Plug-in Electric Vehicles – State of Technology and Market Perspectives

Invited Paper

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Abstract **— Transportation sector is contributing in great percentage (23%) to GHG emission in EU countries. In order to reach EU 202020 targets significant efforts to reduce vehicles´ exhausting gases have been made. Plug-in vehicles are foreseen as a part of solution, as it is expected that their share in GHG emission will be decreased below 10% in 2050. In the paper, an overview of plug-in vehicles technologies is presented. All systems are classified and details of electric power processing units are given. Special attention is placed to market perspectives of presented solutions. A review of present state in plug-in passenger cars production and prediction for coming years are given.**

Keywords - Plug-in Vehicles, Power train technologies, Market perspectives

I. INTRODUCTION

Although EU 2020 policy target to decrease GHG emission by 20% in 2020, the transportation sector will actually increase the emission and their share up to 26% in 2020 from 16.5% in 1990 [1]. This alarming trend, which is presented with dotted line in Fig.1, needs swift and effective counter-measures and additional policies applied in a short time. Effects of these measures will hold the GHG emission rise at the level of 22%. Significant reduction is possible if low and zero emission vehicles are implemented. In this case it is expected that by 2050 the transportation sector will reduce GHG emission down to 7% - 9% (Fig.1 [1]).

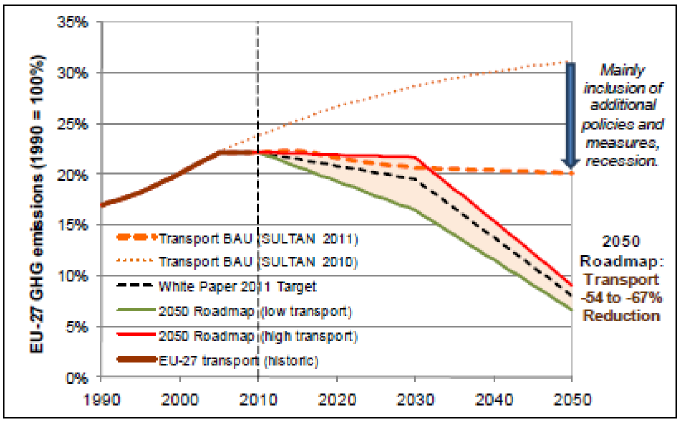


Figure 1. GHG emission of transportation sector [1]

However, there are several options of technological solution, which may ensure such future mobility. This can be achieved with the development of mobility technologies and by focusing on the sustainable business concepts. The solution should include social aspects, environmental issues and economic views, also [2]. Besides electric mobility, management strategies must also consider other alternatives like hydrogen, biogas or fuel cells. These strategies actually are considering different energy sources and engine types, although the vehicle's exhaust gasses depend on applied engine and its efficiency. In that sense (if the propulsion motor is considered) possible vehicles may be classified into three categories:

1. IC engine vehicles - gasoline, diesel, biodiesel, natural gas (CNG, LNG, LPG), hydrogen (H_2)
2. Electric motor vehicles – Battery, Fuel-cells
3. Hybrid ICE/electric motor vehicles – series, parallel, series/parallel

Regarding reduction of GHG emission, future development is oriented toward low emission vehicles (LEV). Above classification indicates that there are several options for such development. Many research studies predict that there will be no single solution, i.e. that different vehicle types will be competing on the market [3, 4, 5].

The study prepared for the European Commission predicts significant improvements in transportation power train efficiency [3]. This will be achieved mainly by fuel substitution; in particular switching from diesel to electricity in areas where electrification is an economically viable option Fig. 2 shows two projections for future development (up to 2050): shares by vehicles´ structure in car stocks (in %, left bars) and by fuel (energy) consumption by cars (in %, right bars). Left bars show significant decrease of classical IC engines (gasoline conversion and diesel conversion) share - from 96% in 2010 down to 55% in 2050. These vehicles will be replaced mainly by electric and hybrid ones and in smaller percentages by LPG and CNG powered cars. Plug-in hybrid vehicles (PHEVs) will hold the largest share among this new group due to their ability to use both power-trains alternatively (ICE or electric motor). However, it will not mean that the oil consumption (gasoline and diesel) will be decreased in the same percentage – from 92% it will drop to 81%, only.

Another study shows that annual sales of passenger light-duty vehicles LDV sales will dramatically change structure in next decades (Fig.3). Conventional gasoline and diesel cars share will drop from 98% in 2010 down to only 8.5% in 2050, while hybrid, plug-in hybrid and electrical vehicles will grow up to their domination in the market (71% in 2050) [4].

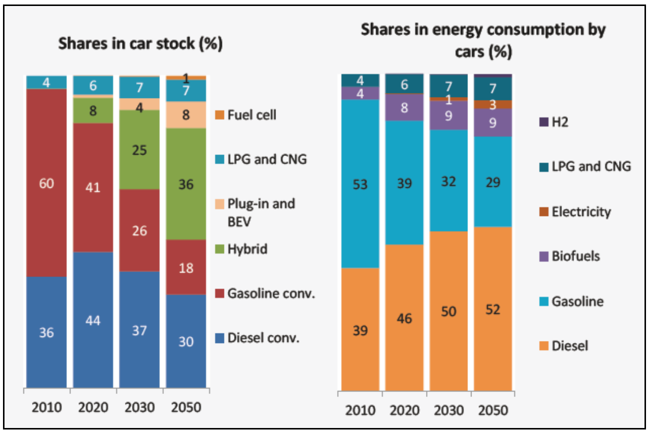


Figure 2. Projections of vehicles´ structures and fuels consumptions [3].

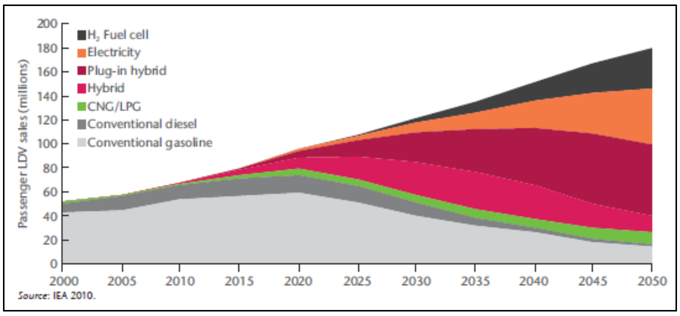
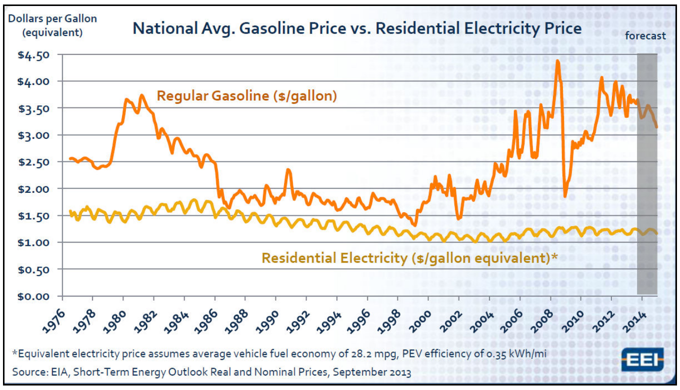


Figure 3. Annual (LDV) sales by technology type (Blue map scenario) [4]

Still, some authors are more conservative and show that different models for analyzing future developments do not give (predict) single vehicle or fuel technology for sustainable mobility to dominate in next decades [5]. They concluded that both regarding the lowest cost solutions and carbon constrains, only a diversity of technology combinations may give acceptable effects, so they highlights the need for research and development of multiple technologies. Still, the main technologies are based on electrical and hybrid sources.

The success of electric mobility products depends on the fulfilment of users' expectations. But in the past, electric vehicles (EV) were not able to meet all the needs of users and to survive on the market. The first ones appeared way back in the past, at the end of 19th century. In early 20th century they were relatively popular (38% of U.S. Market) until the internal combustion engine displaced them, due to better driving range and open-road energy supply infrastructure [6, 7]. They re-appeared in 1970s, when oil prices increased rapidly and fears about possible depletion of fossil fuels started to upset the public. Although environmental awareness contributed also to significant investments to R&D in this field, the resources soon became very limited, as driving range limitation and gasoline prices decrease discourage further investments. Fig. 4 shows U.S. market data – regular gasoline ($/gallon) vs. residential electricity ($/gallon equivalent). It can be seen that in that period these prices were very close, so there is no economic interest for the users to switch from ICE to electric motor vehicles [8].



*Equivalent electricity price assumes average vehicle fuel economy of 28.2 mpg, PEV efficiency of 0.35 kWh/mi
Source: EIA, Short-Term Energy Outlook Real and Nominal Prices, September 2013

Figure 4. US average gasoline prices vs. Residential electricity prices – a long term overview.

In the last decade the EVs are entering the third age as several factors are working in their favour, like enhanced technology, extended range, environmental awareness, very good performances, significantly lower energy prices, much better energy efficiency, etc. Today, all major car manufacturer companies are offering such products in a form of electric or hybrid ICE/electric motor vehicles (dual fuel vehicles). They are known with common name plug-in electric vehicles (PEVs).

The paper gives an overview of present technology of PEVs and some future trends, with special look on market perspectives. The technical aspects are considered regarding driving train, while market trends are stated according to applied technology and present research studies.

II. PLUG-IN ELECTRIC VECHICLES CLASSIFICATION

Usually the PEVs are classified into plug-in hybrid electric vehicles (PHEVs), extended-range hybrid electric vehicles (E-RHEVs), or battery electric vehicles (BEVs) [7, 9]. Such classification is presented in Fig. 5.

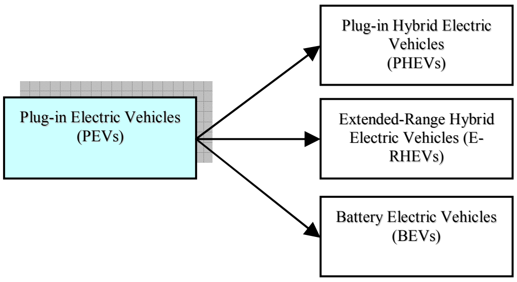


Figure 5. Standard PEVs classification

The PHEV is an evolutionary extension (successor) of the hybrid electric vehicle (HEV), which originated in the nineties in the form of the famous Toyota's Prius model [7]. The HEVs may be classified into serial HEVs, parallel HEVs and serial/parallel HEVs [7, 9, 10, 11]. They have different engines – ICE and electrical ones, so they are often called dual fuel vehicles. In that sense, they represent the first step in ICE vehicles electrification, which is further extended with PHEVs. The main advantage of the PHEVs, beside enlarged capacity of battery is ability to charge the battery from external power supply in contrary to HEVs where the battery is charged only internally (by ICE-Electric generator train or by energy recuperation). The PHEVs may be divided in the same manner into serial PHEVs, parallel PHEVs, and serial/parallel PHEVs [11].

The extended-range hybrid electric vehicles (E-RHEVs) are developed to overcome the main disadvantage of electric vehicles – the limited range. The batteries are enlarged and hybrid structure has been applied. With appearance of PHEVs this feature of E-RHEVs lost its importance. However, additional options to achieve range extensions have been proposed using renewable energy or different fuel-based units [12]. The most feasible solution for renewable energy range extender is application of solar arrays. It could be mounted on the vehicle top (internal source) to supply energy to battery during vehicle operation and parking or used as an external source for battery charging during vehicle parking time. The fuel-based range extenders use fuel-cells and ICE/microturbine generators. The fuel-cells are delivering electrical energy for battery charging, which has been transform from hydrogen (H_2). They could be used as the only source of electricity, but in that case, they are classified as fuel-cells electric vehicle (FCEV) and represent a special type of EVs. The ICE/microturbine generator is not popular solution for passenger cars as it requires additional space and its operation is connected with audio noise.

The battery electric vehicles (BEVs) are also known as full-electric or simply electric vehicles (EVs). Their main source of power is electric battery, which converts chemical energy into electrical one and vice-versa. The energy capacity of lead-acid batteries used to be the main obstacle for wider application of EVs. Today, more advanced battery technologies in a form of NiMH and lithium-ion batteries are giving promising features for further spreading of this type of vehicle [13].

Beside batteries, other electrical storage units may be also implemented - ultra-capacitors, making BEV´s energy storage system a hybrid one. For efficient application of these sources power converters (DC/DC) with specialized control strategies are implemented. Depending on the level of power converters application passive hybrids (parallel connection of battery and ultra-capacitor without power conversion units), semi-active hybrids (power converters are applied for control either battery or ultra-capacitor source) and active hybrids (power converters are applied for control of both battery and ultra-capacitor sources) are distinguished [12].

To enable power transfer, conversion and processing in power flow of electrical energy a complex internal electrical power system is needed [9, 11, 13, 14, 15, 16, 17]. Both DC and AC voltage lines are may be used, so BEVs with single or dual voltage systems can be distinguished. In single voltage systems a low DC voltage level of 12V or 42V are applied. For a wider driving range, such system has limiting transfer capabilities, so dual one is implemented. Dual power system combines DC and AC voltage lines. The DC grid consists of low voltage DC (12V) and high voltage DC (200-400-600V), while AC voltage of 600V is used for AC motor [15]. A schematic of a BEV´s electric power dual voltage system is presented in Fig. 6 [16]. In both single and dual power systems, AC voltage exists at the battery charger inputs (230V/400V), also.

Although different electric motor types may be used for propulsion purposes in PHEVS, E-RHEVs or BEVs, classification regarding this item is not preset in literature or practice. Still, it should be noted that serial DC motor and a number of AC motor types (induction, synchronous, permanent magnet (PM), switched reluctance) are used [9, 13].

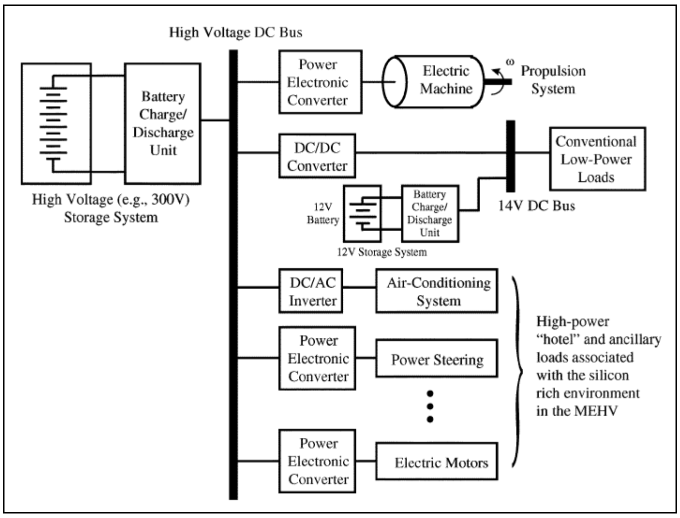


Figure 6. BEV´s electric power system configuration [16].

III. PEV´S POWER FLOW

The conventional ICE vehicle power train consists of energy source (tank), hydraulic link (fuel delivery and preparation), engine (ICE), transmission, a drive shaft and wheels (Fig. 7.a). The plug-in hybrid vehicles bring in power-train the electric system and electric motors/generators units.

In series connection hybrid power train is supplied from an ICE and from batteries (Fig. 7.b). The ICE is driving an electrical generator producing electricity for propulsion done by an electric motor. In excess of electrical energy or in motor recuperating mode the electrical energy is stored in batteries. The batteries are also supplying the electric motor, but their role is restricted, due to limited stored energy. The batteries can be charged from outside, using on-board or off-board level 1 or mode 1 chargers [18, 19].

Parallel plug-in hybrid vehicles have both ICE and electrical motor for propulsion, connected in parallel (Fig. 7.c). To achieve low emission, electric power train is used for start and acceleration, while ICE is used in steady driving conditions and for range extension.

A combination of the series and parallel power-train is called series/parallel plug-in hybrid (Fig. 7.d). Again, the batteries may be charged from outside, using on-board or off-board chargers. In this case ICE may be used directly for propulsion, but also for driving an electricity generator for battery charging.

The BEVs power flow is presented in Fig. 7.e. Huge batteries are now the main (and only) energy source for propulsion. Advanced energy management is applied, so energy is stored in batteries during braking and downhill driving. For start fast acceleration a supercapacitor module may be added. The batteries are charged using on-board or off-board chargers, but the charging time can be shortened down to 20 min. (level 3 or mode 3, 4 chargers) [18, 19].

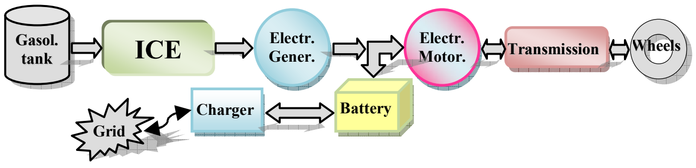
IV. PEV´S TECHNOLOGY

For transferring energy from the battery to the electric motor a complex power system with different power electronics converters is needed. In such a system four main areas can be distinguished:

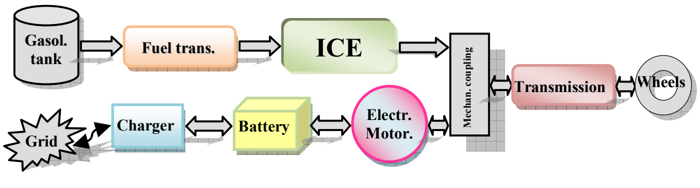
1. High voltage energy source/storage system with charging-discharging unit
2. Electric Propulsion system
3. Low voltage energy source/storage system with conventional low power loads.
4. High power grid with ancillary loads

Many books, papers, expertises, studies and other documents have been devoted to these topics, so in this paper they will be only slightly mentioned [7, 9, 11, 12, 14, 20, 21, 22, 23].

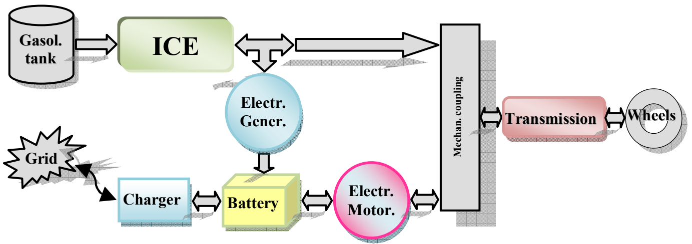
a) Conventional ICE Vehicles Power flow



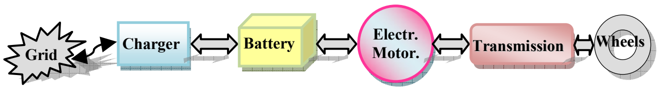
b) Plug-in Series Hybrid Vehicles Power Flow



c) Plug-in Parallel Hybrid Vehicles Power Flow



d) Plug-in Series/Parallel Hybrid Vehicles Power Flow



e) Battery electric vehicle Power Flow

Figure 7. The structure of an ICE, different plug-in hybrid and electric vehicles

A. *HV energy source/storage and charging/discharging systems*

The main sources of electrical energy for propulsion are batteries. They form a high voltage source (200-600V) using stored electrical energy [13]. But, the energy supply is obtained from battery charging stations, where the energy, coming from the public grid is converted into electrical one in a form suitable for transferring it to the batteries. Different types of electric chargers are available [14].

Batteries have dual role in EVs, as electrical energy storage unit in charging mode and energy source in powering mode. The main features are energy density (in Wh/kg), which define the driving range, and power density (in W/kg), which define start and acceleration capabilities. Important characteristics are weight, cycle life, volume and costs. Four types of batteries were considered for the BEVs - Lead Acid, Nickel Cadmium (NI-Cd), Nickel-Metal hydride (NiMH) and Lithium Ion (Li Ion), but nowadays Li Ions are becoming dominant. Comparison of their main characteristics is given in Fig. 8 [24]. In future some improvements in lithium based batteries (Lithium-Metal, Lithium-Polymer, Lithium Phosphate....) are expected, although concerns on available Li reserves are present.

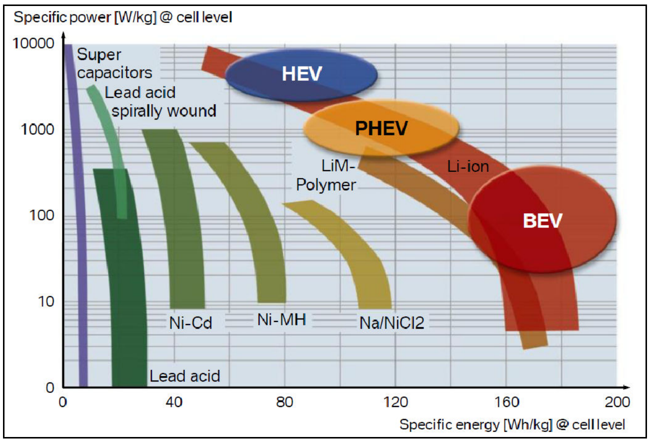


Figure 8. Power and energy densities of selected energy storage technologies [24]

For charging process a special power converter is needed. The charger could be placed off-board or on-board (lower size, long time charging). On-board charging systems can be conductive or inductive. Conductive chargers have wired (direct) contact with the grid using special socket/plug unit, while inductive have wireless (magnetic) transfer of energy [11, 14, 18, 19, 25].

In conductive system a grid-isolated AC/DC converter system is needed. Such a converter in a grid-to-vehicle (G2V) power flow should enable AC voltage rectification (AC/DC), voltage level adaptation (DC/DC) and galvanic isolation of vehicle from the grid (DC/DC). Fig. 9 presents a typical schematic of this charger supplied from a three-phase public grid.

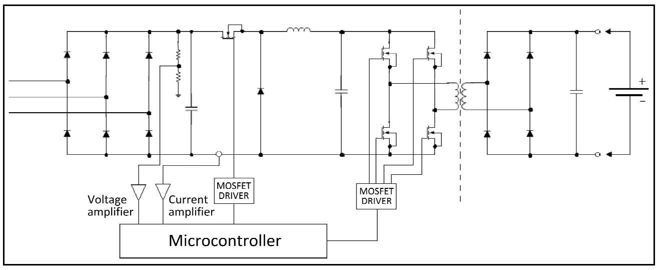
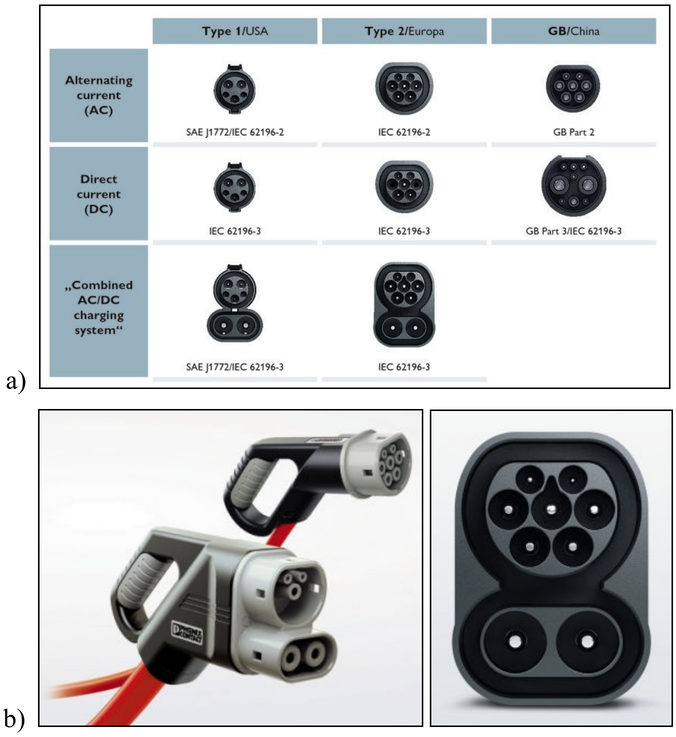


Figure 9. Topology of battery charging station.

Depending on its power size and complexity three levels are distinguished in USA [14, 18], and four charging modes in EU [14, 19, 25]. Usually a charger is on-board (Level 1, Mode 1 or 2), giving EV flexibility and autonomy. Due to weight and size limitation for on-board chargers, recently chargers are placed in public, outside the vehicle, off-board, forming a wide network of battery charging station and completing energy supply infrastructure for EVs. They enable fast charging in 15-20 min or moderate speed charging in 2-3 hours (Level 3, Mode 3 or 4). The main obstacle is different plugs and sockets, which have been developed Worldwide. Three types can be distinguished and they are presented in Fig.10.a. A plug and inlet of the combined AC/DC charging system developed in Europe is presented in Fig. 10.b.



	Type 1/USA	**Type 2**/Europa	**GB**/China
Alternating current (AC)	SAE J1772/IEC 62196-2	IEC 62196-2	GB Part 2
Direct current (DC)	IEC 62196-3	IEC 62196-3	GB Part 3/IEC 62196-3
„Combined AC/DC charging system“	SAE J1772/IEC 62196-3	IEC 62196-3	

Figure 10. a) Charging plug-in systems Worldwide; b) DC and AC Charging plugs Type 2/Europe (left) and inlet of the combined AC/DC plug-in system (right)

Future solutions predict a case of vehicle-to-grid (V2G) operation, so above mentioned power converters should be constructed in a way to provide bilateral power flow [26].

Some of the proposals gives unified role of traction hardware (electric motor and inverter) and charging one making their functions integrated - integrated charger [14, 27]. In that case problems of charger weight, space, and cost are avoided. The integration may also allow galvanic isolation, voltage level adaption, better efficiency, low current harmonic content, and mandatory unity power factor operation. Application of multi-phase electric motor enables easier charger integration and improved reliability of the whole driving train [28].

Inductive chargers are attractive as there is no wired contact (cables and cords are eliminated) [14, 22]. The energy is transferred via electromagnetic coupling, which makes them very convenient for the user. There are several solutions for the coupling itself, but all are based on high-frequency off-board AC source and on-board pickup inductance (charge port) which should be brought together on close distance. Disadvantage includes relatively low efficiency and power density, manufacturing complexity, size, and costs.

B. *Electric propulsion system*

Electric propulsion system consists of high-power DC/AC converter (traction inverter), which is connected to the HV DC grid, and traction motor with mechanical coupling (transmission) to the wheels. In some cases (4 wheel drive) the motors may be built into the wheels, so separate inverter for driving each motor is needed. There is a huge experience and practical solutions from industrial electric drives, including very sophisticated control algorithms [9, 20, 23, 29, 30, 31, 32].

The traction inverter, which function is to provide AC power to the main, traction AC motor, has input voltage range between 190 V and 400 V. The inverter is H bridge topology, composed of IGBT switches with free-wheeling diodes and controlled with space vector modulated PWM or similar advanced control algorithms. Different other solutions, like multi-level inverters, multi-phase configurations and others, have been proposed in order to provide easier and more precise control, increased reliability, higher efficiency and lower costs [13, 29, 33]. Although these converters are operating in switch-mode, with high efficiency and low losses, a sophisticated energy management is needed to coordinate energy flow and provide rational energy usage. Further improvements in these directions are expected in the future.

A number of electric motor types are considered for a role of traction motor. Traditionally the DC motor is used in different electrical vehicles. It offers good driving characteristics and very simple and cost-effective speed control. However, high maintenance costs, due to sparkling and a need for frequent brush replacement, size and weight made DC motor unattractive in comparison to AC ones.

Most of today's solutions are based on different AC motors. Induction or synchronous AC motors are used as traction motors, due to their lower weight and costs, higher reliability and lower maintenance requirements.

In HEVs and EVs interior permanent magnet synchronous machine (IPMSM) is employed in most of current available models because of its high efficiency, high torque, high power density, and relatively ease of field weakening operation. For example Toyota Prius is using 60 kW motor and 42 kW generator, Chevy Volt model has 110 kW motor and 55 kW generator built-in and Nissan Leaf a 80 kW machine. For four wheel drive vehicles, IPMSM are mounted inside the wheel, eliminating mechanical gears and differential. This gives higher efficiency, less weight, and improved reliability, but has usual size and weight restriction. The problem with all PM machines is that their price strongly depends on current market conditions and availability of rare earth-based magnets.

For high power propulsion, induction motor is used. For example, Tesla Roadster is using a 3-phase 4-pole induction motor of 185 kW power and with maximum speed of 6,000 rpm. They have reasonably good performance, simple structure and people have long experience in their industrial drives applications. Still, some improvements in increasing operating voltage, using copper cage rotors and custom design for automotive applications are possible [13, 30].

Significant research work is going on to improve operational characteristics of switched reluctance machine (SRM), which is a type of synchronous machine and has the simplest mechanical design. At the moment they are extremely noisy, have torque pulsation, and larger size and weight in comparison to PM machines. They also have lower efficiency, but the lowest costs and most robust structure [13, 23, 30]. They are seen as possible alternative solution EVs propulsion engine, if costs of rare earth magnets become too high.

C. Low voltage energy source/storage system with conventional low power loads.

This part of the system is dedicated to the conventional low-power loads, which operate on 14V (or 12V) bus and which can be seen at the ICE vehicles, as well. As number of such loads is growing, there were concerns about ability of standard battery to supply them. In the past decade, very strong ideas to introduce 42V bus in traditional ICE vehicles, instead of 14V existed, in order to meet increased electricity demand [16]. However, it was decided not to make such a change, so this part of the system remains in current shape.

D. High power grid with ancillary loads

Other electrical loads, which require higher power is planned to be attached to the HV grid. It will enable installation of more powerful electrical and electronic equipment, and widening the scope of their application. Still, the concerns rise over safety issues, as HV on board may be hazardous for the vehicle and dangerous for passengers. This is especially a problem in case of traffic accidents, when HV wires may be hanging unprotected [34].

V. MARKET PERSPECTIVES

Plug-in electric vehicles are young at the market, coming in a new wave in automotive industry, with a goal to establish electrical transportation in a domain of passenger vehicles. A number of leading car manufacturers is turning their product lines in this direction. They are driven by imposed restrictions to emission levels of exhausting gasses introduced in USA legislation, new market regulation in some states of USA, huge subsidies by European and far-east Asian governments and increased awareness of population for environmental protection and climate change fighting. These products are entering to a huge, lucrative marked, which has been growing for more than hundred years. Therefore, the challenge for companies is to find a sustainable and economically competitive solution. The PEVs offer such a feature. Their high efficiency brings the energy costs to very low level. A comparison on energy costs per mile of two ICE vehicles (gasoline costs), a HEV and two EVs is presented in Fig. 11. It can be seen that ICE gasoline costs are almost five times higher than the EV´s and twice the HEV´s, which is very attractive feature of the PEVs [35].

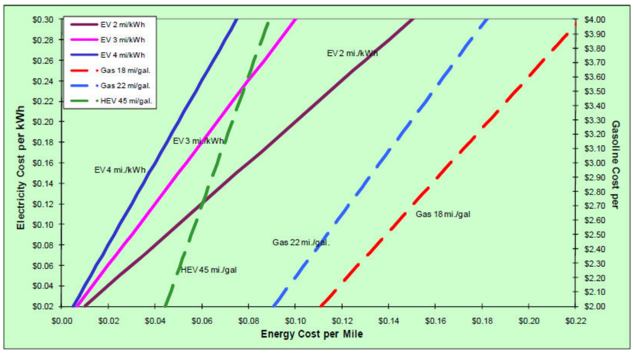


Figure 11. Comparison of energy costs per mile [35]

However, limited range and poor energy supply infrastructure is main obstacle for the EVs. In that sense, for current conditions on the road and for average driving daily schedule the PHEVs are more attractive, although it is not zero emission solution. Figs. 2 and 3 are actually showing these perspectives. Similar conclusion can be obtained from a Deutsche Bank study report, which shows that PEVs´ penetration in 2015 and 2020 will be 11% (2015) and 23% (2020) [36]. These results are presented in Fig. 12. It can be seen that EVs share in 2015 will be only 1% of total sale or 10% of PEVs. In 2020 it is predicted that EVs´ share will be increase to 4% (or 17% of PEVs).

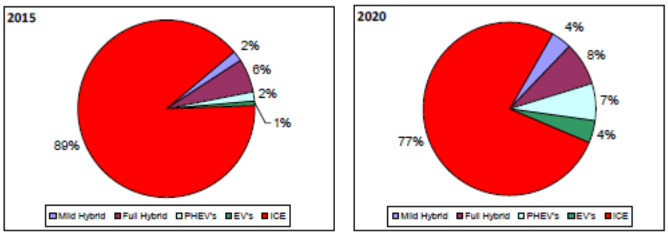


Figure 12. U.S. PEVs penetration by type (2015 and 2020) [36].

Current overview of data for PEVs cumulative sale in the World, given in Fig. 13 shows that the most of PEVs (43%) are sold in U.S. [37]. Next are far-eastern markets of Japan and China (29% in total) and then EU sales with 25% of share.

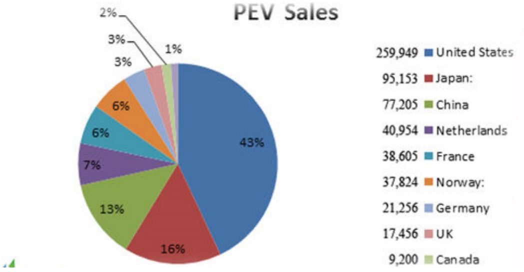


Figure 13. PEVs sales share by countries [37.]

Data for U.S. market are available for each month and by vehicle models. Fig. 14 shows an extract for the period from December 2010 up to August 2014. It can be seen that the sale is constantly increasing and that the most popular models are Chevrolet Volt, Nissan Leaf and Toyota Prius PHEV.

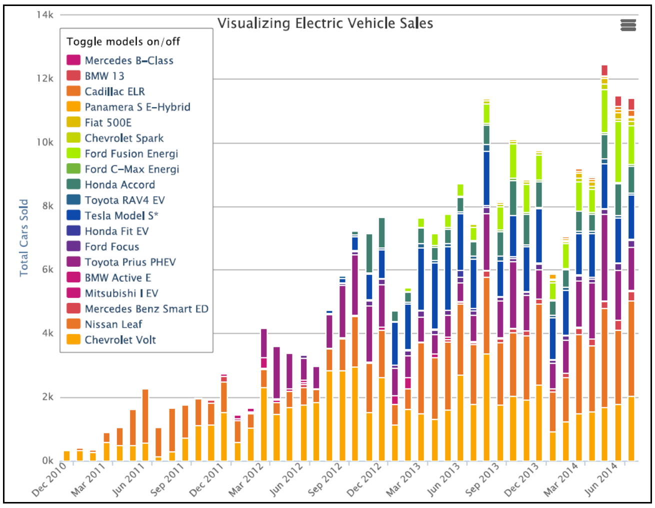


Figure 14. EV sales in US (2010-2014) by models – updated Aug.2014.
(Source: US Dept. of Energy, http://energy.gov/articles/visualizing-electric-vehicle-sales)

VI. CONCLUSIONS

Plug-in vehicles are gaining momentum and more and more models are offered to the market. For the present state of technology, especially battery characteristics, the ICE and Electric motor hybrid solutions are more popular. All forecasts for future market sales predict that PHEVs will be dominant. However, improvement in technology and development of electricity charging infrastructure in cities and on open road ion future may bring full electric vehicles in buyers' attention. The main driving force will be their low energy consumption (high efficiency) and zero emission of gasses.

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