1

Introductory Aspects of Electric Vehicles

1.1 Introduction

Energy is used in all aspects of life, and it is considered an essential part of the existence of the ecosystem and human civilization. Thus, energy-related issues are one of the most important problems that we face in the twenty-first century. With the onset of industrialization and globalization, the demand for energy has increased exponentially over the past decades. Especially with a population growth of faster than 2% in most countries, along with improvements on lifestyles that are linked to energy demand, the need for energy is ever-increasing. Based on the current global energy consumption pattern, it is predicted that the world energy consumption will increase by over 50% before 2030. Thus, based on this pervasive use of global energy resources, energy sustainability is becoming a global necessity and affects most of the civilization (Dincer, 2010).

Currently, the world relies heavily on fossil fuels such as oil, natural gas and coal, which provide almost 80% of the global energy demands, to meet its energy requirements. It is estimated that most of large-scale energy production and consumption of energy causes degradation of the environment as they are generated from these sources. It is believed that climatic changes driven by human activities (especially greenhouse gas emissions) have significant direct negative effects on the environment and contribute to over 160,000 deaths per year from side effects associated with climate change, which is estimated to double by 2020. Moreover, the nominal prices of retail gasoline have increased approximately five times more between the years of 1949 and 2005 (Asif and Muneer, 2007; Shafiee and Topal, 2006). These aforementioned reasons have motivated researchers, scientists, engineers and technologists to look for more efficient, cheaper and ecofriendly options for energy usage. As the transportation sector is a major contributor to this problem, several alternatives to conventional vehicles are developed which can be competitive in many aspects, all while being significantly more efficient and environmentally benign. Among these alternatives are electric and hybrid electric vehicles, which are two of the leading candidates to replace conventional vehicles in the future.

Over the last few decades, concerns over the dependence and ever-increasing prices of imported oil, as well as environmental pollution and global warming, have led scientists to conduct more proactive research on vehicles with alternative energy sources. Today, approximately 15 million barrels of crude oil per day are used in the United States alone. About 50% of this crude oil is used in the transportation sector, a sector where 95% of the energy supply comes from liquid fossil fuels (Kristoffersen *et al.*, 2011). Moreover, the increasing demand and relatively static supply for petroleum

Thermal Management of Electric Vehicle Battery Systems, First Edition.
İbrahim Dinçer, Halil S. Hamut and Nader Javani.

and stricter pollutant regulations have caused an increase and instability in crude oil prices. Furthermore, since the majority of the crude oil reserves are located in a few countries, some of which have highly volatile political and social situations, it presents a problem for diversified energy supply and potential cause for political conflict. In addition, the conventional vehicles using these fossil fuels cause excessive atmospheric concentrations of greenhouse gasses (GHG), where the transportation sector is the largest contributor in the United States with over a quarter of the total GHG emissions.

It is important to note that electric vehicle (EV) and hybrid electric vehicle (HEV) technologies have been improved significantly, due to recent enhancements in battery technology, and they now compete with conventional vehicles in many areas. They offer solutions to key issues related to today's conventional vehicles by diversification of energy resources, load equalization of power, improved sustainability, quiet operation as well as lower operating costs and considerably lower emissions during operation without significant extra cost. Especially, with plug-in hybrid electric vehicles (PHEVs), it has become possible to achieve further energy consumption and emission reductions as well as potential applications for performing ancillary services by being able to draw and store energy from the electric grid and utilizing it in the most efficient operational modes for both the engine and the motor. Thus, hybrid and electric vehicles are currently considered some of the best alternatives for conventional vehicles.

1.2 Technology Development and Commercialization

It would be agreed by many experts in the industry that the history of EV and/or HEV is composed of three main periods. At the dawn of mechanic traction, until the beginning of twentieth century: steam, internal combustion and electric motors (EMs) had very similar market penetration. At the time, EVs had various advantages compared to the alternatives since steam vehicles were highly dangerous, dirty and expensive, and internal combustion vehicles were newly developed and still had certain technical issues. Moreover, since the cities were considerably smaller with a very small percentage of paved roads, electric range was not a significant limitation to the users. However, with the extension of the modern road networks and large distribution of petrol stations along with mass production; internal combustion technology become significantly cheaper and the predominant technology in the vehicle market.

First HEVs were developed as early as 1899 by Porsche due to the higher efficiencies that can be achieved when internal combustion motors are operated with combination of electric traction motors. Moreover, the second resurge is triggered with the development of power electronics. The research of motor control for EVs was founded in the 1960s. With the Arab oil embargo of 1970s, which increased the oil prices significantly, U.S. interest in federal policy to decrease fossil fuel consumption in the transportation sector began, which also led to average fuel economy standards to mandate an increase in efficiency standards in passenger cars. Among these, the Clean Air Act of 1965 also triggered numerous research institutes and firms to conduct research on electric vehicles. Thus, the interest in EVs and HEVs increased and various prototypes were built to reduce the fuel consumption, which established the foundation of today's modern hybrid and electric vehicles. However, they have not attained significant developments and were not able to penetrate into the vehicle market mainly due to the low energy density and high prices of the batteries at the time, which made them inferior to conventional vehicles in many aspects. At the end of 1970s, fewer than 4,000 battery electric vehicles were sold worldwide and it was not until the late 1980s and early 1990s that the research accelerated again due to oil prices and environmental concerns, which resulted in a significant comeback for EVs in the vehicle market, both in commercial and passenger vehicles (de Santiago *et al*., 2012).

Even during the years 1990–2005, European automakers were still highly concentrating on further developments of ICEs on various topics (especially on variable-valve-timing and direct fuel injection systems) since over 80% of the patents were awarded on this technology against only 20% for the technologies associated with EVs and HEVs (Dijk *et al*., 2013). Meanwhile, Japan had a considerable rise in EV and HEV patent applications in the early 1990s, which plummeted significantly after 1995, showing that the majority of the researchers and most of auto makers did not find electric propulsion technology profitable during this period compared to ICE vehicles. The main reasons behind the failure of this technology to become widespread can be listed as using lead-acid batteries at the time (which have very low energy densities and limited lifetime), unsatisfied customers (mainly with respect to price and range) and lobbying efforts from the auto industry (especially on loosening up the emission regulations). Thus, between the years of 1995 and 2000, only a few thousands of EVs and HEVs were sold worldwide.

During this time, the biggest successes of EV and HEV technologies were Toyota and Honda, which realized a business opportunity in this market and moved towards the mass commercialization of low emission vehicles utilizing alternative powertrains regardless of the relaxed emission regulatory measures. This included launching the Toyota Prius in Japan (in 1997), Prius II in California (in 2000) and Prius III worldwide (2004). Toyota subsequently sold over 1 million Prius between the years 1997 and 2007. In 1996, General Motors introduced EV1, a pure battery electric vehicle and leased it to a limited number of customers. However, the vehicle was not very successful due to various negative customer feedback, such as “range anxiety” and the fear of becoming stranded with a discharged battery. Meanwhile, most other car manufacturers started allocating significant R&D resources towards this technology after 2005, based on the heightened climate change concerns and peak oil prices during that time.

In 2012, around 113,000 EVs were sold in the world, more than twice of the previous year, mainly in the United States, Japan and China, and 20 million EVs are projected to be on the roads by 2020. Currently, Chevrolet Volt, Nissan Leaf and Toyota’s Plug-in Prius are the most widely sold electric vehicles in the world. With the government incentives, significant increase in R&D and infrastructure for electric vehicle technologies and reduction in battery costs, the market penetration of these vehicles is expected to become more prominent in the near future.

In addition, there were significant national and local government involvements in the market preparation and the provision of infrastructure along with the allocation of R&D funds in this area in order to increase the market penetration of EVs and HEVs. Until 2005, the U.S. federal government provided a flat $2,000 tax deduction for all qualifying hybrids, which then replaced with a tax credit–based system on an individual model’s emission profile and fuel efficiency from a few hundred to several thousand dollars. In addition, many states also offered additional incentives on top of the federal tax credit. Today, as compiled from various sources on the internet, many countries provide tax incentives for EVs and HEVs; Finland (€5M), France (€450M), Italy (€1.5M), Holland (12% of vehicle cost), India (20%), China (60,000 RMB), Spain (€6,000+), Sweden (€4,500) and United States ($7,500) being the leading countries in this regard.

It should be noted that during the past two decades fuel cell technology has started finding applications in many sectors, including transportation sector. Even though the inverse process of the one occurring in hydrogen fuel cells, which is the decomposition of water into hydrogen and oxygen using electricity was discovered in as early as 1800, the actual phenomenon of fuel cell was not discovered until 1838. However, it was still not until 1933 that the technology reached its adolescence, where the first practical use of fuel cells was established by converting air and hydrogen directly into electricity. This technology was later used in submarines of the British Navy (1958) and the Apollo Spacecraft. In 1960s, fuel cells that could be used directly with air as opposed to pure oxygen were developed (Andújar and Segura, 2009).

Fuel cells developed since 1970 have offered several advantages, such as less expensive catalysts, increased performance and longer lifetime. Thus, after a century of its invention, fuel cells became an important candidate for a paradigm shift in the field of electric power generation due to achieving high efficiencies and low emissions. In the last two decades, the specific powers of fuel cells have increased as much as two orders of magnitude and are started to be considered for various applications, especially the automotive sector.

Currently, a large majority of the vehicles using fuel cells are utilized for research and development and testing. The first commercially available fuel cell vehicle model, FCX Clarity, was developed by Honda in 2007 and was manufactured in series. Since then, various models of vehicles have been developed by different manufacturers including Fiat Panda, Ford HySeries Edge, GM provoq, Hundai I-Blue, Peugeot H2Origin and Toyota FCHV-adv. Moreover, due to their relatively high levels of emissions per liter of fuel consumed, this technology was also adopted in motorcycles and ships.

As the densities of the cities increased considerable the advantage of ICs reduced due to the health issues associated with the negative environmental impact of this technology. It is expected by many that the European Commission will eliminate the conventional fueled vehicles in cities by the year 2050 which will enable all electric and fuel cell operated vehicles to dominate the market in close future.

1.3 Vehicle Configurations

In order to be able to elaborate further on electric vehicles and their subsystems; first the definition and characteristics of different vehicle configurations is necessary to be clearly understood. Thus, in the next sub-sections, a brief description of various commonly used vehicle configurations is provided to convey the readers with the fundamentals of the basic vehicle configurations.

1.3.1 Internal Combustion Engine Vehicles (ICEV)

Internal combustion engine vehicles (ICEV), which are generally referred to "conventional vehicles" from now on, have a combustion chamber that converts chemical energy (of the fuel) to heat and kinetic energy in order to provide rotation to the wheels and propel the vehicle. ICEVs have relatively long driving range and short refueling times

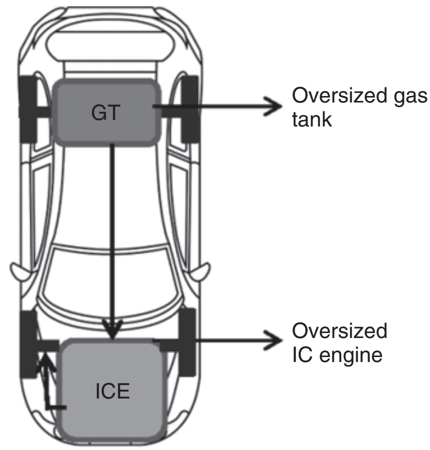


Figure 1.1 Illustration of internal combustion engine vehicle configuration.

but face significant challenges with respect to oil consumption and associated cost and environmental impacts. The vehicle configuration for ICEVs is illustrated in Figure 1.1.

The main advantages of ICEVs are listed as follows:

- The vehicle can store high volume of liquid fuel (typically gasoline or diesel) onboard in a fuel tank.
- The utilized fuel has high energy density sufficient to travel several hundred miles without refueling.
- It has short refueling times.

There are some drawbacks of these vehicles as follows:

- The vehicle is not satisfactorily efficient with less than 20% energy of the gasoline used as propelling power.
- The remainder of the energy is lost to the engine and to the driveline inefficiencies as well as idling.
- It is a significant contributor to environmental pollution and global warming, mainly due to hydrocarbon fuels utilized.

ICEVs have a plethora of moving parts, which makes the system complicated and hard to maintain (from regular oil changes, periodic tune-ups, to the relatively less frequent component replacement, such as the water/fuel pumps as well as the alternator) and reduces the system efficiently considerably. Moreover, it needs a fueling system to introduce the optimal fuel-air mix and an ignition system to have a timely combustion, a cooling system to operate safely, a lubricating system to reduce wear, an exhaust system to remove the heated exhaust products. Even though significant advancements have been made on ICEs in the past decades, they require fossil fuels which have unstable and ever-increasing prices, have political and social implications and causes environmental pollution and global warming.

In the past decades, substantial advancements have been made in using alternative fuels, including alcohol fuel derived from biological sources, such as food crop which mitigates the negative environmental effects; however these resources are also used very inefficiently due to the nature of the combustion process and the mechanical linkages (Electrification Roadmap, 2009).

1.3.2 All Electric Vehicles (AEVs)

All electric vehicles (AEVs) on the other hand, use the electric power as their only source to propel the vehicle. Since the vehicle is only powered by batteries or other electrical energy sources, virtually zero emissions can be achieved during operation. However, the overall environmental impact depends significantly on the method of energy production, thus a cradle-to-grave analysis is usually needed in order to get a much realistic measures of the environmental impact. Since they do not incorporate an ICE and its corresponding mechanical or automatic gearbox, the mechanical transmissions can be eliminated, making the vehicle much simpler, reliable and more efficient. Thus, EVs can attain over 90% efficiencies (in the battery) compared to 30% efficiencies of ICEs. Moreover, they can utilize regenerative breaking which increases their efficiency even further. In addition, they have the advantages of having quite operation and using electricity that can be generated from diverse resources. As the energy portfolio in many countries become significantly more diverse with various forms of renewable energy (especially solar and wind), the benefits of AEVs will become more much apparent in the future. The vehicle configuration for AEVs is provided in Figure 1.2.

The main advantages of AEVs are listed as follows:

- The vehicle is propelled using an efficient electric motor(s) that receive power from an onboard battery.
- Regenerative breaking is used to feed the energy back to the battery when the brakes are used.

There are some drawbacks of these vehicles as follows:

- It has the largest size batteries compared to HEVs or PHEVs since batteries are the only source of energy.
- The vehicle has limited range compared to conventional (ICE) vehicles.
- Full charging can take up to 7 hours in Level 2.

However, the specific energy of gasoline is incredibly high compared to that of electric batteries. Thus, in order to provide the same energy levels, the battery pack becomes significantly large, which adds considerable weight and cost to the vehicle. Thus, AEVs have very limited driving ranges and higher costs compared to ICEVs, which are the

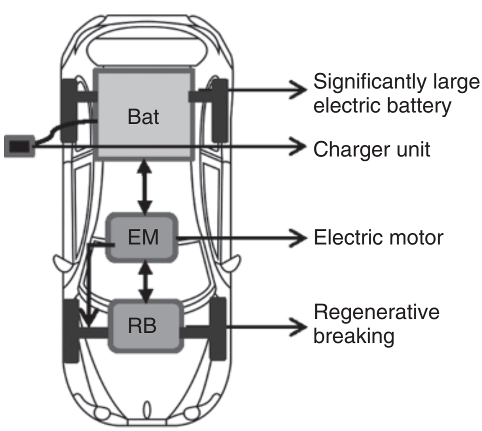


Figure 1.2 Illustration of the electric vehicle configuration.

main barriers of this technology to widely enter the vehicle market. However significant research is being conducted to increase the capacities associated with the batteries, supercapacitors and reduced-power fuel cells to overcome these issues.

1.3.3 Hybrid Electric Vehicles (HEVs)

Hybrid electric vehicles (HEV) on the other hand combines a conventional propulsion system with an energy storage system, using both ICE and electric motor as power sources to move the vehicle and therefore represent an important bridge between ICEVs and EVs. Hybrids are closer to conventional cars since they depend solely on fossil fuels for propulsion. The EM and the battery are generally used for maintaining engine efficiency by avoiding idling and providing extra power, therefore reducing its size. Thus, HEVs can achieve improved fuel-economy (compared to ICEVs) and longer driving range (than pure EVs). The vehicle configurations for HEVs and PHEVs are provided in Figure 1.3.

The main advantages of HEVs are listed as follows:

- The vehicle has both a battery/EM and an ICE/fuel tank.
- Either EM or both ICE and EM provide torque to the wheels depending on the vehicle architecture.
- A/C and other systems are powered during idling.
- Efficiency gains of 15 – 40% can be attained.

There are some drawbacks of these vehicles as follows:

- The vehicle still relies heavily on the ICE.
- All electric range is usually limited to 40 – 100 km.
- It costs more than its conventional counterparts.

Plug-in HEVs (PHEVs) are closer to AEVs based on the large size of the battery pack but can even have longer driving range since they be recharged simply by plugging into an electric grid. The success of Toyota Prius on the market shows that PHEVs are a real alternative to conventional vehicles. By having the appropriate energy generation mix of electricity and the suitable driving applications, both HEVs and PHEVs can

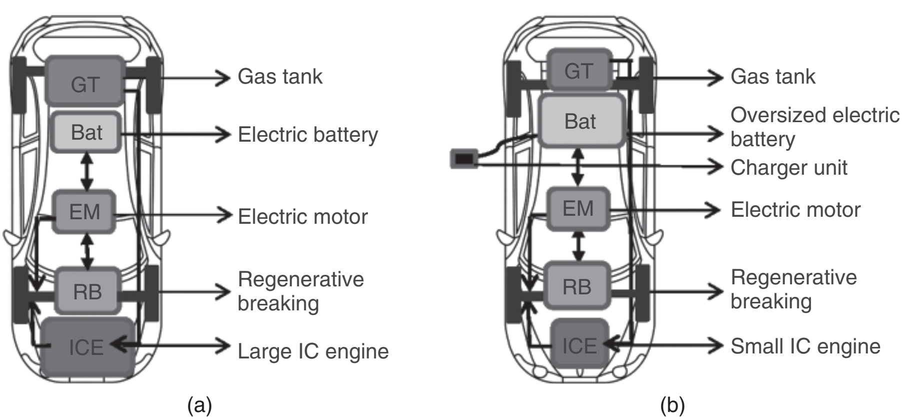


Figure 1.3 Illustrations of (a) hybrid and (b) plug-in hybrid electric vehicle configurations.

use significantly less gasoline and produce fewer tailpipe emissions than conventional vehicles.

The main advantages of PHEVs are listed as follows:

- Batteries can be charged/recharged by plugging into the electric grid.
- The vehicle is ideal for commuting and doing errands within short distances.
- There is no gasoline consumption or emissions during all electric mode.

There are some drawbacks of these vehicles as follows:

- Batteries used in the vehicle are larger and more expensive than HEV batteries.
- Charging may take up to 4 hours in Level 2.

Moreover, unlike EVs that can have their full capacity withdrawn at each cycle, an PHEV battery has a capacity draw that ranges around 10% of the nominal operating level (which is 50% state of charge) in order to deal with charge/discharge current surges without going into overcharge above 75% and deep discharge below 25% state of charge (SOC). Thus, only around half of the battery capacity is being used in PHEVs. The energy management modes for these vehicles are listed as follows.

Charge Depleting Mode (CD-mode): In this mode, the battery SOC is controlled in a reducing fashion when the vehicle is being operated. After charging PHEVs through conventional electrical outlets, they operate in charge-depleting mode (CD-mode) as they drive until the battery is depleted to the target state of charge, which is generally around SOC of 35%. In this mode, the engine may be on or off, however a portion of the energy for propelling the vehicle is provided by the energy storage system (ESS).

Charge Sustaining Mode (CS-mode): In this mode, the battery SOC is controlled to remain within a narrow operating band. After the previous operation (where the battery is depleted to the targeted SOC), the vehicle shifts to charge-sustaining mode (CS-mode) by utilizing the internal combustion engine to maintain the current SOC. PHEVs can be further categorized based on their functions in CS-mode. The conceptual illustrations of CD and CS modes are provided in Figure 1.4.

Electric Vehicle (EV) Mode: In this mode, the operation of the IC engine is prohibited and therefore the ESS is the only source of energy to propel the vehicle. Range-extended PHEVs act as a pure EV in CD-mode using only the electric motor, whereas blended

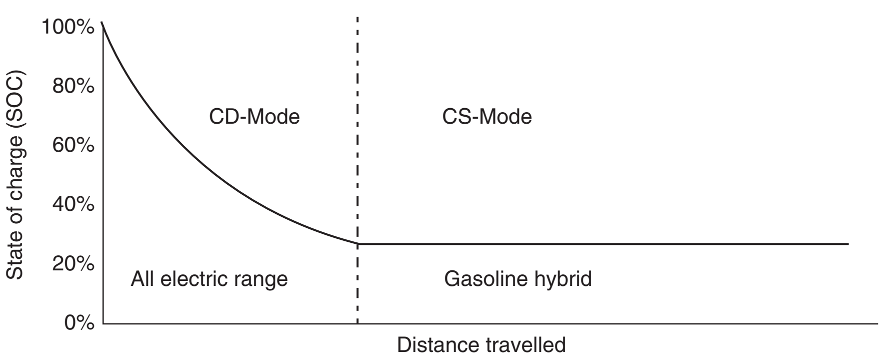


Figure 1.4 Conceptual illustration of battery discharge.

PHEVs use the electric motor primarily with the occasional help of the engine to provide additional power.

Engine Only Mode: Finally, after CS-mode, if the vehicle is still driving, it enters the engine-only mode where the operation of the electric traction system does not provide tractive power to the vehicle.

Finally, the factors effecting the use and market penetration of the aforementioned technologies are shown in Figure 1.5. The green and red colors of the arrows indicate some of the enabling and disabling factors in the development or integration of the different powertrain technologies.

Moreover, the electric configurations can also be mapped into a fit-stretch scheme of technical form and design of innovation in the x-axis and user context and functionality on the y-axis. The more innovation is similar to the established practice, the higher the fit and the smaller stretch. Combining these two dimensions makes it easier to compare different technologies with each other on a multi-dimensional facet.

Figure 1.6 shows two pathways showing that the alternative fuel vehicles may be used an additional vehicle which is more sustainable or can be used in combination

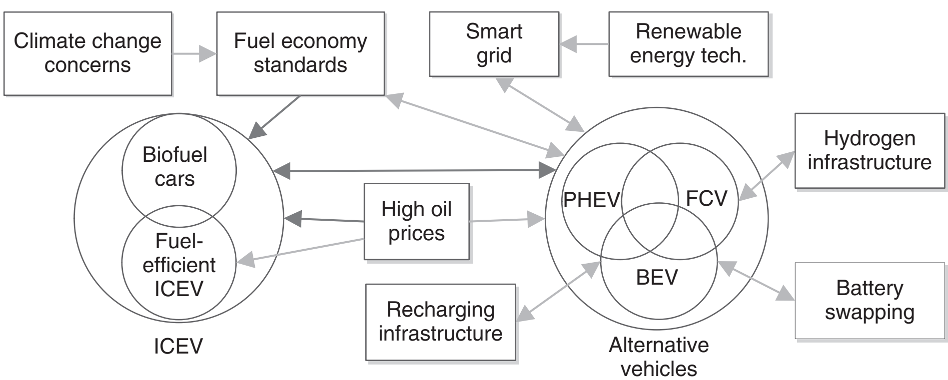


Figure 1.5 The factors influencing the market penetration of various technologies (adapted from Dijk *et al.*, 2013).

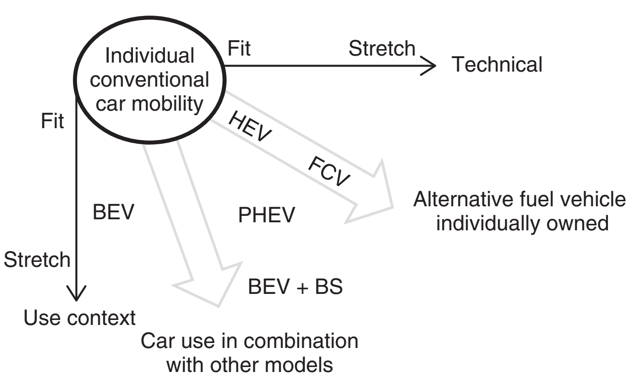


Figure 1.6 Fit-stretch pattern for different powertrain technologies (adapted from Hoogma, 2000).

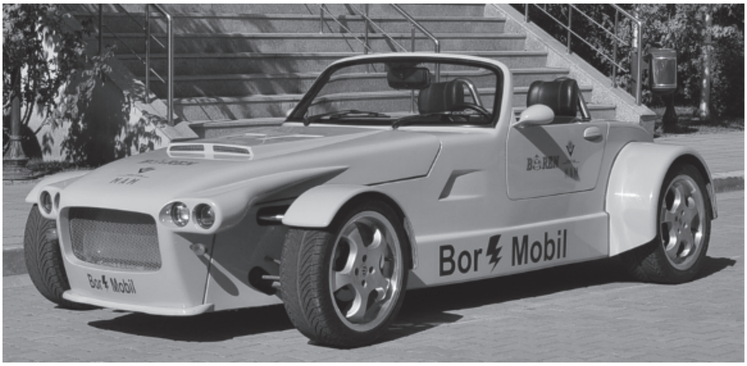


Figure 1.7 Sodium borohyride fuel cell vehicle (courtesy of TUBITAK Marmara Research Center).

with other transport modes, the difference being the degree in mobility patterns and travel behavior. Thus, in the upper pathway, they remain mostly unchanged, where even though the vehicles have better efficiencies and lower emissions, the users do not change their travel behavior accordingly. The second pathway considers more active planning, wide range of transport modes and reduced sense of ownership of the vehicle as well as technological, infrastructural and regulatory reinforcements.

1.3.4 Fuel Cell Vehicles (FCVs)

Fuel cell vehicles can be considered as a type of series hybrid vehicle where the fuel cell acts as an electrical generator using hydrogen. The electricity produced by the fuel cell can either (or both) used to power the EM or stored in the energy storage system (such as battery, ultracapacitor, flywheel) (Chan *et al.*, 2010). The National Research Council (NRC) of Canada report on alternative transportation technologies showed that unlike biofuels or advanced ICE vehicles, FCVs can set the GHG emissions and oil consumptions at a steady downwards trajectory. An example of a fuel cell vehicle using sodium borohydride is shown in Figure 1.7.

1.4 Hybridization Rate

Electric and hybrid electric vehicles have considerable advantages over conventional vehicles in terms of energy efficiency, energy source options and associated environmental impact. Electric vehicles can be powered either directly from an external power station, or through stored electricity, and by an on-board electrical generator, such as an engine in HEVs. Pure electric vehicles have the advantage of having full capacity withdrawn at each cycle, but they have a limited range (Hamut *et al.*, 2013). HEVs on the other hand, have significantly higher ranges, as well as the option of operating in electric only mode, and therefore they will be the main focus of the analysis.

Hybrid electric vehicles take advantage of having two discrete power sources; usually primary being the heat engine (such as diesel or turbine, or a small scale ICE) and the auxiliary power source is usually a battery. Their drivetrains are generally more fuel efficient than conventional vehicles since the auxiliary source either shares the

Table 1.1 Characteristics of vehicles with different hybridization rates (adapted from Center for Advanced Automotive Technology, 2015).

Hybridization Characteristics	Micro Hybrid	Mild Hybrid	Full Hybrid	Plug-in Hybrid
Vehicle Examples	Mercedes Benz A-class, Smart car, Fiat 500, Peugeot Citroen C3, BMW 1 and 3 series, Ford Focus and Transit	BMW 7 series ActiveHybrid, Honda Civic and Insight, Mercedes Benz S400 BlueHybrid	Toyota Prius and Camry Hybrid, Honda CR-Z Chevrolet Tahoe Hybrid, Ford C-Max	Chevrolet Volt, Toyota Prius Plug-in, Porsche Panamera S E-Hybrid
Engine	Conventional	Downsized	Downsized	Downsized
Electric Motor	Belt Drive/Crankshaft	Belt Drive/ Crankshaft	Crankshaft	Crankshaft
Electric Power	2–5kW	10–20kW	15–100kW	70kW+
Operating Voltage	12V	60–200V	200+	200+
Fuel Savings	2–10%	10–20%	20–40%	20%+

power output allowing the engine to operate mostly under efficient conditions such as high power for acceleration and battery recharging (dual mode), or the auxiliary sources furnish and absorb high and short bursts of current on demand (power assist). Moreover, in both architectures, the current is drawn from the power source for acceleration and hill-climbing, and the energy from braking is charged back into the HEV battery for reuse which increases the overall efficiency of the HEVs. Currently, a wide range of configurations exist for HEVs based on the role and capability of their battery and electric motor as shown in Table 1.1.

These hybridization rates can provide various functionalities in different extends to the HEV such as engine stop/start operation, adjustments of engine operating points, regenerative braking and various levels of hybrid electric propulsion assist as shown in Figure 1.8. More information regarding different hybridization rates are provided in the next subsections.

1.4.1 Micro HEVs

Micro-HEVs have a starter-generator system coupled to conventional engine, where limited-power electric motor helps the ICE to achieve better operations during startup which is used as a starter alternator and combine automatic engine stop/start operation with regenerative breaking. They have typical generator capacities up to 5 kW and conventional 12 V batteries to reduce the fuel consumption of the vehicle, usually between 2% to 10% in urban driving cycles (depending on the vehicle, drivetrain and driving conditions), and are currently only found in light-duty vehicles. Moreover, the electric motor does not provide additional torque to the engine when the vehicle is in motion.

1.4.2 Mild HEVs

Mild HEVs provide electrically-assisted launch from stop and charge recuperation during regenerative breaking, but have a more slightly larger electric motor (than Micro

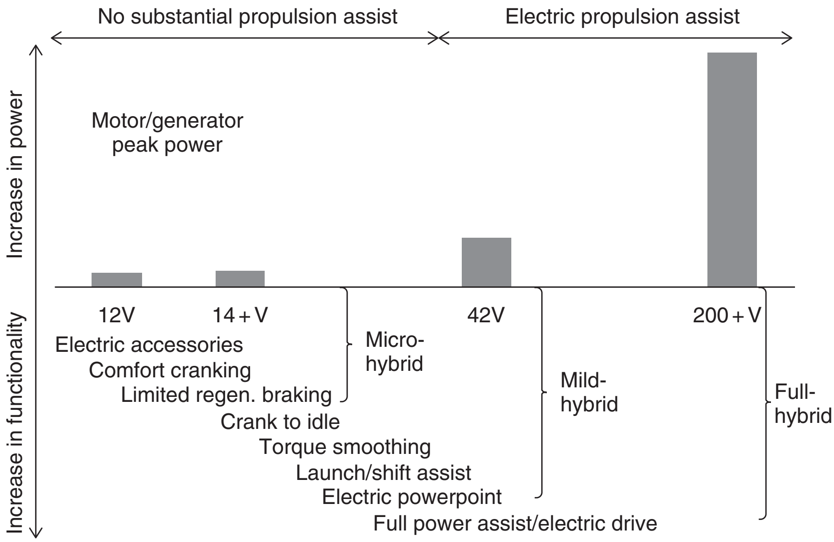


Figure 1.8 Hybrid classification based on powertrain functionality (adapted from Karden *et al.*, 2007).

HEVs) with 6–12 kW power and around 140 V operating voltage which assists the ICE. They still do not provide a sole source of driving power use the electric motor to boost the ICE during acceleration and breaking by providing supplementary torque, since it cannot run without the ICE (the primary power source) as they share the same shaft. With this configuration, fuel efficiencies of up to 30% (usually between 10 to 20%) can be acquired and can reduce the size of the ICE. Among the vehicles available in the market, GMC Sierra pick up, Honda Civic and Accord and Saturn Vue are known as some examples for Mild HEVs.

1.4.3 Full or Power-Assist HEVs

In full (or power-assist) hybrids, the electric motor can be utilized as the sole sources of propulsion since they have a fully electric traction system and provide power for engine staring, idle loads, full-electric launch, torque assistance, regenerative breaking energy capture and limited range and unlike Mild HEVs, they can split power path by either running the ICE or the electric motor or both. When used in full electric mode, the vehicle achieves virtually zero emissions during operation.

Full HEVs usually have a high capacity energy storage system with used power around 60 kW and operating voltage above 200V, this configuration with a wide range of architectures (series, parallel or combinations). As a result, this configuration can reduce the fuel efficiency up to 40% without any significant loss in driving performance (usually between 20 to 50%). However, they usually require significantly larger batteries, electric motors and improved axillary system (such as thermal management system) than the aforementioned configurations (Tie and Tan, 2013).

1.4.4 Plug-In HEVs (or Range-Extended Hybrids)

Plug-in HEVs are very similar to full HEVs (can use both fuel and electricity for propulsion) with the additional feature of the electrochemical energy storage being able to be charged by being plugged into an off-board source (such as the electrical grid) instead of using fossil fuels alone. They can either be used as a BEV with limited-power ICE or to extend the driving range by having ICE act as a generator that charges the batteries, which is also called "range extended EV".

In PHEVs, since the vehicle has an alternative energy unit and a battery that can be charged from the grid, the mass of the battery is significantly smaller than EVs (and typically have batteries larger capacity than HEVs), thus enabling the PHEVs to operate more efficiently in electric-only mode (due to the reduction in power required to propel the vehicle) than similar EVs. PHEV chargers must be light-weight, compact and highly efficient in order to maximize the effectiveness of the electric energy from the grid. By utilizing the stored multi-source electrical energy from the grid and stored chemical energy in the fuel tank together or separately, PHEVs can achieve even better driving performance, higher energy efficiencies, lower environmental impact and lower cost than conventional HEVs, mainly depending on the driving behavior and energy mix of the electricity generation.

The electrical power requirement depends on various factors (especially vehicle weight) and is above 70 kW. Since the power is drawn from the grid (instead of the ICE), the efficiency and vehicle performance could be improved significant in short distances and urban drive as the vehicle can be driven in electric motor mode. Thus, plug-in HEVs become very desirable for both in city driving and highway patterns.

1.5 Vehicle Architecture

In all hybrid electric vehicles, the arrangement between the primary and secondary power sources can be categorized as parallel, series, split parallel/series (and even complex) configurations. The hybrid vehicles configurations can be seen in Figure 1.9. There are complex trade-offs among these configurations in terms of efficiency,

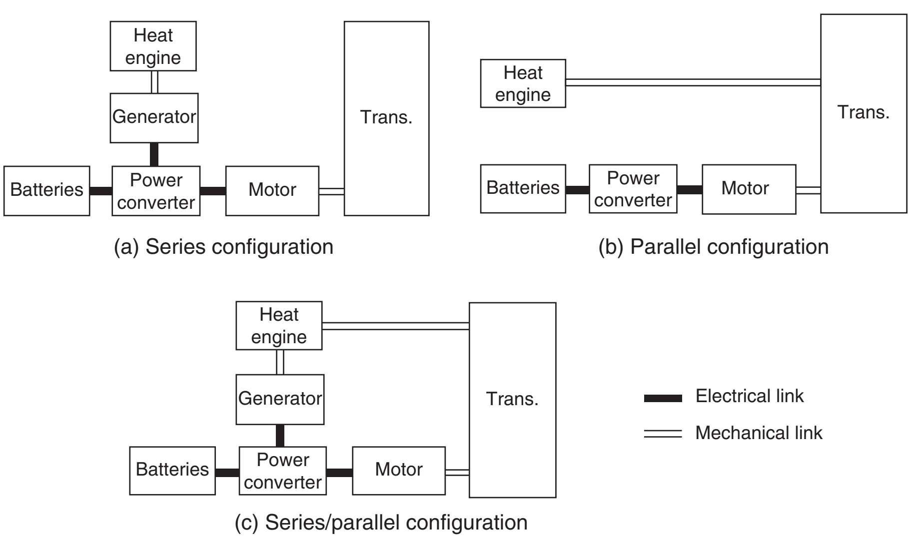


Figure 1.9 Hybrid vehicles configurations in (a) series, (b) parallel and (c) series/parallel.

drive-ability, cost, manufacturability, commercial viability, reliability, safety and environmental impact, and therefore the best architecture should generally be selected based on the required application, especially driving conditions and drive cycles.

1.5.1 Series HEVs

In a series configuration the engine generally provides the electrical power through a generator to charge the battery and power the motor. Conceptually, it is an engine-assisted EV which extends the driving range in order for it to be comparable with conventional vehicles. In this configuration, the output of the heat engine is converted to electrical energy that, along with the battery, powers the drivetrain. The main advantage of this configuration is the ability to size the engine for average rather than peak energy needs and therefore having it operate in its most efficient zone. Moreover, due to a relatively simplistic structure and the absence of clutches, it has the flexibility of locating the engine-generator set. In addition, it can reserve and store a portion of its energy through regenerative breaking. On the other hand, relatively larger batteries and motors are needed to satisfy the peak power requirements and significant energy losses occur due to energy conversion from mechanical to electrical and back to mechanical again. This configuration is usually more suitable for city driving pattern with frequent stop and run conditions. In general, this configuration has worse fuel economy (due to power conversion) as well as cost (due to extra generator) compared to the parallel configuration but has a flexible component selection and lower emissions (due to the engine working more efficiently).

1.5.2 Parallel HEVs

In a parallel configuration (such as Honda Civic and Accord hybrids), both the engine and motor provide torque to the wheels, hence much more power and torque can be delivered to the vehicle's transmission. Conceptually, it is an electric assisted conventional vehicle for attaining lower emissions and fuel consumption. In this configuration, the engine shaft provides power directly to the drivetrain and the battery is parallel to the engine, providing additional power when there is an excess demand beyond the engine's capability. Since the engine provides torque to the wheels, the battery and motors can be sized smaller (hence, the lower battery capacity) but the engine is not free to operate in its most efficient zone. Thus, a reduction of over 40% can be achieved in the fuel efficiency. This configuration is usually desirable for both city driving and highway conditions.

1.5.3 Parallel/Series HEVs

Finally, in a split parallel/series powertrain (such as Toyota Prius, Toyota Auris, Lexus LS 600h, Lexus CT 200h and Nissan Tino), a planetary gear system power split device (shown in Figure 1.9c) is used as well as a separate motor and generator in order to allow the engine to provide torque to the wheels and and/or charge the battery through the generator. This configuration has the benefits of both the parallel and series configurations in the expense of utilizing additional components. However, the advantages of each configuration are solely based on the ambient conditions, drive style and length, electricity production mix as well as the overall cost.

1.5.4 Complex HEVs

Lastly, complex configuration is very similar to the parallel/series configuration with the main difference of having a power converter as well as the motor/generator and motor which improves the vehicle's controllability and reliability compared to the previous system. The main disadvantage of this configuration is the need for a more precise control strategy.

1.6 Energy Storage System

Once the various types of vehicle configurations and architectures are examined, the use of the most appropriate energy storage system for the intended application becomes one of the main selection criteria in HEVs. Therefore, descriptions along with the advantages and drawback of these ESSs are briefly described below.

1.6.1 Batteries

Battery is a portable storage device which usually incorporates multiple electrochemical cells that are capable of converting the stored chemical energy into electrical energy with high efficiencies and without any gaseous emission during operation stage. In batteries, the chemical reactions take place throughout the bulk of the solid, thus the material should be designed in order to allow the ingress and removal of the reaction species throughout the material over hundreds/thousands of cycles to deliver a practical rechargeable battery (Whittingham, 2012). All types of batteries contain two electrodes, an anode and a cathode as shown in Figure 1.10.

Several battery chemistries have been developed in the past decades. However, among the ones available, Li-ion chemistry currently dominates the market in a wide range of applications. These batteries are available in four different geometries, namely small and large cylindrical, prismatic and pouch. Note that cylindrical cells are produced in high volumes and with high quality and can retain their shape, while other formats require

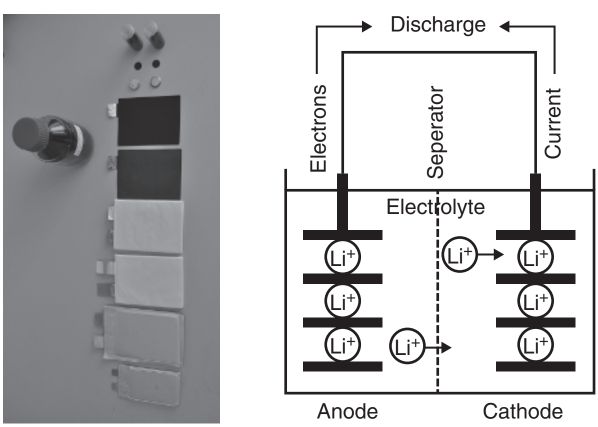


Figure 1.10 Images and schematics of a common battery (courtesy of TUBITAK Marmara Research Center).

and overall battery enclosure to retain their expansion. Moreover, cylinder volumes have the advantage of being robust and structurally durable (against shock and vibration); however their heat transfer rates reduce with increasing size. Moreover, it is very hard for the large ones and is almost impossible for the small ones to be replaced. Prismatic cells on the other hand are encased in semi-hard plastic cover and have better volume efficiencies. They are usually connected with threaded hole for bolt and have easy field replacement but require retaining plates at the ends of the battery. The soft pouch packaging has high energy/power densities (without the extra packaging) and usually has tabs that are clamped, welded or soldered. Like prismatic cells, they also require retaining plates and have poor durability unless additional precautions are taken, which would in turn increase the volume and the weight of the cells (Pesaran *et al*., 2009).

Currently, they offer the most promising option to power HEVs and EVs in a relatively efficient manner. The most important characteristics of batteries are the battery capacity (which is proportional to the maximum discharge current) measured in Ah, the energy stored in the battery (capacity x average voltage during discharge) measured in kWh as well as the power (voltage x current) measured in kW. The maximum discharge current (typically represented by the index of C) indicates how fast the battery can be depleted and is affected by the batteries chemical reactions and the heat generated. Another important parameter in batteries is the state of charge (SOC) which displays the percentage of the charge available in the battery (Tie and Tan, 2013).

Batteries are currently the most commonly used technology for EVs and HEVs due to being able to deliver peak and average power at excellent efficiencies, but have inherently low specific energy, energy density and refueling/charging rates (compared to fossil fuels), which limits their range, increases their size and cost which in turn prevents their wide-spread adoption. Their power and energy characteristics with respect to the alternative ESSs are provided in Figure 1.11.

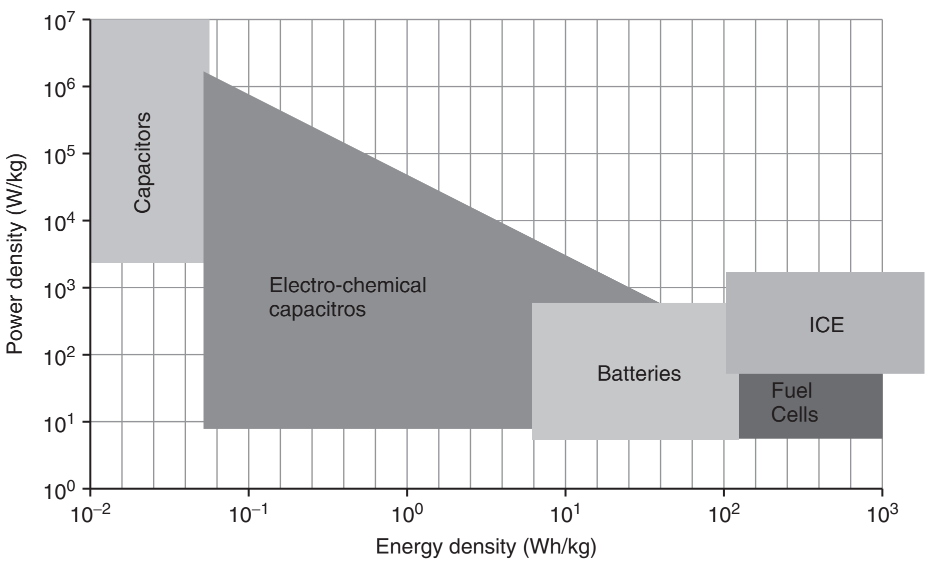


Figure 1.11 Comparison of the power versus energy density characteristics of various ESSs (adapted from Guerrero *et al*., 2010).

Typical battery electric vehicles achieve between 3–6 mile kWh^{-1} depending on various factors including the vehicle design and driver behavior. As an example, current technology requires roughly 150 kg of Li-ion cell (or over 500 kg lead acid cells) in order to travel a range of 200 km for an average passenger car under a non-demanding drive cycles. In order to double this range, the power, weight and the corresponding cost must also be almost doubled, which presents important limitations. Currently, some of the common technical demands on the batteries are to have high discharge power, high battery capacity and cycling capability, good recharging capability and high power capacity for electric vehicle applications. Further information regarding different battery chemistries, their performance, cost and environmental impact will be described in Chapter 2.

1.6.2 Ultracapacitors (UCs)

(H)EV requirements are becoming more and more demanding as the technology improves and as they become widely available in the market. Even though significant improvement have been made on the battery technologies in terms of charge rate, capacity and battery life, there are still significant barriers to fuller use of electric vehicles. In this regard, ultracapacitors (also known as supercapacitors) can provide potential benefits in many areas where battery technologies currently face challenges.

Unlike batteries where the electric energy is stored as chemical energy, in capacitors it is stored in terms of surface charge and therefore a large surface area is required to attain high storage capacities. Since the capacitor material's structural integrity is not damages through charging/discharging process, pure capacitors can be virtually charged/discharged millions of times without any significant degradation of the materials.

Ultracapacitors (shown in Figure 1.12) have similar structures with normal capacitors but with much higher capacitance (with a factor of 20 times) than capacitors and much shorter charging times than electric batteries. They are hybrids between batteries and capacitors, involving both surface charge and some Faradaic reaction in the bulk of the material. Their characteristics include virtually maintenance-free operation, longer

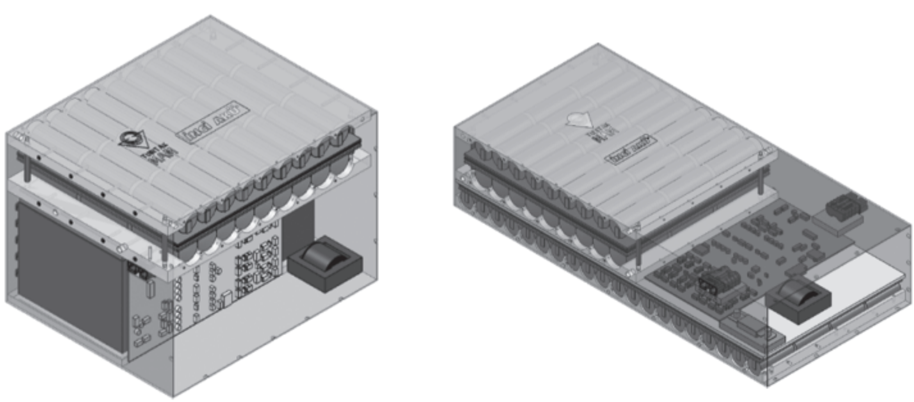


Figure 1.12 Illustrations of powerpacks using ultracapacitors with VRLA and li-ion batteries, respectively (courtesy of TUBITAK Marmara Research Center).

cycle-life and insensitivity to changes in the environmental temperatures, shocks and vibrations and can be used as standalone or in conjunction with an onboard battery.

There are currently three types of ultracapacitors that are mainly used in electric vehicles, namely electric double layer capacitors (EDLC)-carbon/carbon (more power density but lowest energy density with 5–7 Wh/kg), pseudo-capacitors and hybrid capacitors (both with 10–15 Wh/kg energy density) based on the energy storage mechanism and their electrode materials. The lifetime of ultracapacitors can reach up to 40 years which is the longest in all energy storage systems.

Electric double layer capacitors have different ways of storing energy than conventional electrochemical energy storages, where in EDLC the energy is stored directly in the electric field. The main advantage of this technology is its surface phenomenon without faradic reactions which implies very fast kinetics, ensuring a high power performance as well as a considerable cycle life.

On the other hand the energy density is significantly lower (25 times less) than a similar sized Li-ion battery. However, with the current advancements in nanotechnology (especially in carbon nanotubes), the ion-collection surface area of the ultracapacitor can be increased considerably, increasing the associated energy storage capacity up to a quarter of the energy storage capacity of a conventional Li-ion battery. Moreover, electric battery/ultracapacitor hybrid technologies are also being developed in the past couple of years which combines an ultracapacitor and a lead-acid battery in a single unit cells in order to improve the power and cycle life of the lead-acid battery. Although there are numerous vehicles driven only by ultracapacitors which exist today, they are still at the developmental stage (with prototypes mostly) and are used in relatively limited applications.

1.6.3 Flywheels

The flywheel is an energy conversion and storage device (also known as electromechanical battery) which stores energy in a rotatory mass. This principle has been used for a while to stabilize the output voltage of synchronous generators, but the recent developments have made this technology compatible to be also used in the transportation sector. Flywheels usually consists of a high strength carbon fiber wheel, magnet floating bear supporting device, motor/generator (for electric/kinetic energy conversion) and power electronics control device.

Flywheels can attain cycle efficiencies around 90%. They have around 40 Wh/kg specific energy, but much higher specific power than ordinary chemical batteries, which enables them to be charges much faster (Vazquez *et al.*, 2010). Their high peak power is only limited by the power converters. No chemical reactions take place in flywheels (which prevents the possibility of gas emissions or waste materials harmful to the environment) and therefore they are virtually maintenance free and have almost infinite number of charge/discharge cycles. This makes them very attractive for applications that use high number of charge/discharge cycles such as regenerative breaking in EVs and HEVs.

1.6.4 Fuel Cells

In this ESSs, chemical energy (hydrogen gas) is converted into mechanical through either by burning hydrogen (in internal combustion engines) or by reacting with oxygen

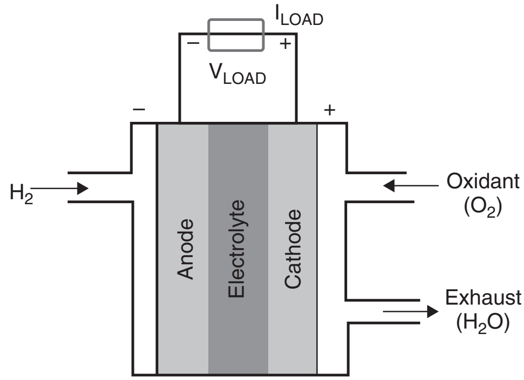


Figure 1.13 A basic configuration of a proton exchange membrane fuel cell.

(in fuel cells) to produce electricity (without the need to go through inefficient thermodynamic cycles) that can be used for the vehicle propulsion and powering accessories. As briefly mentioned in Section 1.3.4, FC vehicles emit only water vapor and can be highly efficient. The proton exchange membrane fuel cell (PEMFC) can achieve much higher energy density than any of the aforementioned technologies due to much lower atomic mass of the hydrogen and has the favorable characteristics including high energy efficiency, low operation noise and environmental compatibility. The configuration of hydrogen fuel cell and its electrochemical reaction are shown in Figure 1.13.

The European Commission co-funded project HyWays which explored a range of hydrogen scenarios for the European Union and concluded that, by the year 2050, if 80% of road vehicles were hydrogen-fuelled this would result in 50% less CO_2 emissions, compared to the extension of current scenarios (Offer *et al.*, 2010).

Even though FC technology seems like a newly emerging energy sources, it dates back to 1839, where the first FC is assembled by Sir William Grove. After decades of research, it was started to be used mainly in aerospace applications in 1960s and become more widely explored in the 1980s.

Today, if a comparison was to be made between current ICE, electric battery and fuel cell vehicle technologies; in order for a diesel vehicle to travel 500 km, a tank that weighs over 40 kg would be needed (with a volume of less than 50 L), whereas this becomes 830 kg for a Li-ion electric battery (for a potential usable energy density of 120 Whkg^{-1} and 100kW of electrical energy) and 125 kg for hydrogen (based on 700 bar compressed gaseous hydrogen vessel and 200 kWh chemical energy) to achieve the same range. Moreover, refueling the vehicle would take somewhere between 30 minutes (with up to 80 kW DC fast charging) to several hours for the electric battery as opposed to 3 to 5 minutes for the hydrogen vehicle (Eberle and von Helmolt, 2010).

However, the technology is not still not mature enough for practical EV applications due to operational problems related to electro-catalysis in direct FCs as well as issues associated with hydrogen generation, storage and distribution as well as system complexity and manufacturing cost. The manufacturing cost is mainly associated with expensive membrane and raw materials (used as catalysts) and fabrication processes (especially for collector plates). In addition, when starved from fuel or oxygen, significant performance degradation and the cell voltage drop leading to cell reversal which accelerates the corrosion of carbon components which is harmful to the FC stack and components. Moreover, the fact that hydrogen tanks are characterized by high specific energy but low volumetric energy density requires a bulkier hydrogen tank (than equivalent gasoline tanks), which creates a drawback to for it to be utilized in vehicles. Furthermore, FCs are also produced in low quantities and may require additional infrastructure for refueling, which increases their cost significantly. However, hydrogen tanks can provide significantly larger range ($50-100$ mile $kg^{-1} H_2$) and be refueled in minutes (as opposed to batteries that may take hours) which make it more comparable to conventional vehicles in terms of refueling.

FCs normally perform the best performance on pure hydrogen or at least hydrogen rich gas, which requires them to store on board hydrogen. Hydrogen can be stored via three possible solutions, namely compression (at pressures 700 times the atmospheric), cryogenic system (liquefaction at $-253°C$) and hydrogen absorbing materials (through metal, charcoal and by holding captive in solid matrix). Moreover, FC hybrid vehicles that uses hydrogen fueled internal combustion engines are also receiving significant attention since they can operate at a very lean stoichiometry which enables them to achieve top brake efficiencies (over 45%) while permitting Euro 6 emissions without any after-treatment.

As a result, FC hybrid vehicles can improve vehicle performance and fuel economy, and hydrogen, like electricity, can be produced from any primary energy source including many of the renewables and therefore can also assist in breaking the link between oil and transport.

1.7 Grid Connection

Charging capabilities, strategies and power flow play a significant role in gaining wide acceptance of plug-in electric and hybrid electric vehicles in the market since most important barriers related with the cost and cycle-life of the batteries, obstacles related to the use of chargers and the lack of charging infrastructure. Charging systems can be divided into off-board (with unidirectional) and on-board (with bidirectional) power flow. On-board charger system can be conductive or inductive and off-board charger system can be designed for high charging rates with Level 1 (convenience), Level 2 (primary) and Level 3 (fast) power levels (Yilmaz and Krein, 2013). Inductive chargers have preexistent infrastructure and are inherently safer. On the other hand, conductive chargers are lighter, more compact and allow bidirectional power, thus can achieve higher efficiencies. The impact of charging the vehicles on the grid can significantly affected by picking the optimum times to charge the vehicles (smart charging) and the ability to feed back the charge when the grid has the peak load (V2G).

1.7.1 Charger Power Levels and Infrastructure

Adequate and well-structured charging and its associated infrastructure is imperative for electric vehicles to be able to create a solution for customers' "range anxiety" and a successfully penetration into the vehicle market as they are the main contributor of the "chicken-and-egg" problem of the EV development. The problem describes the reluctance of vehicle manufacturers to introduce alternative vehicles in the absence of supporting infrastructure and similarly the reluctance of fuel producers to invest in infrastructure when no alternative vehicles are available. Moreover, selecting the appropriate location and the type of charging infrastructure has an important impact on the vehicle owner and the grid. In addition, charger power level also plays an important role for the user since it has a significant impact on acquiring the necessary power at a given time span, the associated cost as well as the impact on the grid. There are 3 levels of charging equipment currently available. Level 1 charging is the slowest method that would require no additional infrastructure for home and business sites (expected to be integrated to the vehicle) and uses a standard 120 V/15 A single-phase outlet. Level 2 charging, which is currently the primary method for dedicated private and public facilities, offers a faster charging from 208 V or 240 V and the associated infrastructure can also be onboard to avoid redundant power electronics. Otherwise, it may require dedicated equipment and installation for home and public units which costs between $1000 and $3000. Lastly, unlike the first two levels which are typically used for overnight charging (which utilizes low off-peak rates) Level 3 can provide fast charging in less than 1 hour with 480 V or higher three-phase circuit and is usually allocated in refueling stations. The characteristics of charging power levels are shown in Table 1.2.

The infrastructure cost for this level is reported between $30,000 and $160,000 and they can overload the distribution equipment. Although the number of charging stations are very limited today, with the further enhancement of the electric vehicle technology (especially in terms of increasing all electric range and reducing total cost) and the associated penetration of them in the market, the number of charging equipment/stations will be increased significantly throughout the world.

1.7.2 Conductive Charging

Currently, chargers for EVs are mainly plug-in connections where the user needs use insert a plug into the car's receptacle to charge the batteries. These systems use direct contact and a cable, that is either fed from the outlet (in Levels 1 and 2) or from a charging stations (in Levels 2 and 3), between the EV connector and charge inlet. A concept Level 3 charging station is shown in Figure 1.14.

This technology has several disadvantages such as the cable and connector delivering 2–3 times more power than standard plugs in the houses, which poses a risk for electrocution, especially under wet environments. Moreover, during cold climates, the plug

Table 1.2 Charging power levels.

Power Level Types	Charger Location	Typical Charging Location	Expected Power Level	Charging Time	Vehicle Technology
Level 1 120 VAC (US) 230 VAC-EU)	On-board 1-phase	home/office	1.4 kW (12A) 1.9 kW (20A)	4–11 hours 11–36 hours	PHEVs (5–15 kWh) EVs (16–50 kWh)
Level 2 240 VAC (US) 400 VAC (EU)	On-board 1- or 3-phase	Private or public outlets	4kW (17A) 8 kW (32A) 19.2 kW (80A)	1–4 hours 2–6 hours 2–3 hours	PHEVs (5–15 kWh) EVs (16–30 kWh) EVs (3–5 kWh)
Level 3 (208–600 VAC/VDC)	Off-board 3-phase	Commercial	50 kW 100 kW	0.4–1 hour 0.2–0.5 hour	EVs (20–50kWh)

Source: Yılmaz and Krein (2013).

Figure 1.14 Level 3 charging station concept.

Table 1.3 Charging infrastructure costs.

		Low ($)	Base Case ($)	High ($)
Home	1.4 kW	25	75	550
	7.7 kW	500	1,125	4,000
Away	1.4 kW	1,050	3,000	9,000
	7.7 kW	2,500	5,000	15,000
	38.4 kW	11,000	20,000	50,000

Source: Peterson and Michalek (2013).

in charge point may become frozen onto the vehicle. In addition, the long cables can have tripping hazards and may look aesthetically unappealing. The cost of the charging infrastructure, including the installation and equipment costs, are provided in Table 1.3. It should be noted that this cost can vary significantly based on several factor such as the availability of existing outlet, maintenance and even potential vandalism (for public charging points).

1.7.3 Inductive Charging

An inductive charger on the other hand, transfers power magnetically and is explored mainly for Level 1 and 2 devices. This technology requires large air gaps, high efficiency and a large amount of power and eliminates the aforementioned disadvantages by not using any cables. In inductive charging, a power supply produces high frequency alternating currents in the transmitter pad or coil that transfer power to the receiving coil inductively, where the receiver electronics converts it to direct current (DC) to charge the battery. The main operating parameters of inductive charging systems are power level, maximum charging distance, efficiency, charging tolerances and size and weight.

The main advantage of this technology is that instead of deep charging/discharging the battery, the vehicle can be often topped-off while being parked at home/work (static

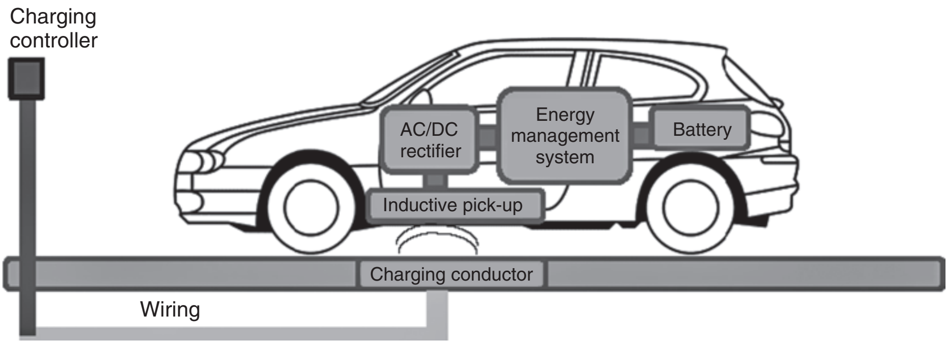


Figure 1.15 Illustration of the inductive charging technology.

inductive charging). Moreover, the technology also leads way into semi-dynamic and dynamic charging, where the vehicle can be charged wirelessly as it is traveling at low and "regular" speeds respectively. This would provide solutions to many key issues associated with availability of charging stations and electric range. Thus, methods for charging/discharging of electric vehicles with the emphasis on simplicity/convenience, cost effectiveness, high efficiency and flexibility have gained even a wider importance among industrial and academic communities. An illustration of the concept is shown in Figure 1.15.

Inductive power transfer (IPT) has acquired global recognition as a method for applications with no physical contact, through the weak or loose magnetic coupling. This method can offer high efficiency (up to 85–90%), robustness and high reliability without being significantly affected by dust or chemicals. Currently many IPT systems with a wide range of topologies and levels of complexity in control have been research and tested. Even though some of these technologies are focused on improving the contactless power flow in unidirectional applications, there are also some bidirectional systems under development for EV application that can enable regenerative breaking and V2G applications. Such systems include a coupled magnetic circuit to facilitate bidirectional power transfer while operating as a voltage source. However, it is currently not profitable to sell the electricity back into the grid using IPT. The main disadvantages of this technology however include lower charging efficiency and power density as well as manufacturing complexity and size, and cost.

1.7.4 Smart Grid and V2G/V2H/V2X Systems

Even though EVs and PHEVs can provide significant benefits in terms of reduction of fossil fuel consumption and related emissions, they still needed to be plugged into the grid to get the energy to charge up the battery, which can increase the electricity demand especially when they are in growing numbers. Most conventional charging method for PHEVs is plugging it to the household outlet (so called V0G) to be charged when needed, which can add significant load to the grid, especially as the number of PHEVs increase in the future. In order to provide common grounds and methods/procedures for EV charging, various standards on energy transfer, connection interface and communications have been developed over the years (and still continue to do so) which are summarized in Table 1.4.

Table 1.4 Vehicle charging standards.

Standard	Code/Description
NEC Article 625	EV charging system (wires and equipment used to supply electricity for charging an electric vehicle)
SAE J2293	Energy transfer system for EVs
SAE J2836	Recommended practice for communication between plug-in vehicles and utility grid
SAE J1772	Electric vehicle conductive charge coupler
SAE J1773	Electric vehicle inductively coupled charging
IEC 62196	Plugs, socket outlets, vehicle couplers and vehicle inlets, conductive charging of electric outlets
IEEE 1547.3	Interconnecting distributed resource with electric power system

Source: Young *et al*. (2013).

Moreover, their load on the system can be reduced significantly and even feed electricity back to the grid with the implementation of indirect charging and bi-directional power transfer systems. This concept of integrating the battery powered vehicles into the grid and charge when the electricity demand is at its lowest, when there is excess capacity (and/or related other metric) is commonly called smart charging (so called V1G).

In this regard, integration of distributed resources load and generation/storage device between the EVs and the grid is commonly called vehicle-to-grid (V2G) system (although smart charging and V2G are used widely starting to be used interchangeably). The vehicle can also communicate with the building, as opposed to the grid, as home generators during periods of electrical service outage (or even for the purpose of self-generated renewable energy use) which is commonly called V2B. Finally, there are systems that include both along with additional features such as storage of power to a remote site or to other PHEVs, which are commonly called V2X. These interactions are represented in Figure 1.16.

The aforementioned charging schemes are also provided in Table 1.5. As shown in this table, communication between the grid and the vehicle exists in smart charging, usually

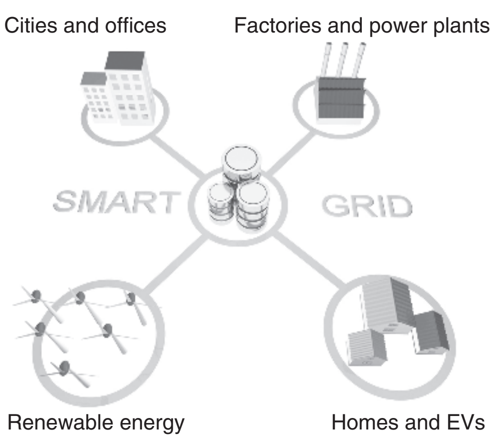


Figure 1.16 Illustration of smart grid operation.

Table 1.5 Charging schemes for electric vehicles.

Features	V0G	V1G	V2G	V2B	V2X
Real-time communication		√	√	√	√
Communication with the grid		√	√		√
Communication with the building/Home generator feature				√	√
Provide power to a remote site					√
Transfer energy to other PHEVs					√
Timed charging		√	√	√	√
Backup source			√	√	√
Controllable load		√	√	√	√
Bidirectional grid ancillary service			√		√
Load shifting for renewables			√	√	√

Source: Young *et al*. (2013).

through advanced metering infrastructure. In addition, energy stored in the batteries can also be transferred back to the grid and building in V2G and V2B schemes respectively. Finally, V2X has all the previous with the addition of providing power to remote sites and/or other PHEVs.

Thus, these concepts can provide solutions and link two critically important problems; the petroleum dependency of the transportation sector and the imbalance between electricity supply and demand, in ways that may address significant problems in both issues. Moreover, smart grid/V2G systems can enable PHEVs to have even more impact on enhancing the reliability, technical performance, economics and environmental impact of the grid operations by provision of capacity and energy based ancillary services and the reduction of the need for peaks and load levelization and can even generate revenues to the owners of these vehicles. In turn, this can help reducing the petroleum use, strengthening the economy, enhancing natural security and reducing the carbon footprint.

In order to have such a system where the electricity resources could be utilized better, vehicles must incorporate a power connection to the electricity grid, a control or logical connection for communication with the grid operators and high accuracy metering on the vehicle to tract energy transfers. The control of the grid operator is essential must be overridden in order to prolong the battery life and have the vehicle ready for operation. Since most of these vehicles stay idle in parking lots or garages over 90% of the time in the United States, the size of these resources can be quite large. However, in order for V2G (or V2X) systems to be successful, the requirements of the grid system operator and the vehicle owner must be satisfied. The grid system operator demand industry standard availability and reliability from these systems, whereas the vehicle owner desires a quick returns on the additional hardware cost associated with the system.

The literature studies show that in 2020, with a quarter of people in 13 regions of the United States having EVs/HEVs, 160 new power plants would be required if all the EV/HEV owner plugs their vehicle to the grid around 5 p.m. On the other hand, smart-grid technology can utilize these vehicles to provide valuable generation capacity at peak times (along with ancillary services) and enable the demand for electricity to be supplied within the existing capacity by better utilizing the daily load. Moreover, since the electricity price is lower during the charged off-peak hours than the generated peak hours, the owners of these vehicles would be able to make revenues from this process. However, currently the estimated profit from this technology ranges significantly, from -$300 to $4600 profit per vehicle per year with most estimates ranging of $100 - $300. Since this may not be economically adequate to gain significant participation by individuals or aggregator organizations, governments may need to support these technologies with policies in order to reinforce customer and business participation.

Even though V2G/V2B/V2X systems can have the aforementioned positive impact on the efficiency, cost and environmental impact of the energy used from the grid or the house, it can also reduce the capacity of the battery as a result of cycling based on the number cycles, depth of discharge (DOD) and the actual chemistry of the battery. Even though currently not enough data are available to demonstrate the exact impact of these systems on the battery degradation, some studies have determined that using the battery for V2G/V2B/V2X energy incurs approximately half the capacity loss per unit energy processed compared to that associated with the more paid cycling encountered while driving. Moreover, new standards and certifications as well as updates/modifications to the building codes and electrical regulations will be necessary to be able to utilize these technologies.

In addition, this technology would also help with the integration of renewable energies (especially solar and wind) and the transformation of the electricity system used today. In wind energy, the power generated from the wind turbines fluctuate significantly due to wind gusts, cloud cover, thermal cycles, the movement of weather fronts and seasonal changes, whereas in solar energy, this changes are mainly based on the time, season and the associated solar irradiation. A concept of renewable energy integration into smart grid systems is shown in Figure 1.17.

V2G systems could help level the daily fluctuations of these renewable energy sources and help with the integration of these intermittent resources into the grid. Studies

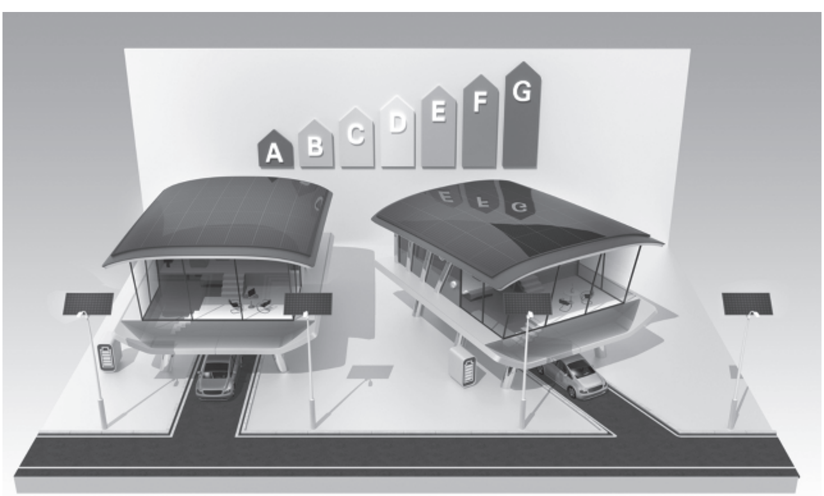


Figure 1.17 A conceptual representation of integrating renewable energy into a smart grid system.

show that in the next century, the installed renewable energy capacity could increase by up to 75% with V2G capable EVs, however, this depends on the electric vehicle storage capacity, through more vehicles and/or larger batteries. In addition, charging directly with solar energy would avoid both the DC/AC conversion and transmission losses. When installed in parking lots, a significant portion of personal vehicle and city passenger transportation energy demand could be provided through solar PVs, especially during summer time.

1.8 Sustainability, Environmental Impact and Cost Aspects

EVs, conventional HEVs and PHEVs provide significant reduction in emissions compared to conventional vehicles (CVs) with ICEs, while having competitive pricing due to government incentives, increasing oil prices, and high carbon taxes combined with low-carbon electricity generation. The emissions of CVs increase significantly for short distance travels due to the inefficiencies of the current emissions control systems during cold starting of the gasoline vehicles. It is estimated that vehicles travelling fewer than 50 km per day are responsible for more than 60% of daily passenger vehicle kilometers travelled in the United States. Powering this distance with electricity would reduce gasoline use significantly and yield a considerable reduction of emissions. Even when traveling with the use of gasoline in HEVs and PHEVs, the efficiency of the ICE is significantly higher than the ICE of CVs. However, the reduction in fuel and emissions depends primarily on the energy generation mix used to produce the electricity. The balance of the 2006 US electricity mix is composed of coal (49%), nuclear (20%), natural gas (20%), hydroelectric (7%), renewable (3%) and other (1%). Therefore, for the U.S. average GHG intensity of electricity, PHEVs can reduce the GHG emissions by 7 – 12% compared to HEVs. This reduction is negligible under high-carbon scenarios of electricity production and 30 – 47% under the low-carbon scenarios. When PHEVs are compared against CVs, the reduction in GHG emissions is about 40% for the average scenarios, 32% for high cases and between 51 – 63% for low-carbon based scenarios. The detailed life cycle GHG emissions (g CO_2−eq/km) for CVs, HEVs and PHEVs under various scenarios are shown in Figure 1.18. The number after PHEV (PHEV30 or PHEV90) represents the all-electric range of the vehicle in km.

When the emissions for PHEVs are examined, the majority of emissions come from the operational stage. A large portion is due to the gasoline used for traveling, followed by electricity used for traveling based on the carbon-intensity of the electricity generation source. When the emissions from the electric power increase significantly under a high-carbon scenario (coal-based generation capacity), the reduction in volatile organic compounds (VOCs) and CO are offset by a dramatic increase in SO_x and slight increase particulate emissions (PM10). However, the total GHG emissions are still lower compared to CVs since the increase in upstream emissions has a lower magnitude than the decrease in tailpipe emissions (Bradley and Frank, 2009). The GHGs associated with most battery materials and production generates a relatively small portion of the emissions and accounts for 2 – 5% of the life cycle emission from PHEVs. Moreover, the GHG emissions from the vehicle end-of-life are not shown since they are relatively negligible. The reduced fuel use and GHG emissions for PHEVs depend significantly on vehicle and battery characteristics, as well as the recharging frequency. Using PHEVs

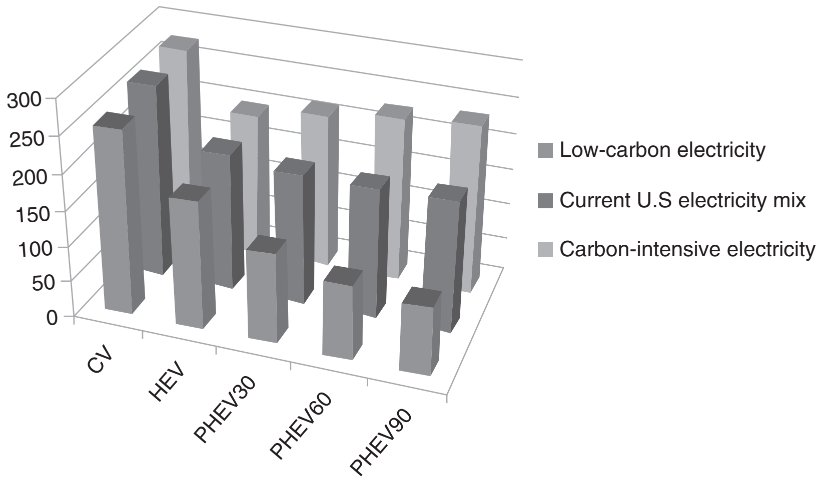


Figure 1.18 Life-cycle GHG emissions sensitivity of CVs, HEVs, PHEV30 and PHEV90 under different carbon intensity scenarios (data from Samaras and Meisterling, 2008).

also has a significant impact on the operating costs of the vehicle. PHEVs in all-electric mode can reduce the gasoline consumption by half, by shifting 45–77% of the miles from gasoline to electricity, which would reduce the operating costs assuming the electricity cost per mile is significantly less than the gasoline cost. Battery life also has a significant role on the cost associated with PHEVs since replacing the battery would increase the life cycle cost of a PHEV by between 33% and 84%. However, the overall cost savings would be based on the overall cost of the vehicle, range and driving behavior, as well as economic incentives such as taxes on carbon emissions and gasoline.

Even though EVs and HEVs compete with conventional vehicles in terms of performance and cost with much less environmental impact, their benefits depend mainly on the battery technology utilized in these vehicles. Although many battery technologies are currently being analyzed for EVs and HEVs, the main focus has been mainly on lead-acid, NiCd, NiMH and Li-ion battery technologies. Thus, in order to understand the effects of EVs and HEVs, further analysis is needed for these battery technologies based on various criteria.

1.9 Vehicle Thermal Management

Thermal issues associated with EV and HEV battery packs and under hood electronics can significantly affect the performance and life cycle of the battery and the associated system. In order to keep the battery operating at the ideal parameter ranges, the discrepancy between the optimum and operating conditions of the batteries need to be reduced significantly by implementing thermal management systems (TMS) in EVs and HEVs. These systems are utilized to improve the battery efficiency, by keeping the battery temperature within desired ranges. Thus, freezing and overheating of the electrochemical systems in the battery can be averted which can prevent any reduction in power capability, charge/discharge capacity and premature aging of the battery. Most electric and hybrid electric vehicle thermal management systems consist of four different cycles to keep the associated components in their ideal temperate range in order to operate safely and efficiently. Even though the components and structure of these loops may vary from vehicle to vehicle, their purposes are usually the same; creating an efficient and robust system that is not adversely affected by internal and ambient temperature variations. Generally, the overall vehicle thermal TMS is composed of the radiator coolant loop, power electronics coolant loop, drive unit coolant loop, and air-conditioning (A/C) and battery loop. A brief description of these loops is provided as follows.

1.9.1 Radiator Circuit

In the radiator loop, the engine is kept cool by the mixture of water and anti-freeze pumped into the engine block to absorb the excess heat and draw it away from the crucial areas. When this superheated engine coolant leaves the engine block, it returns to the radiator. The radiator has a very large surface area through the internal chambers where the excess heat of the coolant is drawn out through the walls of the radiator.

As the vehicle moves, the front of the radiator is also cooled by the ambient air flowing through the car's grill. The loop also includes a surge tank, which acts as a storage reservoir for providing extra coolant during brief drops in pressure, as well as to absorb sudden rises of pressure as shown in Figure 1.19. Next, a coolant pump is used for moving the coolant back and forth to the radiator. When the ICE is off, the coolant heating control module is used to provide heat to the coolant. A portion of the heat in this loop is also transferred to the passenger cabin with help of the heater core.

1.9.2 Power Electronics Circuit

The power electronics coolant loop is mainly dedicated to cooling the battery charger and the power inverter module to ensure the main under-hood electronics do not

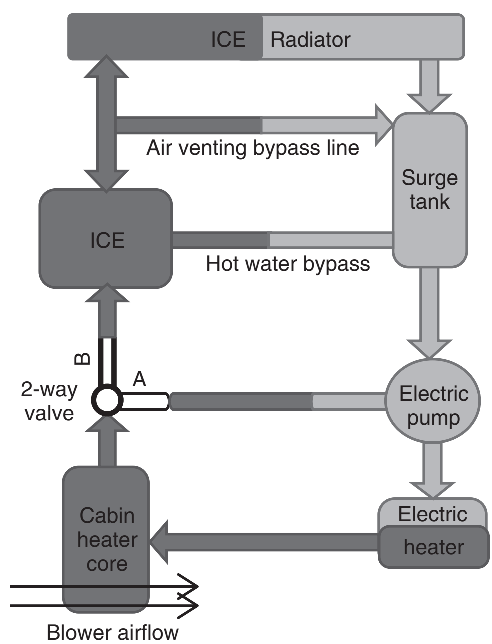


Figure 1.19 Simplified radiator circuit of a HEV (adapted from WopOnTour, 2010).

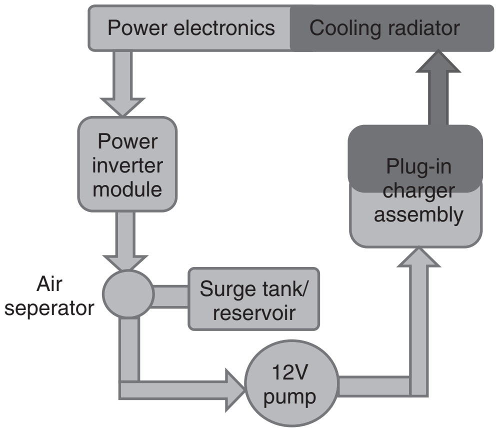


Figure 1.20 Simplified power electronics cooling circuit of a HEV (adapted from WopOnTour, 2010).

overheat during usage. The power inverter module converts direct current (DC) from the high-voltage battery into 3-phase alternating current (AC) motor drive signals for the motor generator units. The module is also responsible for converting AC to DC for charging operations during regenerative braking.

In these operations, a large amount of heat is generated in the system. In order to prevent overheating, the loop incorporates a high flow electric pump to produce and control the coolant flow which passes through the plug-in battery charger assembly, the radiator, and the power inverter module before it flows back to the pump as shown in Figure 1.20. This loop also includes a coolant pump for the circulation of the coolant and an air separator to ensure that the coolant does not have any air bubbles that would affect the cooling performance before traveling through the major electronic parts.

1.9.3 Drive Unit Circuit

The drive unit loop is designed to cool the two motor generator units and electronics within the drive unit transaxle that are used to propel the vehicle using electric power (in addition to generating electricity to maintain high voltage battery state of charge).

It provides lubrication for the various associated parts. Significant heat is generated in these parts due to high power levels during normal operation. The drive unit uses a system of pressurized automatic transmission fluid to cool the electronics in the loop, especially the motor generator units to prevent overheating. The simplified diagram of the drive unit circuit is provided in Figure 1.21.

1.9.4 A/C Circuit

Even though all of the circuits mentioned above have significant roles in enabling the vehicle to operate as robustly, efficiently and safely as possible, in EVs and HEVs, a majority of the focus is given to A/C and battery cooling loops due to its direct effect on the battery performance, which has significant impact on the overall vehicle performance, safety and cost. For this reason, various studies are conducted in this cooling loop to optimize their operating conditions of the associated components, the cabin and the battery. Thus, different cooling systems and configurations will be analyzed based on various criteria and operating conditions.

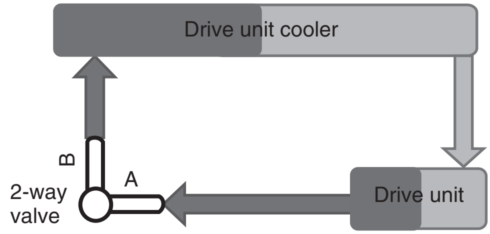


Figure 1.21 Simplified drive unit circuit of a HEV.

The main goal of the A/C cycle is to keep the battery pack at an optimum temperature range, based on the cycle life and performance trade-off, in a wide spectrum of climates and operating conditions as well as keeping even temperature distributions with minimal variations within cells, while keeping the vehicle cabin at desired temperatures. Meanwhile, the system should also consider trade-offs between functionality, mass, volume, cost, maintenance and safety.

Since the main focus will be the A/C and battery loops, they will be called the thermal management systems (TMSs) for the rest of the analysis. They will be categorized based on their objective (providing only cooling vs. cooling and heating), method (passive where only the ambient environment is used vs. active cooling where a built-in source is utilized for heating/cooling), and heat transfer medium (air distributed in series/parallel or liquid via direct/indirect contact).

A passive cabin air cooling system utilizes the conditioned air to cool the battery in warm ambient conditions. It was used on early EV and HEV battery packs (Honda Insight, Toyota Prius and Nissan Leaf) mainly due to cost, mass and space considerations. This is a very effective cooling method for the battery at mild temperatures (10°C to 30°C) without the use of any active components designated for battery cooling. It is highly efficient since it utilizes the heat from the vehicle air conditioning. The ideal battery operating temperature (for Li-ion) is approximately 20°C on the low end, which is highly compatible with the cabin temperature. However, air conditioning systems are limited by the cabin comfort levels and noise consideration, as well as dust and other contaminants that might get into the battery, especially when air is taken from outside. Certain precautions should be taken in this system to prevent toxic gases from entering the vehicle cabin at all situations. In independent air cooling, the cool air is drawn from a separate micro air conditioning unit (instead of the vehicle cabin) with the use of the available refrigerant. Even though this may provide more adequate cooling to the battery, the energy consumption as well as cost and space requirements associated with installation of the blower and the micro air conditioning unit increases significantly. The rate of heat transfer between the fluid and the battery module depends on various factors such as the thermal conductivity, viscosity, density and velocity of the fluid. Cooling rates can be increased by optimizing the design of air channels; however it is limited by the packaging efficiency due to larger spacing between the cells. Air can flow through the channel in both serial and parallel fashions, depending on whether the air flow rate splits during the cooling process. In series cooling, the same air is exposed to the modules since the air enters from one end of the pack and leaves from the other. In parallel cooling however, the same air flow rate is split into equal portions where each portion flows over a single module. In general, parallel airflow provides a more uniform temperature distribution than series.

Refrigerant cooling is a compact way of cooling the battery, with more flexibility compared to a fan with ducts, by connecting the battery evaporator parallel to the evaporator in the cooling loop. Heat generated by the battery is transferred to the evaporating refrigerant. This system only requires two additional refrigerant lines, namely suction and pressure lines. The battery evaporator uses some portion of the compressor output that was reserved for the air conditioning, and thus this might cause conflict in some conditions. However, the compressor work needed to cool the battery is usually considerably lower than the air conditioning evaporator need.

Liquid cooling utilizes the previous cooling method with the incorporation of an additional liquid cooling loop specifically for the battery that connects to the refrigerant. This additional cooling loop usually has water or a 50/50 water-glycol mixture and it is kept cool via different procedures depending on the cooling load and ambient conditions. The coolant can be cooled either by ambient air through the battery cooler (if the ambient temperature is low enough) or by transferring the heat to the refrigerant through the chiller. Both methods increase the efficiency of the system since the additional compressor work (that is used in refrigerant cooling) is no longer needed. A simplified diagram of an A/C circuit with liquid battery cooling is shown in Figure 1.22.

In addition, battery cooling can also be done with phase change materials (PCM) integrated cooling systems. PCMs have significant advantages over the aforementioned TMSs, due to their simple design, light weight and compact size, safety and relatively low cost, especially when the integration is considered from the outset and it is improved with the addition of aluminum foam and fins. PCMs are capable of keeping the magnitude and uniformity of the cell temperatures under stressful operating conditions without the need of a complicated system or fan power. Moreover, the heat transfer

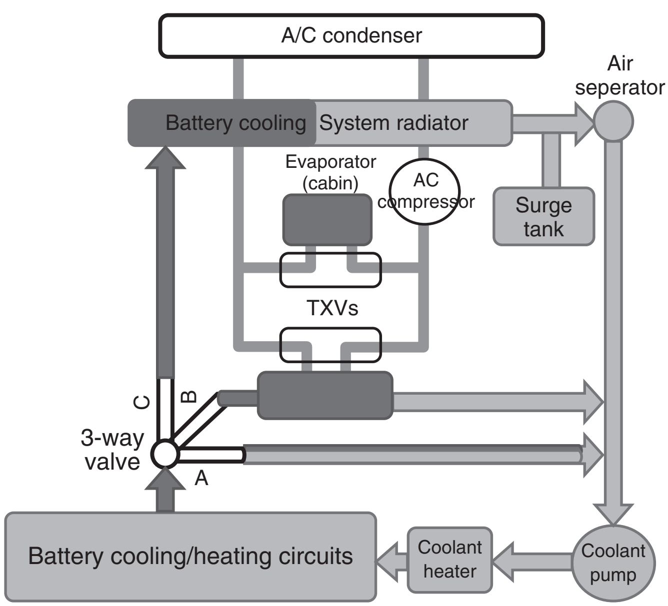


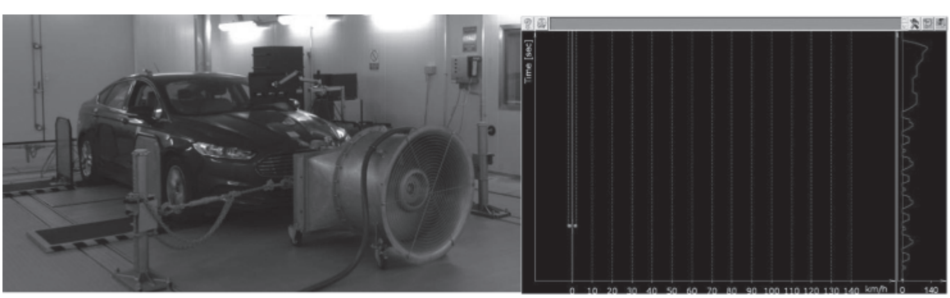
Figure 1.22 Simplified A/C circuit of a HEV (adapted from WopOnTour, 2010).

associated with adding PCMs to a cell can prevent the propagation of thermal runaway, when the cell temperature reaches critical levels. Furthermore, PCMs can be used to have both an active and passive role (complementary/secondary) in thermal management of the battery packs which can reduce the complexity and cost of the system.

1.10 Vehicle Drive Patterns and Cycles

A driving cycle is a time series compilation of vehicle speed (speed versus time curve) established in order to represent typical driving patterns (usually to represent in a specific location and mode of driving) to estimate fuel consumption, emissions and the impact of traffic. The experienced speeds, acceleration, start conditions, gear changes, temperature and loading are some of the important recorded conditions. The first drive cycles were developed in 1950s by Los Angeles County Air Pollution Control District for emissions measurement of typical Los Angeles driving and more realistic drive cycles were achieved in 1969, mostly representing “typical” home to work driving in Los Angeles which formed the basis of Urban Dynamometer Driving Schedule (UDDS) and Federal Test Procedure (FTP). In the later years, similar data collection procedure was established for highways which resulted in Highway Fuel Economy Test (HWFEET). These cycles were used by EPA to publish city and highway driving fuel economy numbers.

The drive patterns and cycles play an important role in electric vehicles since they determine the power and energy requirements and have major implications for the real life battery performance and electricity infrastructure. Information regarding how much of the time the vehicle is at motion and at rest during the day and how long the trips are play an important role on determining when and how often the drivers would need to charge their vehicles. In addition, the drive cycle information together with the equations of motion for the vehicle can provide the power profile requirements for the battery. A drive cycle testing of a vehicle on a dual axle chassis dynamometer and its drive characteristics are shown in Figure 1.23. Drive cycles represent the velocity against time relationships for a given vehicle in a certain type used in a specified manner. There are usually two types of tests, namely highway and urban driving where the initial is characterized by relatively constant velocities over 60 mph and the latter has frequent stops and starts with velocities averaging in 20–30 mph. Generally regional driving



Dual axle chassis dynamometer Drive cycle software

Figure 1.23 Vehicle performance testing using a preloaded drive cycle (courtesy of TUBITAK Marmara Research Center).

cycles have to be developed in order to imitate real-world condition in specific parts of the world to conduct representative analyses. However, this still presents significant challenges to cope with extremes that lie outside of the test capabilities as traditional evaluations generally achieve limited success.

1.11 Case Study

In this section, a case study is provided to show the readers how the aforementioned information is taken into consideration in real life to make decisions on selecting the most appropriate vehicle technologies to be utilized in a country. In this regard, the market penetration of Turkey is selected, since the country has interesting and unique features in terms of the ratio of the country's energy import/exports, its technological capability and governmental regulations. Thus, a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis of H&EV Turkish market penetration is conducted in the light of the recent domestic and global developments in this area to provide information on factors that played key roles on the decision making process along with their underlying considerations and reasons.

1.11.1 Introduction

During the past decade there has been increasing interest in the deployment of HEVs and EVs. For example, in 2012, around 113,000 EVs were sold in the world, more than twice of the previous year, mainly in United States, Japan and China and 20 million EVs are projected to be on the roads by 2020. With the significant increase in R&D and infrastructure for electric vehicle technologies and reduction in battery costs, the market penetration of these vehicles is expected to become more prominent in the near future. However, in Turkey – the country that has one of the fastest growing economies in the world with the largest increase in the energy demand among the OECD countries – the hybrid and electric vehicle market is still in its initial stages. Therefore, transportation sector is among the highest contributors to this energy demand with respect to the liquid fuels used by conventional vehicles. Since the country has limited reserves of oil, this increase in energy demand is not able to be met through domestic energy production alone and increases the energy imports which possess a threat on the country's economic growth, national security and industrial well-being. Moreover, in the last decade, the effects of rising fossil fuel prices and environmental awareness became more prominent within Turkish industries, research and development organizations, and Turkish society as a whole. Thus, significant work has been done by the government in the past years in terms of policies and legislation to encourage the entrance of H&EVs in the market and various efforts are made to develop these vehicles domestically in the country. However, significant technical knowledge, tremendous investments and abundant infrastructure will be required to achieve these goals.

1.11.2 Research Programs

The Turkish automotive industry's awareness and interest on electric vehicles have been increasing in the past decades, and research projects on electric vehicle technologies and system components are being carried out by several research institutions, programs and platforms.

One of the most important platforms in this area, the National Automotive Technology Platform (OTEP), was formed in 2008 in order to determine a vision for the Turkish automotive industry and identify strategic research areas to be addressed and increase the countries international competitiveness. Moreover, in 2010, "Turkish Automotive Industry Vision and Strategic Research Program for 2023" document was initiated by the associated working groups in the platform. Moreover, an "Electrical Vehicles" group was also established in order to generate new ideas and provide advancements in a wide range of electric vehicle technologies, subcomponents and infrastructure (IA-HEV, 2010–2012). In 2011, with the progress of these groups and the introduction of EVs in the vehicle market, various joint projects and ventures between universities/institutes and private companies have been initiated.

Since 2012, the government launched major research programs by supporting research and development projects at universities, research institutes regarding EVs and subcomponent technologies. Among these, the main focus has been the electric motors and battery technologies in H&EVs along with energy management systems and dynamics and control of these vehicles along with attention on internal combustion engine performance and emission control in HEVs. The duration for the selected projects were determined to be 2–3 years, with an approximate budget of $6.5–7.5M. Moreover, a support programme for industry has been established for the development of electric motors/generator and driver systems (up to $10.5M with 5 projects), energy management, control system, hardware and algorithm (up to $5.9M with 3 projects), vehicle electronics and electromechanical system components (up to $32.5M with 8 projects) and innovative vehicle components and systems (up to $43.6M with 16 projects) for H&EVs (IA-HEV, 2010–2012).

In parallel with the support programs described above, various government incentives such as purchasing guaranty, tax benefits, infrastructure development (such as increasing the number of charging stations and improving their access) and new legislation and implementation programs and are also started to be employed.

1.11.3 Government Incentives

1.11.3.1 Tax Benefits

Turkey implements two different taxation measures for vehicles in the market. The first is a tax on an initial new vehicle purchase (special consumption tax), whereas the second one (motor vehicle tax) is an annually paid based on the engine cylinder volume and the age of the vehicle. The special consumption tax (SCT) for conventional vehicles is increased in the beginning of 2014 with respect to the previous years. Depending on the engine volume, the tax has increased from 40% to 45% for under 1600cc, from 80% to 90% for between 1600cc and 2000cc and from 130% to 145% for over 2000cc as shown in Table 1.6. With the new regulations, the current prices of conventional vehicles are expected to increase approximately by 10%. Since the SCTs on EVs have not changed (with maximum of 15% on passenger vehicles), EVs gathered a wider economic advantage based on the new tax system compared to conventional vehicles when a new vehicle is purchased, especially since electric vehicles are also exempt from the motor vehicle tax (MTV).

Table 1.6 Special consumption tax classification categories for new vehicle sales[a)].

	Conventional		Electric Only	
Vehicle Type	**Engine Cylinder Volume (cc)**	**Special Consumption Tax (%)**	**Electric Motor Power (kW)**	**Special Consumption Tax (%)**
Passenger Vehicle	<1,600	45	<85	3
	1,600–2,000	90	85–120	7
	>2,000	145	>120	15
Motorbike	<250	8	<20	3
	>250	37	>20	37

a) The vehicle sales tax reduction includes only battery electric vehicles and battery electric motorbikes and excludes HEVs and plug-in electric vehicles (PHEVs).
Source: ODD (2013).

1.11.3.2 EV Supply Equipment and Charging Infrastructure

In addition, various installation efforts are being made in Turkey to install EV supply equipment across Turkey (especially in Istanbul), however they are a very small in quantities and are mostly done by a few private companies. Aside from these, In January 2013, Sabanci University became the first university in Turkey with a charging station. In June, 2013 the first domestically developed charging station producer Gersan Electric Incorporated Company started building charging stations in pilot areas of Istanbul with a target number of 60 to 65 units. In September 2013, legal ground was established in fuel station areas to build electric charging, CNG, LPG and hydrogen filling stations. In November 2013, Izmir metropolitan municipality installed charging stations to a number of parking stations where electric vehicle owners can charge their vehicles for free in order to increase the number of electric vehicles in the city. It is estimated that over 100 charging stations currently exist in Turkey.

In addition to the aforementioned incentives, implementation programs and new legislation are also are announced. A number of electric vehicles per year for a 5-year period are stated to be purchased by the national ministry. More incentives are projected to be announced for other public institutions to purchase EVs. Based on the targets set by the Turkish government, the electricity grid infrastructure will be strengthened, and electricity tariff deregulation will be completed in the following years. Moreover, access to charging stations near residences, car parks, and shopping centers will be increased and awareness projects will be executed concerning EV technology and EV usage. Furthermore, legislation regarding the recycling of EV batteries will be revised and the capacity of test centers will be improved in the future. Furthermore, several legal and policy instruments were also established to encourage the use of H&EVs in Turkey including a strategy document regarding energy efficiency in transportation by the Ministry of Energy and Natural Sources and automotive industry strategy document and action plan by the Ministry of Science, Industry and Technology.

1.11.3.3 EV Developments in the Turkish Market

The funding support in electric vehicle R&D projects, reduction in their consumption and vehicle taxes along with increased efforts on building associated infrastructure encouraged many private companies to start conducting research on electric battery and motor, emission reduction methods and vehicle system integration domestically.

Among these, in 2009, the Turkish bus manufacturing company TEMSA introduced the Avenue Hybrid, which had a series hybrid powertrain that enabled 25% fuel reduction and lower CO_2 emissions compared to its standard conventional buses. The vehicle was also quitter due to not having a gearbox and claimed to have a better riding experience due to lack of vibrations that exists in the conventional version. The same year Otokar announced a concept hybrid urban bus Doruk 160LE Hibra with electric battery and diesel engine which claimed to have a 20% reduction in fuel consumption.

In November 2009, TOFAŞ started developing the all-electric version of the vehicle, Doblo EV which became “the first electric vehicle designed and developed for mass production in Turkey” and introduced its prototype in 2010. The vehicle has 105 kW maximum power output and can travel 150 km on a single charge and has regenerative breaking. The vehicle can be charged approximately in 7 hours, but this time can be reduced to 1 hour with fast charging.

In addition, Fluence Z.E. production has begun solely at the Oyak Renault Bursa Plant in 2010. The vehicle uses 22 kWh Li-ion battery, 70 kW electric motor that provides an all-electric range of 185 km and can speed up to 135 km/h. It can be charged in 10–12 hours using a household outlet, but is also compatible with fast charging stations for much quicker charging times (Renault, 2014). The batteries are also designed for “quick drop” technology which can be switched in a battery exchange facility. However, the production was stopped in 2013 due to the low number of sales in Turkey and Europe.

At the beginning of 2013, Derindere Motor Vehicles (DMA) launched its pure electric vehicle “DMA All Electric”, the first Turkish vehicle with type approval certificate for electric vehicles in Turkey, and made the first test drives. The vehicle will be able to be charged in 8 hours on 220V, would be compatible with European Standard type 2 charging stations and travel approximately 280 km in one charge. It will come both with buying (US $53,500) and renting (US $1200 per month) options for operational fleets. The company is targeting to produce 100 vehicles per month. The motor and the battery for the vehicles are currently being imported; however the ECU is developed in Turkey. The vehicle has a 40 kWh Li-ion battery and 62 kW electric motor (with 225–325 Nm torque) and will have 3 year 100,000 km warranty (DMAOTO, 2013).

In addition, after a year of research, In mid-2013 Malkoçlar Automotive has developed a pure electric vehicle with all the R&D and manufacturing done in Turkey (with the exception of the electric motor) that can travel 100 km with an energy cost of under a dollar. The vehicle has 2 versions, one with a 2-seater and another with 4 seats and is mainly designed for inner city traveling and commercial use. It is mostly made out of plastic and had aluminum construction space frame for collusion safety. It weighs approximately 800 kg and can travel up to 130 km/hr with maximum range of 150 km. Charging from the regular outlet will take approximately 6–7 hours with a fast charging option of 45 minutes. The vehicle is currently under testing and waiting for type approval certificate with a plan to be sold for US $13,500 in 2014 after the all tests are successfully completed (Elektriklioto, 2013).

Finally, initiated by the Ministry of Science, Industry and Technology, TUBITAK MRC has taken imperative steps in early 2015, towards establishing a Turkish National Car

Brand and the Industrialization of its first products, in line with the the Supreme Council for Science and Technology agenda and 2023 National Technology Targets. In this regard, TUBITAK MRC has been working on vehicle design, engineering, testing and certification as well as widening its corresponding workforce and infrastructure to introduce the first vehicles to the Turkish market before 2020.

1.11.3.4 HEVs on the Road

The number of vehicles on the Turkish roads is increasing rapidly. Even though the total fleet of vehicles on the road reached up to 18 million at the end of 2013, only a negligible percentage of them are currently electric vehicles. The number of vehicles between 2005 – 2013 can be found in Figure 1.24.

Meanwhile, the passenger car sales have also increase significantly in the past years reaching to 664,655 in the year 2013 (19.48% increase compared to 2012) as provided in Table 1.7. The light-commercial market on the other hand, shrank and therefore the combined total passenger car and light-commercial market had a 9.72% increase from 777,761 units in 2012 to 853,378 units in 2013. When the passenger car market is examined according to the engine volumes, the passenger cars under 1600 cc received the highest share of sales every year due to the lower tax rates (compared to larger engine sizes). In 2013, only 31 EV passenger cars were sold in Turkey compared to 184 the year before.

When the passenger car market is examined according to average emission values, even though the total emissions for the passenger cars increased in 2013 due to high number of sales, cars that have emission values under 140 gCO_2/km limit has accounted for more than 75% of the vehicle sales (Table 1.8). This is primarily a result of the lower tax values for the engine volumes ≤1,600 cc, which also helps in bringing down the increase in total fleet emissions average of the vehicles in Turkey.

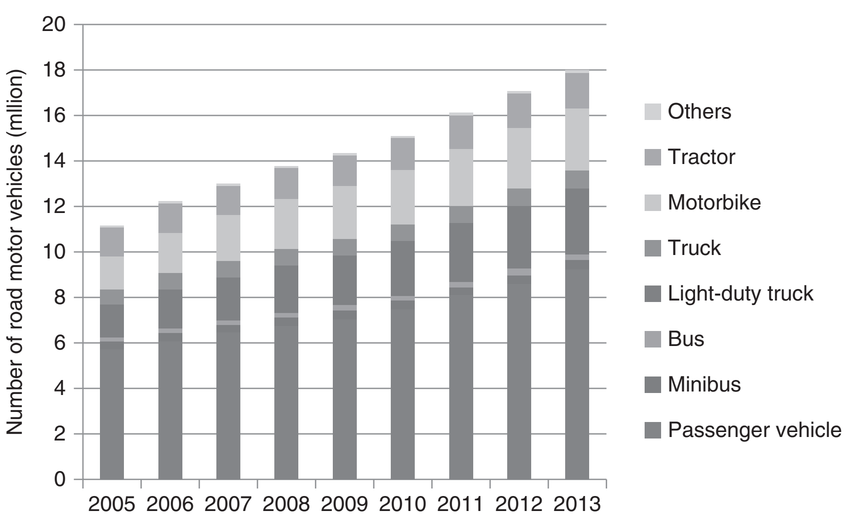


Figure 1.24 Total vehicle fleet according to the vehicle types between 2005 and 2013 (data from road motor vehicle statistics report, 2013).

Table 1.7 Passenger car market according to the engine/electric motor size for 2009–2013.

Engine Size	Engine Type	2009	2010	2011	2012	2013	SCT Tax Rates[a)]	VAT Tax Rates
≤1600 cc	Gas/diesel	304,755	412,162	530,069	514,861	625,621	45%	18%
1601 cc to ≤2000 cc	Gas/diesel	56,766	87,246	52,396	35,850	33,035	90%	18%
≥2001 cc	Gas/diesel	8268	10,376	11,054	5385	5968	145%	18%
≤85 kW	Electric	0	0	0	184	31	3%	18%
86 kW to ≤120 kW	Electric	0	0	0	0	0	7%	18%
≥121 kW	Electric	0	0	0	0	0	15%	18%
Total		**369,819**	**509,784**	**530,069**	**556,280**	**664,655**		

a) 2014 SCT tax rates.
Source: ODD Press Summary (2013).

Table 1.8 Passenger car market according to average emission values for 2001–2013.

Average Emission Values of CO_2 (g/km)	2011 Cumulative		2012 Cumulative		2013 Cumulative		2013/2012
	Units	%	Units	%	Units	%	%
<100 g/km	3820	0.60	18,635	3.30	56,570	8.51	203.57
≥100 to <120 g/km	172,652	29.10	173,218	31.10	238,816	35.93	36.19
≥120 to <140 g/km	223,020	37.60	202,118	36.30	216,016	32.50	7.83
≥140 to <160 g/km	109,013	18.40	118,107	21.20	116,245	17.49	1.29
≥160 g/km	85,014	14.30	44,202	7.90	37,008	5.57	16.28
Total	**593,519**	**100.00**	**556,280**	**100.00**	**664,655**	**100.00**	**19.48**

Source: ODD Press Summary (2013).

1.11.3.5 Turkey's Standing in the World

When the countries that have high share of H&EVs are examined, it can be seen from Figures 1.25 and 1.26 that out of the 18 countries with the highest electrified market share in 2013, 12 of them have the highest gasoline prices in the world. When the remaining 6 countries are analyzed, 4 out of the 6 (Japan, United States and Spain and Estonia) have among the highest incentives for H&EVs. Among those, Japan pays one-half of the price gap between EV and corresponding ICE vehicles up to 1 million yen (around 10,000 USD). Spain provides incentives up to 25% of vehicle purchase price before taxes, up to 6,000 Euros (around 8,200 USD) along with possible additional incentives up to EUR 2000 Euro (around 2,500 USD) per EV/PHEV. The United States has incentives with up to 7,500 USD tax credit for vehicles along with additional incentives depending on the state. Finally, Estonia has grants for purchasing electric cars that are 50% of the purchase price (as a part of the ELMO program) up to 18,000 Euros (25,000 USD). Among the remaining 2 countries, even though Austria does not have significant incentives for electric cars, the country has high taxes for purchase of a vehicle along with taxes on fuel consumption and CO_2 emissions which the electric vehicles are exempt from (up

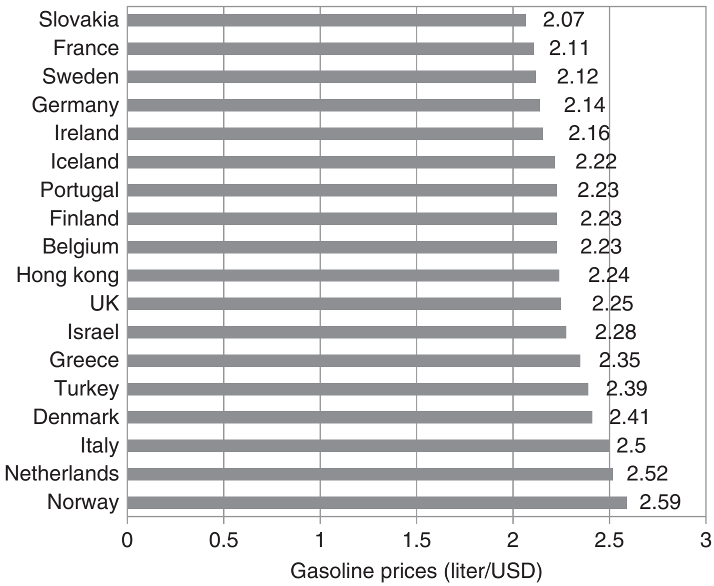


Figure 1.25 Market share percentages for electrified vehicle compared to all vehicles in 2013 (data from ABB, 2014).

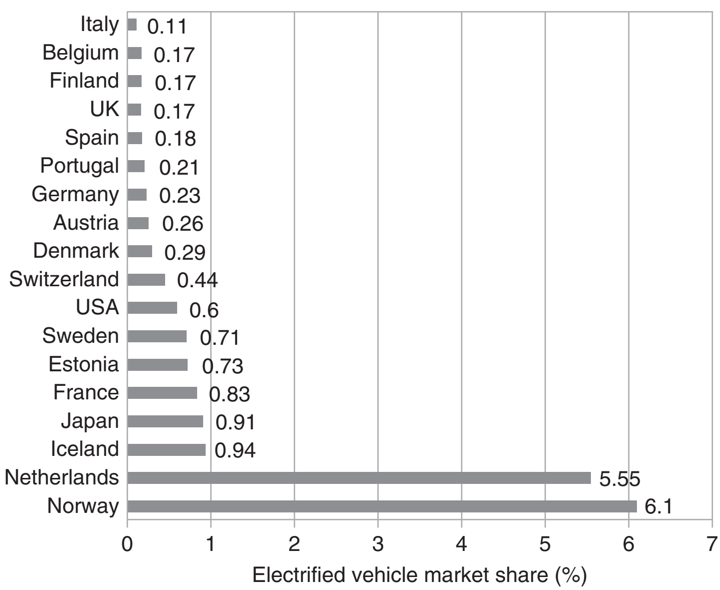


Figure 1.26 Gasoline prices as of 07, july 2014 (data from GlobalPetrolPrices, 2014).

to 16%, can be over 1,000 USD per month). Finally, Switzerland also has reduction or even exemption from vehicle taxes as well as taxes associated with CO_2 emissions.

Thus, it can be seen that, gasoline price and tax incentives play a major role in the penetration of H&EVs in the market. Turkey, however, has a unique situation in this regard

Table 1.9 SWOT analysis for domestic and global market penetration of H&EVs.

Strengths

Global

- The reduction in the fossil fuel consumption of the transportation sector, being one of the largest sectors that depend on the limited, globally unevenly distributed and increasingly priced fossil fuels[a)]
- The reduction of foreign oil dependency of many countries that do not possess fossil fuel resources and mitigation of corresponding economic and political implications
- Various advantages such as the diversification and more efficient use of energy sources, load equalization of power, quite operation and lower operating costs
- High sustainability and low environmental impact with respect to conventional vehicles

Domestic

- The success of Turkish market in the light commercial vehicles[b)]
- The existence of large capable motor and battery manufacturers and sub-industries that are currently being utilized solely for the conventional vehicles[c)]
- The advantage of the geographical location and the potential of being an international hub.

Weaknesses

Global

- The inability of EV and HEV costs to compete with conventional vehicles without the incentives provided by majority of the governments[n)]
- Long charging times and the need for charging infrastructure[o)]
- The limited all electric range[p)]
- The lack of proper standards for the H&EV technology.

Domestic

- The lack of domestic R&D and manufacturing capabilities in value added aspects of technology.
- The incompatibility of apartment layouts that mainly prevents home charging
- The lack of serious investments for the charging infrastructures in the country[q)]
- Fossil fuels being the main contributor of the electricity generation mix of the country[r)]
- The lack of social knowledge and public relations on the EV and HEV technologies

Opportunities

Global

- The rapid advancement in the battery technology which increases the vehicle range and reduces the associated cost and emissions of the vehicle[d)]
- The relatively seamless integration of electric vehicle technology with renewable energy sources[e)]
- The efficient, low cost and safe use of the electric grid with the introduction of EVs[f)]

Domestic

- The large tax incentives for electric vehicles by the Turkish government[g)]
- Turkey having considerably high fossil fuel prices[h)]
- Turkey having high energy imports and correspondingly high current deficits[i)]
- New electric vehicle related funding support for R&D and investment subsidies by the government[j)]
- The recent established targets of emissions and energy efficiency of the country[k)]
- The current plan on establishing a carbon tax for all road vehicles[l)]
- The pre-existing research on the regulations and infrastructure for EVs in Europe and the United States
- The integrability of EVs with the county's abundant renewable energy sources[m)]

Threats

Global

- The possibility of rapid improvements on alternative vehicles technologies, especially on hydrogen fuel cells[s)]
- The possibility of developing cheap, efficient and environmentally benign conventional petroleum alternatives[t)]
- The possible alterations of people's positive perspectives on EVs due to witnessing unsuccessful attempts with the technology[u)]

(*Continued*)

Table 1.9 (Continued)

Domestic
- The years of experience acquired by U.S., Europe and Japan on the EV technology[v)]
- Large R&D budget allocations on (H)EVs, their subcomponents and infrastructure in the United States, China and various European countries[w)]
  The possible undercutting of domestic sales in the Turkish Market by EVs and HEVs designed and manufactured by foreign countries

a) Over 71% of the U.S. crude oil consumption is used in the transportation sector, a sector where 93% of the energy supply comes from liquid fossil fuels in the United States.
b) Turkey had the sixth place for automotive sales among the OECD countries in 2013.
c) In terms of motor, Arçelik, Femsan, Tepaş and Gems; In terms of electric battery, İnci Akü, Mutlu Akü and Yiğit Akü have valuable infrastructure for EV and HEV components.
d) Major breakthroughs have been made on the LCO, NMC and NCA battery technologies and a wide range of research in currently being conducted on the Zinc-air, Lithium-sulfur and Lithium-air batteries.
e) Batteries are compatible with the intermittent characteristics various renewable energy resources (especially solar and wind) and can reduce the DC/AC conversions and transmission losses when charged by them.
f) Since electric grids work under capacity for a large portion of the day, the demand and supply in the grid can be optimized in the near future with the integration of smart grid and vehicle to grid (V2G) technologies.
g) Taxes on electric vehicles range between 3% to 15% in Turkey.
h) Turkey has the fifth highest price of gasoline in the world with $2.39 per liter.
i) By the end of 2013, Turkey is ranked the second among the 57 countries in terms of having the economy with highest ratio of current deficit and over 50% of the trade deficit is caused by oil and oil derived products. Turkey imports over 90% of the country's energy consumption and exports 8 billion USD worth of energy with respect to 60 billion USD worth of imports.
j) TUBITAK provided support for over 30 research programs related to EV technologies, its subcomponents and infrastructure in the next 3–4 years with 65–70M Euros.
k) Turkey is targeting 130 g/km CO_2 emissions established by the OECD countries for the year 2015.
l) New regulations are expected to be effective sometime in 2014 to increase the special consumption and motorized vehicle taxes based on the vehicle emissions to reduce the climate change and air pollution.
m) Turkey has 88 Btoe potential in solar energy potential and 166 TW technical wind energy potential, which is significantly higher than European renewable energy averages.
n) Some of the major electric vehicle incentives include Finland with €5M, France with €450M and Italy with €1.5M incentive pools. Moreover, tax cuts are being applied to 12% of vehicle cost in Holland, 20% in India, 60,000 RMB in China, €6,000+ in Spain, €4,500 in Sweden and $7,500 in the United States. Furthermore, Japan provides government tax cuts to the half of the cost difference between electric and comparable ICE vehicle and Denmark and Germany provides exemption from road taxes for electric vehicles.
o) Electric vehicles can be charged in an hour to travel on average 3–8 km in Level 1 (120V AC), 15–30 km in Level 2 (240 or 208 V AC). In Level 3 (DC fast charging), the vehicle can be charged in 20 minutes to travel approximately 100–130 km.
p) Electric vehicles can have an all-electric range in between 60 km (Scion iQ EV) and 425 km (Tesla Model S - 85 kWh).
q) In 2014, it is estimated to have between 100–200 charging stations in Turkey
r) Over 70% of Turkey's electricity is produced from fossil fuels.
s) Toyota has stated to have a hydrogen vehicle in 2015 that can travel 480 kms in one tank and can be fueled in under 3 minutes.
t) Important developments have been made in the researched alternative fuels such as are biofuels, propane, compressed and liquefied natural gas (CNG and LNG), ammonia and compressed air (CAV).
u) In June 2, 2011, a Chevrolet Volt test vehicle caught fire in the test parking lot after crash testing. In late 2013, 3 Tesla Model S vehicles caught fire within a 6-week time frame due to battery penetration with metal objects (2) and fast collusion (1). Both incidents largely occupied the headlines in the press.
v) As of September 2012, 2.2 million electric vehicles were sold in the United States, 1.5 million in Japan and 0.45 million in Europe and a total of 4.5 million word wide.
w) $2.5B has been spent on R&D on electric vehicles in 2012, its subcomponents and infrastructure by countries who are leading this technology.

due to the discrepancy between gasoline price, taxes/incentives and the electric vehicle sales in the country, especially when compared to countries in similar conditions. Even though it is a country with one of the highest fossil fuel prices and conventional vehicle taxes in the world, the number of electric vehicles sold is negligible (with a few hundred) in the market, especially when it is compared to similar countries in this regard. In Norway, for example (one of the most similar country in terms of the taxes and incentives), is placed on the other end of the spectrum where electric vehicles play a significant role in the countries market with the largest fleet of plug-in electric vehicles per capita in the world (over 3% of vehicles on the road are plug-in electric vehicles). Thus, the reasons behind the current situation of Turkish market should be analyzed thoroughly in order to understand the conditions that make the H&EV sales the way they are in the country.

1.11.3.6 SWOT Analysis

In order to sum up to issues and provide a better understanding of the current state of electric vehicles, and potential strategies to increase their market penetration, a SWOT analysis, (a strategic planning tool used to evaluate the strengths, weaknesses, opportunities and threats) is performed. Within SWOT analysis, the strengths and weaknesses are seen as internal factors which are controllable, and can be acted upon. The opportunities and threats are external, uncontrollable factors. These form the external environment within which the organization operates and may include various key parameters. Conditions associated with both Turkey and the rest of the world are analyzed since the penetration of the Turkish market is highly correlated to the developments that are both domestic and global. The summarized results of the SWOT analysis are provided in Table 1.9. More information and associated data regarding some of the elements are provided in the footnotes.

1.12 Concluding Remarks

It becomes more obvious each passing day that the concerns over the dependence and ever-increasing prices of limited oil, the associated energy security problems, as well as environmental pollution and global warming with respect to transportation sector are becoming more pressing. Thus, there is a general agreement from the policy makers and the scientific and technological community that electric vehicles are currently one of the best alternatives in this regard due to the certain advantageous characteristics, such as diversification of energy resources, load equalization of power, improved sustainability, as well as lower operating costs and considerably lower emissions during operation, of this technology.

Currently, the transportation sector is undergoing a transformation from conventional internal combustion engine vehicles to electric and (plug-in) hybrid electric vehicles, and even hydrogen fuel cell vehicles to a certain extend. Moreover, electric vehicle technologies are starting to compete with conventional vehicles since they can attain superior efficiency, endurance, durability, acceleration capacity and simplicity and are more environmentally benign. However, they still have low energy storage capability, high price and long charging time which are the main barrier to penetrate into the vehicle market.

In the next decade, it is expected that the specific energies of the batteries will be significantly increased since only a small portion of the theoretical limit is currently being used. It is expected that most of these improvements will be achieved with modifications in the chemistry and reduction in the battery dead weight and volume. These improvements will also have a significant impact on reducing the associated cost of the (hybrid) electric vehicles. In addition, in areas where the electric batteries fail, flywheels (mostly in niche applications) and supercapacitors will be the utilized. Moreover, with the introduction of semi-dynamic inductive charging and V2X/smart grid applications, electric vehicles would be able to better intertwine with the energy structure and improve its utilization. As the oil availability peak across the globe, renewables will play a larger role in electricity generation, which will increase the impact of electric vehicles even further.

Nomenclature

Acronyms

BEV	Battery electric vehicle
DOD	Depth of discharge
EV	Electric vehicle
FC	Fuel cell
FCV	Fuel cell vehicle
GHG	Global greenhouse gas
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IPT	Inductive power transfer
PHEV	Plug-in hybrid electric vehicle
SOC	State of charge
TMS	Thermal management system
UC	Ultracapacitors
V2G	Vehicle-to-grid

Study Questions/Problems

1.1 What would be some tangible strategies to mitigate the chicken-and-egg problem of developing electric vehicles and associated infrastructure?

1.2 What are the benefits and difficulties of integrating EVs and HEVs with renewable energy sources?

1.3 Are EVs and HEVs always better for the environment compared to conventional ICE vehicles? What are the key variables in this consideration?

1.4 Consider your daily driving pattern. Which HEV architecture would be most compatible with it and why?

1.5 How balanced/efficient is the grid power use in your city/country and would it make sense to use (H)EVs in the near future in terms of cost and energy savings there?

1.6 What are the main competitive advantages and barriers for market penetration of EVs and HEVs in your city/country?

1.7 Which vehicle hybridization rates are most commonly available in the industry and what would be the underlying reasons?

1.8 Which energy storage system would be dominating the market in the next decades? Explain your reasons.

References

ABB. (2014). Electric vehicle market share in 19 countries. Available at: http://www.abb-conversations.com/2014/03 [Accessed August 2016].

Andújar JM, Segura F. (2009). Fuel cells: History and updating. *A walk along two centuries, Renewable and Sustainable Energy Reviews* **9**:2309 – 2322.

Asif M, Muneer, T. (2007). Energy supply, its demand and security issues for developed and emerging economies. *Renewable & Sustainable Energy Reviews* **11**:1388 – 1413.

Bradley TH, Frank AA. (2009). Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. *Renewable and Sustainable Energy Reviews* **13**(1):115 – 128.

Chan C C, Bouscayrol A, Chen K. (2010). Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling. *IEEE Transactions on Vehicular Technology* **59**:589 – 598.

Center for Advanced Automotive Technology. (2015). Hybrid and Battery Electric Vehicles, *HEV Levels*. Available at: http://autocaat.org [Accessed August 2016].

de Santiago, J, Bernhoff H, Ekergård B, Eriksson S, Ferhatovic S, Waters R, Leijon M: . (2012). Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Reviev. *Vehicular Technology IEEE Transactions 2012*, **61**(2): 475 – 484.

Dincer I: . (2010). Renewable energy and sustainable development: a crucial review. *Renewable and Sustainable Energy Reviews* **2010**, 4: 157 – 175.

DMAOTO. (2013). Technical Specification Document. *Changes Changing the World*. Available at: http://www.dmaoto.com [Accessed August 2016].

Dijk M, Renato J, Orsato RK. (2013). The emergence of an electric mobility trajectory. *Energy Policy* **52**:135 – 145.

Eberle U, Helmolt R. (2010). Sustainable transportation based on electric vehicle concepts: a brief overview. *Energy & Environmental Science* **3**:689 – 699.

Electrification Roadmap, Revolutionizing Transportation and Achieving Energy Security. (2009). *Electrification Coalition*. Available at http://www.electrificationcoalition.org/ [Accessed June 2015].

Elektriklioto. (2013). Turkey's first national electric car to start its engine soon. Available at: www.elektriklioto.com/2013/01 In Turkish [Accessed August 2016].

GlobalPetrolPrices, Gasoline Prices as of 07 July 2014. (2014). Available at: http://www.globalpetrolprices.com [Accessed July 2015].

Guerrero CPA, Li J, Biller S, Ziao G. (2010). Hybrid/Electric Vehicle Battery Manufacturing: State-of-the-Art. *Proceedings of the 6th annual IEEE Conference on Automation Science and Engineering*. Canada.

Hamut HS, Dincer I, Naterer GF. (2013). Exergy Analysis and Environmental Impact Assessment of Using Various Refrigerants for Hybrid Electric Vehicle Thermal Management Systems, Chapter 46. In: *Causes Impacts and Solutions to Global Warming*, I Dincer, CO Colpan, F Kadioglu (eds.). Springer-Verlag New York.

Hoogma R (2000). *Exploiting Technological Niches*. Twente University, Enschede (PhD Thesis).

IA-HEV Annual Reports. (2013). Hybrid and Electric Vehicle Technologies 2010–2013. Available at: http://www.iahev.org [Accessed August 2016].

Karden E, Ploumen S, Fricke B, Miller T, Snyder K (2007). Energy Storage Devices for Future Hybrid Electric Vehicles. *Journal of Power Sources* **168**:2–11.

Kristoffersen TK, Capion K, Meibom P. (2011). Optimal charging of electric drive vehicles in a market environment. *Applied Energy* **88**:1940–1948.

ODD Annual Reports. (2013). Automotive Distributors' Association Press Summary. Available at: http://www.odd.org.tr/web_2837_1/neuralnetwork.aspx?type=35 [Accessed August 2014].

Offer GJ, Howey D, Contestabile M, Clague R, Brandon NP (2010). Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy* **38**(1):24–29.

Pesaran AA, Kim G, Keyser M (2009). Integration Issues of Cells into Battery Packs for Plug-in and Hybrid Electric Vehicles. *EVS 24 Stavanger*, Norway.

Peterson SB, Michalek JJ. (2013). Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption. *Energy Policy* **52**:429–438.

Renault. (2014). ZOE Price and Specifications. Available at: http://www.renault.co.uk/ [Accessed August 2016].

RenaultRoad Motor Vehicle Statistics Report. (2013). *General Directorate of Public Security*. Turkish Statistical Institute.

Samaras C, Meisterling K. (2008). Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles. *Implications for Policy Environmental Science and Technology* **42**:3170–3176.

Shafiee S, Topal E (2008). An econometrics view of worldwide fossil fuel consumption and the role of US, *Energy Policy* **36**:775–786.

Tie SF, Tan CW (2013). A review of energy sources and energy management system in electric vehicles, *Renewable and Sustainable Energy Reviews* **20**:82–102.

Vazquez S, Lukic SM, Galvan E, Franquelo LG, Carrasco JM (2010). Energy storage systems for transport and grid applications, *IEEE Transactions on Industrial Electronics* **57**(12):3881–3895.

Whittingham MS. (2012). History, Evolution, and Future Status of Energy Storage. *Proceedings of the IEEE Special Centennial Issue* **100**:1518–1534.

WopOnTour. (2009). The Chevrolet Volt Cooling/Heating Systems Explained. Available at: http://gm-volt.com/2010/12/09 [Accessed August 2016].

Yilmaz M, Krein PT. (2013). Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles. *Power Electronics* **28**:2151–2169.

Young K, Caisheng W, Li Y, Strunz K. (2013). Chapter 2: Electric Vehicle Battery Technologies. In: *Electric Vehicle Integration into Modern Power Networks*, R Garcia-Valle, JAP Lopes (eds). Springer, New York.