ii) has to be sized in high power peaks since UC has high power components which, in turn, increase the overall size and cost of converter and also reduce the heating on battery pack. One of the advantages of the fixed DC link is that UC can be sized in a minimal size.

For arrangement in Fig. 10(c), the DC–DC converter allows decoupling of both sources where the first converter controls the battery's current while the second converter UC supplies the remaining power required. This is similar to the arrangement in Fig. 10(d)(ii). In this arrangement, the large voltage swings from input source to the second converter, reduces the efficiency due to large IR losses at low UC voltages. Connecting energy storages with two-input bidirectional DC–DC converter in parallel as shown in Fig. 10(d) to decoupling the power supplying paths promises higher flexibility, stability and efficiency to low-level component control. Hence, this reduces the size and weight of the HESS and battery life especially due to the output current stresses significantly. Using more converters increases the weight of vehicle. The last arrangement proposed by the researchers [115,116] is isolated by multiple DC/DC converters. It has high power efficiency, high reliability and long life-cycle operation. It

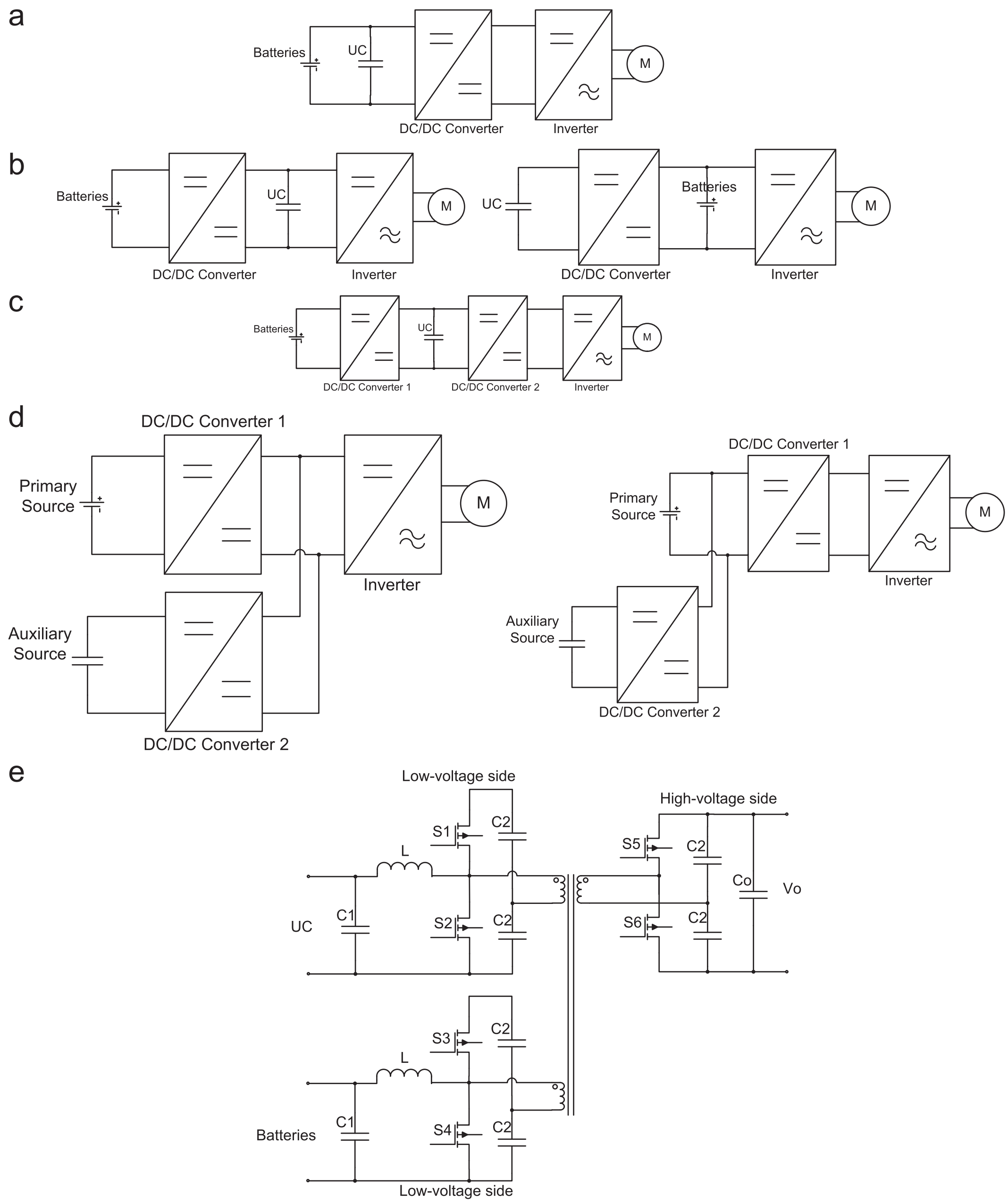

Fig. 10. The configuration of low component control systems: (a) passive parallel connection, (b) one bidirectional DC–DC converter in series, (c) two bi-directional DC–DC converter in series, (d) two-input bidirectional DC–DC converter in parallel, (e) multiple-input ZVS bidirectional DC–DC converter.

uses optimum power sharing between the sources. But it contributes more weight to the overall converter.

4.2. High level supervisory control

The high-level supervisory control is the control of the overall low-level components control. It improves overall vehicle performance because fuel efficiency depends on current data and future data. In other word, this high-level controller usually comprises event-based or time-based conditions that coordinate the component level operation. Characteristic of hybrid drive train is considered as discrete dynamic system, which has time-varying plant, multi-domain variable and nonlinear variable. Therefore, a more intelligent control algorithm is used to improve the low-level component control [117]. There are two classes of control, i.e. rule-based (RB) control and optimization approaches control. The category of control strategies is shown in Fig. 11. The next section summarizes both controls from the paper [118–125].

4.2.1. Rule-based control

Rule-based control (RB) is the control system based on human expertise (engineering knowledge), heuristic, intuition, even mathematical model, pre-defined driving cycles and load leveling strategy on vehicle. RB control can be divided into deterministic rule-based methods and fuzzy rule-based methods. Deterministic rule-based use looks up tables (not a real-time data) to design deterministic rules. It can be sub-divided again into thermostat (on/off) control strategy, power follower (baseline) control strategy, modified power follower (baseline) strategy and state machine-based strategy. However, fuzzy rule-based methods use real-time parameter and suboptimal power split, which are nonlinear data and linguistic knowledge to calculate optimal

output. Main advantages are robustness (tolerant to imprecise measurements) and adaptation (easy to tune) with real-time parameter. It can be sub-divided into conventional fuzzy strategy, fuzzy adaptive strategy and fuzzy predictive strategy.

Thermostat (on/off) control strategy is robustness, simple and easy to control. This control method leads to frequent on and off (charging and discharging) on the sources, which is inconvenient to battery system for example. Sources turn on and off depend on the SOC of sources. In order to turn on and off the sources, power follower (baseline) control is used. This control is designed based on power demand from the vehicles and the SOC of sources. Currently, it is used by ADVISOR. The only disadvantage is that it does not consider the power train component efficiency directly and fuel consumption/emissions minimization policy. This control was used by Honda Insight and Toyota Prius. However, the modified power follower (baseline) strategy is based on energy usage and emissions through cost functions. The state machine-based approach is another control approach, which is based on a change in driver demand. They can have many operating modes through state machine but not promise vehicle able obtain optimize energy usage and emissions.

In conventional fuzzy strategy, a lot of methodologies can be used to design fuzzy logic control. One of the methods is to use sophisticated controller which consists of two fuzzy logic controllers, for example driver's intention predictor (DIP) and power balance controller (PBC) [126]. Another method is to design through load-leveling such as in [127–129]. With load-leveling, the individual components can be optimized effectively. Fuzzy adaptive strategy is based on weight of the equation. This weight defines the relative importance of the parameter. Therefore, it is able to control any parameter decisively. Some authors derive adaptive fuzzy rule-based controller on the basis of the driving environment awareness [130,131]. This control technique uses driving environment awareness (expert knowledge that consist of roadway type, driving situation and energy flow in the drive train) to determine the effective distribution of torque between the motor and the engine through intelligent energy management agent. This agent consists of driving information extractor, driving situation identifier (DSI), fuzzy torque distributor (FTD) and SOC compensator. From the driving profile, intelligent energy management comes to know the roadway type, driver's driving style in driving trend, the driving situation and several characteristic parameters of the driving pattern. This technique neglects the driveline efficiencies. However, overall it gives fuzzy logic energy management system most accomplished. Fuzzy predictive strategy is another control, which is based on the driving history to decide the future state through a look-ahead window along a planned route. The drawback is that it is unable to perform real-time control task for example along a planned route; we do not know the obstacle (heavy traffic, steep grade, downhill, etc.) that will be faced in near future.

4.2.2. Optimization approach control

Optimization approach control is based on analytical or numerical operation which is able, obviously, to minimize the cost function. One of the examples of numerical black boxes is the hybrid vehicle system simulation HE-VESIM . Optimization approach control can be divided into global optimization and real-time optimization methods (RTO). Global optimization is based on knowledge of future and past power demands to minimize the cost function through fuel efficiency (fuel consumption) and emissions over a fixed driving cycle. It is useful in design and comparison purposes if implemented together with rule-based strategies. There are a lot of strategies that are categorized under global optimization, for example linear programming, control theory approach, optimal control, dynamic programming (DP), stochastic DP, genetic algorithm and adaptive fuzzy RB, while real-time optimization consists of equivalent fuel consumption minimization, decoupling control, robust control approach and optimal predictive control. Real-time optimization is based on the system variable at the current data which is instantaneous cost function. Real-time optimization consists of equivalent fuel consumption minimization strategy (ECMS), decoupling control, robust control approach and optimal predictive control. These control strategies include the drivability of the vehicle. The advantages and disadvantages of the abovementioned strategies will be discussed in the next section.

In global optimization, linear programming uses many piecewise-linear approximations to approximate/transform hybrid drive train (as convex optimization) and fuel efficiency (as a nonlinear convex optimization) to linear program. One of the disadvantages of this control is approximation/transformation that may not be applicable in complicated drive train system. The control theory approach is based on two decisions (torque and gear number) to find a global optima solution. This control is superior due to its analytical nature characteristic, but is more difficult in finding an analytical solution if applied in a complicated drive train

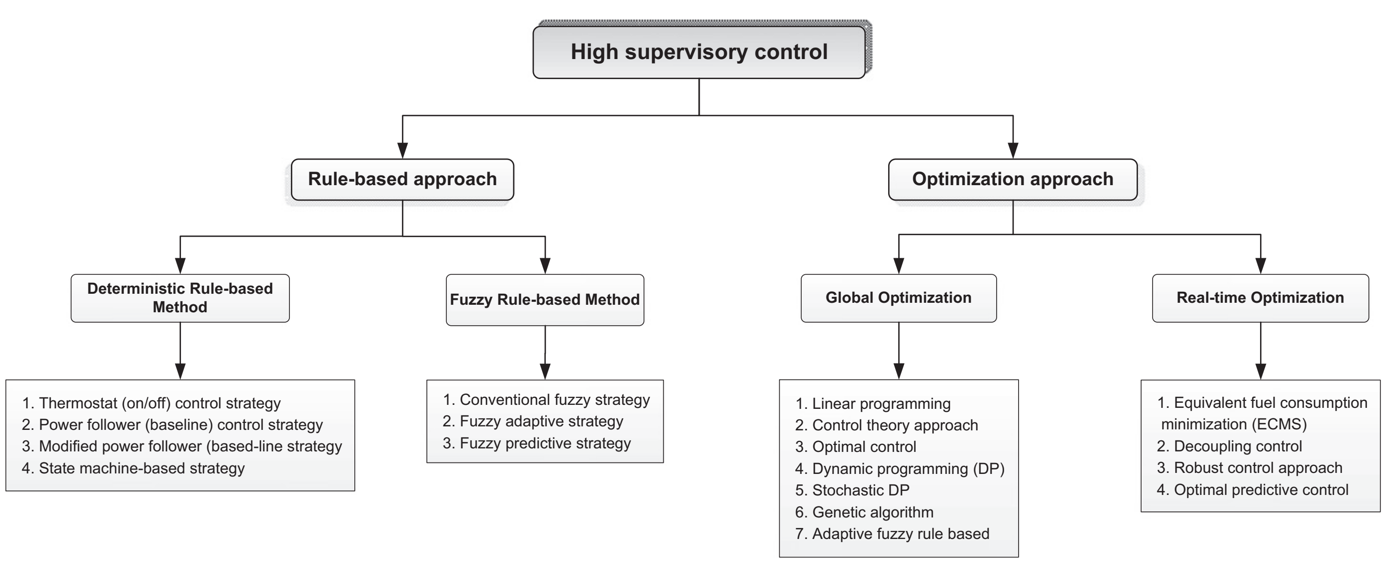

Fig. 11. The available control strategies applied in electric vehicle.

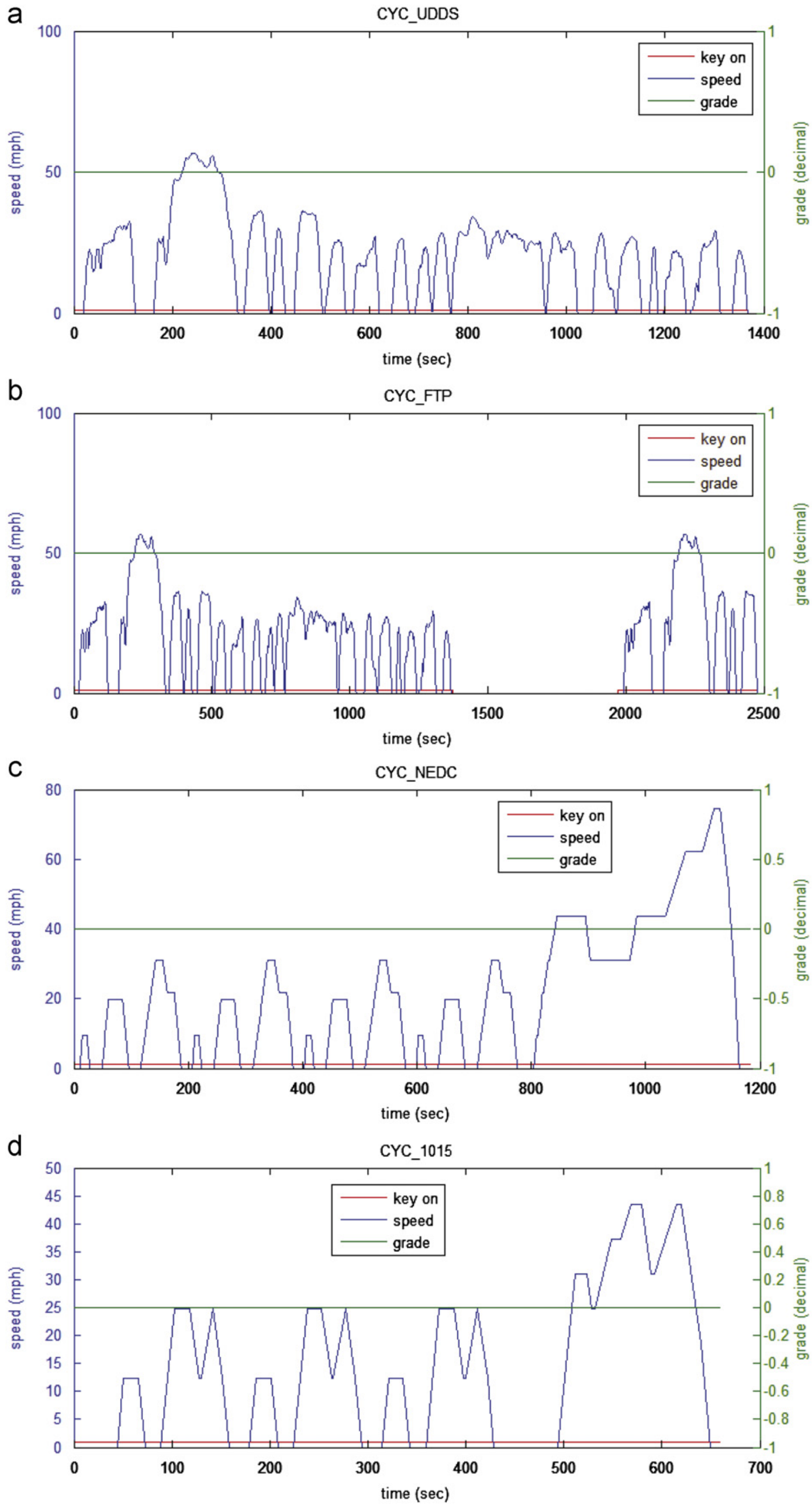

Fig. 12. Some speed profile examples: (a) UDDS, (b) FTP, (c) NEDC, (d) Japanese 10–15 Mode.

structure. The optimal control is similar with control theory approach, which has an analytical nature characteristic. Dynamic programming (DP) is a cost function based dynamic optimization tool which is built from prior knowledge of future driving condition. DP can handle complicated rules, but calculation is time intensive. This control strategy computes segment by segment

Table 10
Characteristic of driving cycles [133–136].

Cycles	UDDS[135]	FTP[135]	NEDC[134]	Japanese 10-15 Mode[136]
Time (s)	1,369	2,477	1,184	660
Distance (miles)	7.45	11.04	6.79	2.59
Maximum speed (mph)	56.7	56.7	74.56	43.48
Average speed (mph)	19.58	16.04	20.64	14.09
Maximum acceleration (ft-s^{-2})	4.84	4.84	3.46	2.6
Maximum deceleration (ft-s^{-2})	−4.84	−4.84	−4.56	−2.73
Average acceleration (ft-s^{-2})	1.66	1.68	1.78	1.87
Average deceleration (ft-s^{-2})	−1.9	−1.89	−2.59	−2.12
Idle time (s)	259	361	298	215
Intermediate stops	17	22	13	7
Maximum up grade (%)	0	0	0	0
Average up grade (%)	0	0	0	0
Maximum down grade (%)	0	0	0	0
Average down grade (%)	0	0	0	0

until the optimal distribution is obtained. Therefore, it can be used as a benchmark for improving other control strategy but it is not suitable for real-time control. However, stochastic dynamic programming (SDP) is very suitable for real-time implementation. SDP is also a cost function, based on optimal algorithm. Genetic algorithm (GA) is easy to use in complex nonlinear programming/optimization problem. It can promise more accurate exploration of the solution space than conventional gradient-based procedure such as gradient-free algorithm particle swarm optimization (PSO). PSO is a robust SDP that has no selection operation; however, it is based on the movement and intelligence of swarms. One of the GA disadvantages is designer's inability to view the calculation of power train unlike analytical approach. Adaptive fuzzy rule is based on the combination of fuzzy logic and an optimization method.

ECMS is another control strategy based on cost function, which replaces global cost function to local. ECMS minimizes the equivalent fuel consumption on power distribution between every energy sources at each instant (sample time). This control is robust and suitable for complex structures. ECMS is able to achieve nearly optimal performance but it does not clearly take charge-sustaining problem into calculation. Decoupling control is another real-time optimization to ensure drivability, power demand and battery SOC in an acceptable range. This control strategy is the combination of other algorithm such as ECMS. Robust control approach uses torque and power input profiles to minimize fuel consumption that solve the power split problem in PHEV. In optimal predictive control, it uses the previews driving pattern and information to achieve optimal fuel economy. Optimal predictive control has look-ahead window that can find a real-time predictive optimal control law. Normally, this approach has global positioning system (GPS) to have look-ahead sample points.

5. Standards of drive Cycles

The drive cycle is the series of points representing the speed of a vehicle versus time. These are established by various countries or organizations to access the vehicle performance (vehicle efficiency and fuel consumption) and some are published by the EPA as the benchmark for industry and researcher purpose. Drive cycles can be created either theoretically or based on practical driving tests. In general, there are three countries generating driving cycles which are Europe (NEDC, ECE15), United States (FTP, SC03SFTP, UDDS, US06 andLA92) and Japan (10-15 Mode).

There are two types of driving cycles. One is the transient driving cycle. This involves many speed changes and is based on typical on-road driving conditions. For example, The American Urban Dynamometer Driving Schedule (UDDS) and Federal Test Procedure (FTP) drive cycles belong to this type. The second type is modal driving cycles. It involves protracted periods at a constant speed. For example, New European Driving Cycle (NEDC) and the Japanese 10-15 Mode and JC08 cycles are of this type [132]. The speed profile and characteristic of drive cycles are shown in Fig. 12 and Table 10.

The drive cycle is to standardize the input driving pattern for vehicle optimization and simulation, although the real drive cycles are often more complex. Currently, new technology can recognize past drive cycle of the vehicle which is called drive cycle recognition (DCR). The DCR uses the past driving information and existing drive cycles that are stored in library to predict the future driving parameter for optimization and control strategy development.

6. Conclusion

This paper reviews the drive trains architectures on HEV and AEV with current technology on energy storage unit and energy generation unit. The power energy management at low-level component control and high-level supervisory control among the HEV and AEV are also reviewed. A conventional ICE vehicle contributes high GHG emission, and low efficiency drive train causes vehicle transforming to electric vehicle as an alternative solution. The mutuality of power electronic brightens the EV future. Among all the control methods, from low level to high level control, each control technique has its advantages and disadvantages. The optimal vehicle performance is not only relying on the low-level component control used but is also heavily depending on the high level control algorithm. The operation area of vehicle should also be taken into the design consideration. In addition, energy sources availability, environment factor and weather factors should not be neglected during designing step.

According to the report by [137], the sales of EV in the US alone have increased from 274,555 in 2010 to 393,938 in 2012 (only up to October 2012). This implies that EV has gained high interest due to awareness of fuel and economic crisis. At present, HEV is an interim step to fully EV without ICE engine. The ultimate goal in EV is to be fully powered by alternative energy sources such as fuel cell or flywheel. Up to date, the EV available in the market may not yet meet the ideal EV specifications. However, the rapid research and development in the EV related field is hoped to bring evolution in near future. Besides that, EV may not only serve for travelling and transportation purposes. It can also be a mobile energy backup system, mobile energy converter hub or mobile office. The rapid growth of EV will also promote the growth of vehicle-related industries as well as will bring up the economy. In addition, small-sized EV such as i-MiEV or Hiriko foldable electric car has been

gaining its popularity especially in urban cities. Small-sized EV saves fuel consumption due to the total kerb weight, saves spaces (for parking purpose), reduces cost of the road construction (narrower road) and also helps in avoiding traffic congestion. In short, the efficiency and performance of EV and its charging infrastructure should be further optimized to make EV a viable option in transportation. Lastly, smart grid control is essential as the growth of EV increases electricity demand as well as the injection of alternative resources for demand management.

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