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RECYCLING OF THE HYBRID AND ELECTRIC VEHICLES

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Abstract: Modern research in the field of motor vehicles covered by a cycle of product development and components to production and exploitation of vehicles in traffic, all the way to retirement and recycling. In this way is decreasing negative impact of motor vehicles on the environment. Application of hybrid and electric vehicles to reduce or eliminate emissions of toxic and harmful gases are emitted into the environment during use of vehicles with conventional drive systems on gasoline or diesel fuel. In parallel with the implementation of such vehicles, it is necessary to set up and solve the problems in more detail their exploitation, as well as problems that precede the use of vehicles (quarrying and raw materials, energy production, and everything is built into a vehicle), and partly to problems that come later (after exploitation period). This particularly applies to the treatment of waste batteries and electrical and electronic circuits that are typical for this kind of vehicle. Requirements for zero emission of waste materials at all stages of the service life of hybrid and electric vehicles are a complex task for researchers, especially in the field of development and application of new materials and advanced and secure technologies in the process of production and application. That way, manufacturers are demands for easy dismantling and recycling of vehicles at the end of life service and safety classification of the material, which is accompanied by certain problems. A particular problem is the lack of specific policies and procedures that can be applied in such vehicles. To meet these requirements it is necessary to develop new materials and equipment to be installed in a vehicle, as well as the development of new manufacturing technologies and processes for recycling. This paper describes the procedures for the retirements of such vehicles, as well as the recycling of specific parts of electrical installations and electronic circuits.
Keywords: hybrid and electric vehicles, recycling, ecology, materials, waste

INTRODUCTION

More intensive use of hybrid and electric vehicles inevitably creates the need for recycling these types of vehicles, which requires certain changes in the existing methods of recycling. From the point of recycling are especially important components of electric and hybrid vehicles which do not exist are underrepresented in vehicles with conventional drive exclusively internal combustion engines (IC engines). These components are generally messy traction batteries, electric motors and generators, as well as other types of electrical devices and on-board equipment, as example in modern vehicles with alternative propulsion systems with hydrogen as the fuel cell.

The introduction of hybrid and electric vehicles is due to the specificity of their devices and equipment enormous challenge. Under pressure, not only companies engaged in recycling of vehicles, due to the requirement for more modern facilities, such as recycling plant for batteries, but also manufacturers of vehicles, parts and equipment suppliers, service centers, as well as the state administration and legislature. Challenges originating, inter alia, from insufficiently developed infrastructure for recycling of such vehicles, the complexity of their assemblies, due to the application of new and more modern materials (more composites and some extremely rare and very valuable metals), and the absence of legislation in this area [1].

However, in the case of mass use of hybrid and electric vehicles, sophisticated recycling technology is very important, not only for the environment but also for reasons of securing long-term supply of necessary raw materials. Advanced technologies of recycling are primarily focused on lithium, nickel and cobalt in the lithium-ion batteries, neodymium and rare metals in electric motors, as well as precious metals, and the tantalum and tin in electronics [2].

Therefore, in recent years, a significant number of initiatives, particularly in developed countries, aimed at encouraging private and public sectors of society in the recycling of electric and hybrid vehicles. The aim of this paper is to present current developments and challenges in the field of recycling of components for hybrid and electric vehicles, a primarily electric motors and power electronics elements.

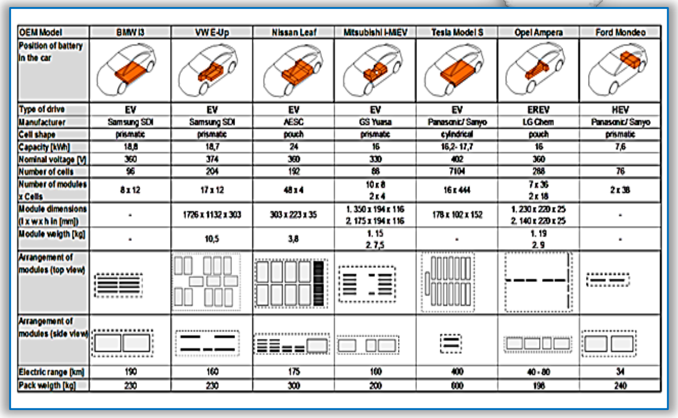
BASIC COMPONENTS OF HYBRID AND ELECTRIC VEHICLES ON ASPECT OF RECYCLING

The basic components, which are the holder of functionality, energy potential and sustainability, which are also the kind of specificity of electric and hybrid vehicles, particularly in terms of recycling are:

- battery as the dominant source of energy;
- electric motors; and
- electrical and electronic equipment.

The batteries to power hybrid and electric vehicles are predominantly used in the form of nickel-metal hydride (Ni-MH) and lithium batteries. Because of the higher-capacity, lithium-ion batteries more suppress the (Ni-MH) batteries that are still in use in power-drive systems of some modern electric and hybrid vehicles [1].

Power batteries, depending on their use in HEV (hybrid electric vehicle), PHEV (hybrid electric vehicles with external charging) or EV (electric vehicles); exist in a wide range of design solutions, size, weight, capacity, power and energy. Traction batteries also differ according to the number of modules, cells, according to the number of charge and discharge cycles, and the autonomy or the radius of movement of vehicles on a single charge with the same battery. The characteristics of the available types of batteries, as well as adequate conception of the vehicle are shown in Figure 1.



OEM Model	BMW I3	VW E-Up	Nissan Leaf	Mitsubishi I-MIEV	Tesla Model S	Opel Ampera	Ford Mondeo
Position of battery in the car							
Type of drive	EV	EV	EV	EV	EV	EREV	HEV
Manufacturer	Samsung SDI	Samsung SDI	AESC	GS Yuasa	Panasonic/ Sanyo	LG Chem	Panasonic/ Sanyo
Cell shape	prismatic	prismatic	pouch	prismatic	cylindrical	pouch	prismatic
Capacity [kWh]	18,8	18,7	24	16	16,2- 17,7	16	7,6
Nominal voltage [V]	360	374	360	330	402	360	
Number of cells	96	204	192	88	7104	288	76
Number of modules x Cells	8 x 12	17 x 12	48 x 4	10 x 8 2 x 4	16 x 444	7 x 36 2 x 18	2 x 38
Module dimensions (l x w x h in [mm])	-	1726 x 1132 x 303	303 x 223 x 35	1. 350 x 194 x 116 2. 175 x 194 x 116	178 x 102 x 152	1. 230 x 220 x 25 2. 140 x 220 x 25	-
Module weigth [kg]	-	10,5	3,8	1. 15 2. 7,5	-	1. 19 2. 9	-
Arrangement of modules (top view)							
Arrangement of modules (side view)							
Electric range [km]	190	160	175	160	400	40 - 80	34
Pack weigth [kg]	230	230	300	200	600	198	240

Figure 1. Contemporary concepts of hybrid and electric vehicles and characteristics of their battery (original equipment manufacturers) [2]

By comparison, hybrid vehicles such as the Toyota Prius and require auxiliary batteries that are necessary for additional power during acceleration of the vehicle and which complement the braking energy recuperation. Therefore, the provision of additional forces for the hybrid vehicle from the auxiliary battery is not required a large amount of energy, and they represent an additional source of power hybrid vehicles. In this way, the hybrid vehicles achieved the ratio of power and energy of about (20:1) or more and are functional at a very low charge level or the capacity of the battery. On average, it is possible to more than 300,000 cycles of charging and discharging the battery during the service of a vehicle.

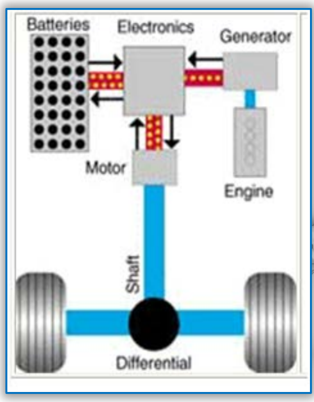
In contrast to hybrid vehicles, electric vehicles require much larger battery power. The relationship between power and energy of an electric vehicle is in average (4:1) or less. Batteries operate at about 90% of the total battery capacity, and it is possible to achieve from 3000 up to 4000 cycle of charging and discharging cycles during battery service period [1, 3, 4].

The electric motors are one of the key elements (aggregates) in all HEV and EV, as the primary purpose of converting electrical energy into mechanical energy. Due to the different design solutions, operating conditions, purposes, and the concept of the drive block and finally making materials, a multitude of different electric motors developed for hybrid and electric vehicles [1, 2].

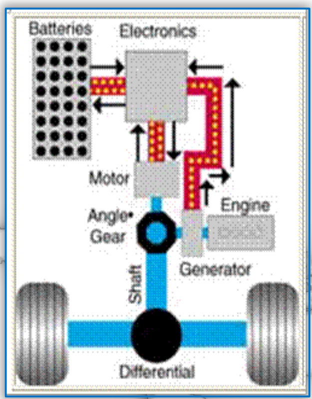
The most common types of electric motors in hybrid and electric vehicles are electric motors, induction motors (also known as asynchronous motors) and synchronous motors, each of these types of electric motor carries a number of advantages and disadvantages [5]. DC electric motors with permanent magnets characterized by high efficiency, good ability to control speed and torque, but on the other hand more complex and expensive to manufacture and maintain. The advantage is that they are cheaper and asynchronous motors do not require the use of expensive elements for making and complex electronic blocks for the management of this kind of electric motors [5, 6]. However, due to limited space in hybrid and electric vehicles, as well as the existence of effective software management mode of operation, in these vehicles is the dominant application of DC electric motors with permanent magnets, which employs the largest number of the world's vehicle manufacturers.

In order to continue the analysis of each component of hybrid and electric vehicles, it is necessary to remind ourselves of their basic concepts. There are two basic configurations of hybrid vehicles: serial and parallel. In addition, there is a combined series-parallel hybrid vehicle concepts, which combines all the advantages of basic concepts of hybrid vehicles. Concepts of hybrid vehicles are shown in the Figure 2.

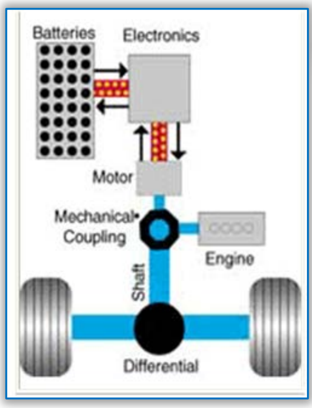
In serial hybrid vehicle IC engine drives a generator that supplies the electric power electricity and supplement batteries. IC engine is used in the optimal mode; a speed control is achieved by electric motor. The existence of the battery and electric motor provides a reversible (engine) braking, thus increasing vehicle efficiency. Parallel hybrid vehicles are designed so that the drive shaft and driven by an electric motor and IC engine-generator. IC engine with this concept vehicle runs in optimal mode, where the electric machine operates as a generator and supplements the battery, when the movement of the lower power output of IC engines, and when you need more power, then electric machine operates as an electric motor using energy from the battery. The point of introducing this concept of hybrid vehicles can be found in the fact that the installed power is less electric machines, which reduced the weight of the vehicle. Instead of separate motors and generators, is used here only one electric machine, whose power is less than the power of the electric motor with the serial hybrid vehicle size. When serial - parallel hybrid vehicle, there are electric motor and generator, or lower power than the pure serial hybrid concept vehicle. According to the needs it is possible to drive IC motor runs only generator or with an electric motor driven drive shaft, and the generator idle [7].



(a)



(b)



(c)

Figure 2. Concepts vehicles with serial (a), parallel (b) and serial - parallel (c) hybrid drive [7]

Fully electric vehicles are vehicles that for their movements using electrical energy stored in batteries or the battery is obtained from a fuel cell. The drive of the vehicle consists of the following subsystems: batteries, inverter power electronics, and electric motor and usually, mechanical force transmission system. The electric motor is the only electric machine installed in the towing vehicle subsystem and its strength is equal to the force required to propel the vehicle. Schematic representation of an electric vehicle with all its subsystems is shown in Figure 3 [7].

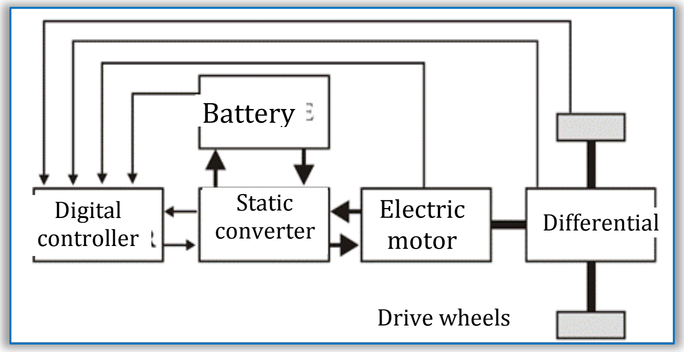


Figure 3. Schematic view of the electric vehicle [7]

Electrical and electronic equipment have the task of electrical energy from the battery to the required values and with the least losses is delivered to the drive electric machines. That equipment is one of the key components of electric and hybrid vehicles and has a high impact on the overall energy efficiency of the powertrain. In order to optimize the flow of energy transformation in these vehicles, electronic blocks for power have several functions performed thanks to its sub-components [8]:

» inverter that converts the direct current from the battery into alternating current for electric machines;
» DC power converter, which provides low-voltage DC power supply for consumers, most of which are located on the dashboard of the vehicle;
» some concept of vehicles provide for an additional inverter that converts the DC current at the output from the battery into electricity higher voltage, before the same is converted into alternating current to power the electric motor. This conversion into electricity higher voltage is performed in order to reduce losses in the transmission of electricity;
» elements of the power electronics, which comprise, inter alia, of the printed circuit board with controllers and other control components; and
» built-in charger and (AC-DC) converter is used in electric and hybrid vehicles as a link between the external electrical network for power supply with battery.

PROCEDURE FOR RECYCLING OF HYBRID AND ELECTRIC VEHICLES

With the introduction of the Directive on recycling vehicles from 2006 in the European Union [9] are intended to wastewater treatment system sales in Europe as much homogenize and standardize. Figure 4 shows a novel method for recycling vehicles, which is expected this Directive by the European Commission, which aims to make this area more standardized, but also to unify the individual elements of the process, to the final end products of this process back into production as many countries across the European Union and beyond.

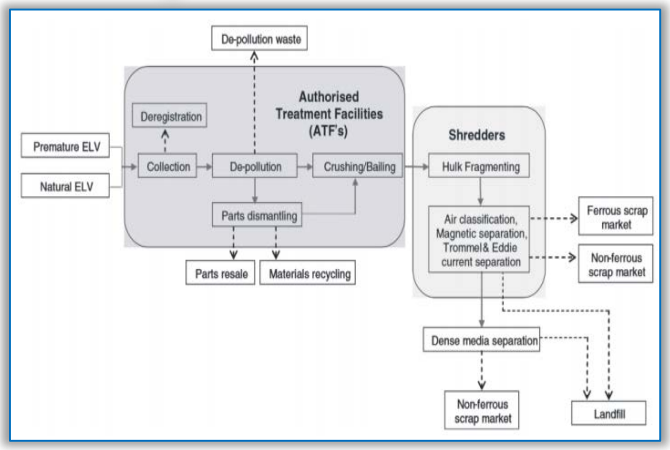


Figure 4. The recycling process of the end of the service of the vehicle [2]

Recycling is mainly composed of purification, dismantling, cutting and grinding, additional grinding and sorting. The first treatment is carried out in dedicated installations, in order to isolate potentially hazardous components and toxic substances such as exploitation of liquid, air bags and batteries. In addition, some parts are dismantled usually for the following reasons: due to the material values of their components (such as catalysts), reuse (engines, tires, electronics) or inefficient recycling process in the following stages of the process [9-12].

After dismantling, usually most of the vehicles crushed by cutting and processing a magnetic separator (iron-based concentrates), current separators (non concentrates) and fluid separators-solutions (for plastics, dust of various materials, light materials). For a long time, the detailed separation allocate parts of the vehicle that cut and grind, given that up to 20% of the total weight of modern vehicles are potentially dangerous waste for the environment [9, 10].

RECYCLING OF ELECTRIC MOTORS OF ELECTRIC AND HYBRID ELECTRIC VEHICLES

Within the recycling of conventional pretreatment vehicle IC engines are usually extracted, separated, and specifically treat their component parts. Separation of IC engine components for their reuse is difficult because in IC engines are represented different kinds of materials, different values in terms of raw material, but also different levels of harm to the environment.

If all these materials are chopped and by crushing, they are diluted, insufficient purity or lost, which leads not only to lower wages in the recycling process, but also to the inability of protection against the harmful effects of hazardous and harmful substances. In principle, the same treatment applies to the electric motors used on hybrid and electric vehicles, although recycling of this type of powertrain is not heavily researched and widespread, and the scarce information on the value of certain parts of electric motors, as well as the justification of allocations and the extent to which the performs disassembly of certain components. However, the integration of the components of electric motors with new design concepts, as well as the tendency towards miniaturization of parts could lead to major difficulties in dismantling assemblies and inevitably increasing costs.

However, because the electric motors and hybrid vehicles contain relatively high concentrations of precious metals (in the form of copper wires and NdFeB-neodymium iron boride magnets) which have low efficiency of recycling during processing, grinding and crushing, dismantling will have a very important role. In fact, very rare and valuable elements in the permanent magnets are lost during processing by cutting and crushing iron to melt fractions and later [13].

Therefore, such a worthy assemblies, primarily the rotors of electric motors must be separated as much as possible on the finer parts during disassembly. For example Research Project: Recycling of Strategic Metals and Components of the Drive Motors [14], process several scenarios for dismantling electric motors with permanent magnets with electric and hybrid vehicles at the end of a century of service, up to the component parts of the rotor and stator. The economic side of the recycling process, dismantling parts of the electric motor is very profitable, mainly because of the content of large amounts of copper, as well as non-ferrous metal prices high, even if very few materials are separated and not recycled in the process.

From the standpoint of obtaining very rare metals from waste electrical circuits, recycling activities are specifically aimed at the recycling of permanent magnets, as an integral part of each electric motor. The problem of recycling of permanent magnets electric motors is particularly studied by the Institute for Factory Automation and Production Systems of the Friedrich Alexander University Erlangen Nuremberg (MORE Project).

Magnets are either embedded on the surface of the rotor (squirrel cage) or grooves close to the surface of the rotor (a rotor with salient poles), and therefore require different techniques of separation. If necessary, the magnets must be removed before the shell of its construction. In Figures 5 and 6 are shown the complete rotor and the rotor segments separated by individual electric motors [15].

Within MORE projects developed different approaches to dismantling. Those are designed, constructed and tested two prototypes of machines for mechanical and electric bed. Wherein the magnetic losses under (1%). Magnets should not be demagnetized before dismantling. In essence, in the cage of the rotor, the thermal treatment may result in damage of the magnet [16-18].

Figure 5. Squirrel-cage rotor and several parts of the rotor motors [15]

Figure 6. Rotor with salient poles and some of its parts [15]

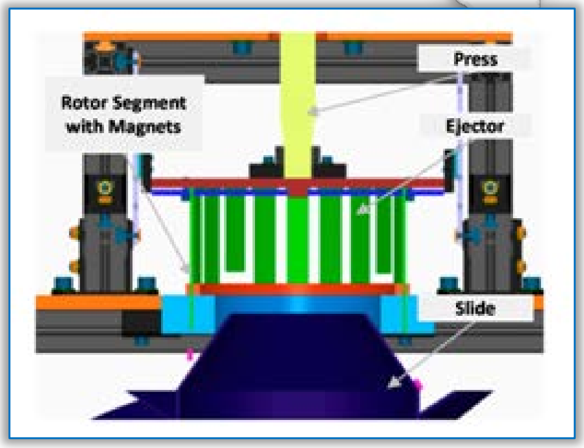


Figure 7. The concept of dismantling the rotor with salient poles [19]

The magnets of the rotor segment of the rotor with salient poles are forced out of a press under the specific ejector (Figure 7). By the non-magnetic stand, the segments of the rotor after dismantling a conveyor belt, which has a built in demagnetization in the form of infrared radiation, are transported into the chamber for storage. In the chamber are sorted according to the polarity of the magnets and along separately with the help of plastic sheet [19].

After dismantling, if necessary, the demagnetization of the magnet can theoretically perform in a plant for recycling. However, the current recycling NdFeB magnet does not exist outside of China where the recycled waste and scrap obtained in various manufacturing processes. How is china's main producer of NdFeB (market share of over 80%), are available in sufficient quantities magnets. The main reasons for the undeveloped procedure of recycling magnets are inefficient collection of worn-out components and machinery, technical difficulty to extract the magnet from the rest of the assemblies, and the lack of economic incentives.

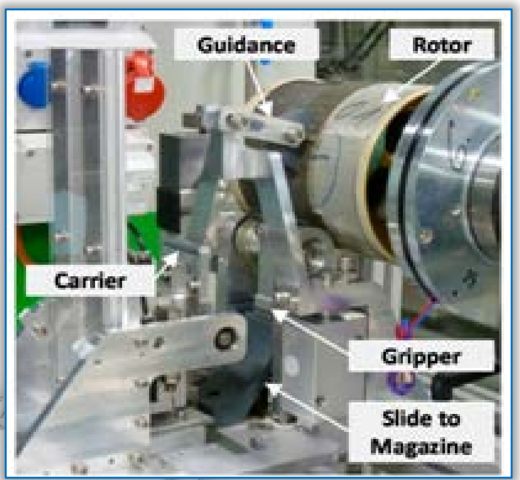


Figure 8. Display devices for dismantling of cage rotors [20]

One of the possible procedures for recycling for re-use magnetic alloy is shown in Figure 9. For the operation of processes, such as remelting, entirely mechanical crushing and baking hydrogen with subsequent fragmentation, of great importance is that better perform the dismantling and cleaning of the magnet [21].

By using any of the recycling process, it is inevitable that a certain amount of impurities (mainly carbon and oxygen), leading to losses caused by the formation of oxides and carbides, in contrast to magnets produced exclusively from pure raw materials, without the participation of recycled materials. The estimated losses would be from 1% to 10% recycled material. Due to the limited space available for installation on vehicles and requirements in terms of less weight, electric motors for hybrid and electric vehicles require magnets with the highest possible purity materials.

The method shown in Figure 9 is currently considered the best option for recycling of NdFeB magnet assembly of electric motors. The main reason for this is that this recycling method allocate metals (very rare metals, cobalt, etc.) having the same characteristics as obtained from the primary metals manufacture and thus do not compromise the properties of the magnetic.

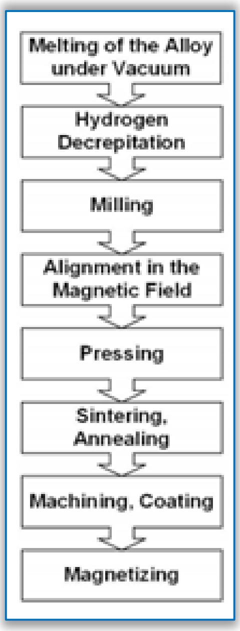


Figure 9. Schematic view of the metallurgical process for obtaining NdFeB magnets from powder [22]

RECYCLING OF ELECTRICAL AND ELECTRONIC EQUIPMENT FOR THE HYBRID AND ELECTRIC VEHICLES

Currently available is very limited information regarding the dismantling of the elements of power electronics for hybrid and electric vehicles. Units of power electronics that are in operation on vehicles are generally compact units of 10 kg or more. They contain expensive materials, so that their removal with appropriate cost-effective technological process and tools for disassembly. In particular, the stator and rotor of electric motors consisting of precious metals and alloys (copper, aluminum, steel), which can be efficiently extracted during the recycling process. Given the trend towards miniaturization and directed towards the decentralization of the electronic blocks, it became even more complex and dismantling procedure inevitably lead to a certain increase in the total cost of dismantling. One of the most representative projects, which handles the recycling of the elements of power electronics for hybrid and electric vehicles under the title: Recycling of electric vehicles 2020; a key component of power electronics, funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, I am ordering the fact that the current elements power electronics are treated as normal electronic waste. This means that after grinding to separate the individual components followed by classification and sorting for the production of metal concentrates which are used in advanced metallurgical treatment processes recyclable materials.

However, this does not mean that there is no need for further investigation, given the significant changes that occur and what can be expected in the coming years. For example, the ability to integrate elements of power electronics in electric motor will require new concepts dismantling of these components within the recycling process. Another challenge could arise from the use of GaN (gallium nitrogen) instead of the SiC as semiconductor or semiconductors based on Si. As the gallium market currently poorly represented, significant effects can be expected in the event of a major breakthrough this element on the market [23]. The first research on the recycling of semiconductor gallium nitride suggest that effective and economically feasible to obtain gallium difficult to achieve due to the small number of gallium in nature, and because of the complexity of the circuits. It should also be noted that today's recycling processes of electronic waste is primarily directed to the recovery of copper and precious metals, and are not sufficiently applicable to extract metals such as antimony and tantalum [24, 25].

CONCLUSIONS

The introduction of hybrid and electric vehicles in the wider application presents great challenges for the recycling industry. Although the amount of recycled material obtained from hybrid and electric vehicles currently small, significant changes can be expected in the coming years. Developments in the field of electric and hybrid vehicles are very dynamic, both for concept development, implementation and use of vehicles, and for their individual components. Therefore, all the forecasts which may possibly anticipate future developments, characterized by a high degree of uncertainty and exploration.

This paper summarizes some of the current developments in the field of recycling of some key components of electric and hybrid vehicles, such as electric motors and power electronics components, and components whose recycling was paid less attention, as opposed to say, from different types of batteries are applying on these types of vehicles. First, it is very important to recognize some of the materials and classify them as critical (cobalt, rare metals, palladium, antimony, gallium, etc.), which irreversibly lose if it approaches the fragmentation of parts, without dismantling parts to the required extent. Other components are produced in a number of variations in non-standard procedures and structure is often not adapted for recycling, particularly in terms of dismantling. This may change over the next decade, but it raises many problems, which primarily necessitate future automation of the process of dismantling assemblies, as well as the automation of other phases of the recycling process. Thirdly, in the considered components can be expected reduction in the concentration of some rare earth metals or a material with a separation from the exhausted assemblies is difficult, for example, a battery with a lower content of cobalt and nickel, NdFeB magnets, the electric motor with the lower representation of very rare-earth metals, as well as a more compact unit of power supply systems. Fourth, now a mass in the recycling process provides the legal and economic, ranging from state institutions, companies, international organizations, and not to the required extent, recognized the need for supporting recycling processes that handle smaller amounts of material, but on the other hand are focused on processing and obtaining extremely rare and valuable materials [25].

Tendencies are that electric motors with permanent magnets continue to be the dominant technology for hybrid and electric vehicles, assuming that there are no extreme increase in prices for neodymium and other rare materials. Recycling electric motor is mainly the efficient production of steel and copper. Therefore, the establishment of recycling very rare materials, and precious metals, the main challenge.

Like electric motors, power electronics elements are recycled according to a similar principle, where the removal of a major challenge in order to efficiently obtain an extremely rare metal, such as tantalum, antimony and gallium.

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