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INFLUENCE OF RECYCLING OF ELECTRIC VEHICLES ON ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS

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Abstract: Electric vehicle, as the most promising clean vehicle technology, has a remarkable significance in the conditions of a huge increase in pollution especially in the regions of the world with a high rate of economic development. The increasing usage of electrical drive systems and stationary energy storage worldwide lead to a high demand of raw materials for the production electric components, electric batteries and components of electronics. To prevent further shortage of these crucial materials and further pollution of the environment especially in urban areas and industrial centers, ecological and efficient recycling processes of electric and electronic component, and specially lithium-ion batteries are needed. Available data are partly taken from US, Chinese and some European development plans in this area by 2025. All available data indicate that the development of new components and hybrid and electric forces in the totality of already used components and materials obtained in recycling processes significantly reduces air, water and soil pollution, reduces production costs and contributes to the improvement of the so-called sustainable development of the community. Specifically, the recycling of steel, aluminum and the cathode material of traction battery, among others, contribute to 20-60% of total reduction, respectively. Although the recycling of conventional vehicle components currently contributes the most to the overall reduction, the recycling of battery has a huge growth potential in the future. As a very efficient instrument in reducing GHG (greenhouse gases) production, efficient and widespread recycling is extremely important in the field of industry and other branches of the economy that are experiencing high growth, such as the increasing production and exploitation of electric and hybrid vehicles.
Keywords: battery, electric vehicle, production, proses, recycles

1. INTRODUCTION

A quickly growing market for electric vehicles (EV) and hybrid vehicles (HEV) will inevitably lead to a high number of EV and HEV batteries, but also other specially electric components, reaching the end-of-life (EOL). Manufacturers have to create processes to ensure a sustainable recycling management system, while still fulfilling government regulations. Recycling used components of EV and HEV presents an economical and ecological challenge, considering the increased volume and diversity of car batteries, electric motors, components of electronics and other specific parts, and the lack of a generalizable disposal process.

The conducted mechanical processes were thoroughly investigated by experiments in a laboratory and within technical scale, describing gas release of aged and non-aged elements of hybrid and electric vehicles during dry crushing, intermediates, and products of the mechanical separation. Conclusively, we found that applying a second crushing step increases the yield of the coating materials, but also enables more selective separation. This leads to millions of tons of waste to be treated, within which huge potential of material recovery exists. In order to obtain the largest environmental benefits from the treatment of ELVs, different strategies have been applied in many countries. The process of increasing the growing amount of waste from electric and hybrid vehicles is inevitable, but at the same time it is a challenge to find the most efficient methods of processing the already used components, separating rare elements, while reducing the harmful emissions of gases during these processes.

Special advantages would be achieved if during the mentioned recycling procedures there would be the possibility of obtaining certain amounts of energy, which would be able to further focus on new production processes.

However, the continued basis for any well-designed and feasible procedure is the need for pre-separation of various components and elements of electric and hybrid vehicles, in order to focus as much of the components as possible in the separation of the section of the recycling plant.

2. RECYCLING TECHNIQUES

In order to describe the standard recycling process of an electric vehicle, the average passenger-car electric car is taken as a model, which is currently in use in high percentage.

Figure 1 illustrates the basic processes that are widely applied in most recycling plants in countries around the world. Clearly conceptually separated processes of cutting involve dismantling, driving the whole, on aggregates, sub-systems and further treatment of the different components of electric vehicles. This is of utmost importance because components of vehicles such as chassis, transmissions, electric batteries, electric drive elements, plastic and rubber elements are further treated with very different recycling methods.

However, a large number of recycling facilities for electric and hybrid vehicles, especially in developing and poorly developed countries, are using the methods used in the recycling of conventional vehicles (with ICE – internal combustion engine), where more attention will be paid to the recycling of steel, aluminum, plastic, rubber and some other metals, which are relatively simple and cheap. Nevertheless, more and more specialized companies in the recycling treatment of electric and hybrid vehicles are receiving dedicated procedures for the treatment of especially those aggregates and components, which do not contain conventional vehicles

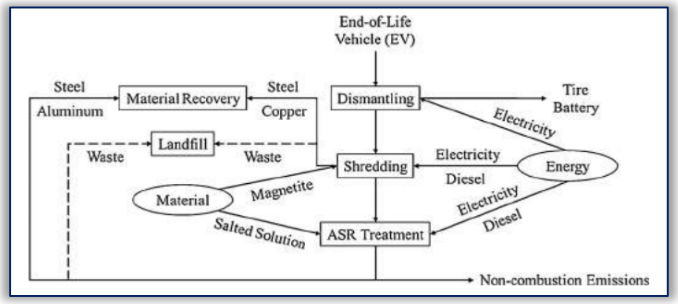

Figure 1. Vehicle recycling process [1]

The scheme shows the entire recycling process, which consists of basic sub-assemblies such as: disassembly, cutting, crushing, treatment after cleaning of metals, further processing of plastic, rubber and glass masses. In the first sub-cycles, metals and metal alloys, steels, alumunium and other metals are separated in a high percentage of purity [1].

There are clearly visible moments when during the process separation of components of vehicles with very different characteristics, for example non-metal metals (rubber and plastics), steel components from electrical components within individual assemblies, as well as special tenological treatments to obtain further purified elements. Especially shown are classic waste, which are a product [1].

Table 1 shows the mass fraction, hardened in tonnes, of certain components of electric vehicles in their total mass. The first column shows the mass fraction of the elements with the largest share, such as steels, aluminum and certain plastics. In the second column, the table shows the mass shares of individual components of electric vehicle batteries, as an essential component of the vehicle, both from the aspect of the energy source, and from the aspect of specific, rare and expensive elements and other materials incorporated in batteries. A particular specificity of looking at the recycling of vehicle batteries is reflected in its ecological aspect, since a certain number of materials in batteries represent toxic elements that are dangerous to the living and working environment. Finally, the third column of the table shows the mass shares of different fluids (exploitation liquids, such as coolants and various oils), as well as the amount of individual parts of the rubber, and in particular the vehicle's tires.

Table 1. Tabular overview of the participation of individual materials and elements in the total mass of a commercial vehicle [1, 2]

EV without batteries, tires and fluids (t)		NMC battery (t)		Others (t)	
Total	**1.70(−)**	**Total**	**0.17(−)**	**Fluids**	0.03
Steel	1.10(−)	Active Material	0.05(−)	Adhesives	0.01
Wrought aluminum	0.02(+)	Graphite/Carbon	0.03(−)	Others	0.02
Cast aluminum	0.09(+)	Copper	0.02(−)	**Tires**	**0.04(3)**
Average plastic	0.20(+)	Wrought Aluminum	0.03(+)	Steel	0.02
Others	0.29	Others	0.04	Rubber	0.02
Total (t)			**1.94**		

Note. "+/–" in the parentheses denotes the upward/downward

It is clear that it recycles vehicles that contain such materials and elements that can be used again in the process of production, as well as the fact that eventual improper rejection or destruction of certain components of hybrid and electric vehicles would inevitably lead to a significant increase in GHG emissions, such as CO_2, CO, SO_2 and other extremely harmful gases and liquids. Batteries and tires of electric and hybrid vehicles are disassembled from the practical engagement of very little energy and time, while for the demon-separation and separation of other components of the vehicle it is necessary to spend significantly more energy and time. Remains are shredded in a specific machine, allowing some steel and copper scraps to be picked straightly. After that, some other steel, copper and aluminum scraps in the residue are picked by magnetic machine and heavy media separation. Other potential outputs such as plastic scraps and recovered energy are sent to the landfill due to the steep technical requirements of recycling [2].

3. BATTERY RECYCLING

One of the tipically battery recycling process of the EV and HEV vehicles is shown in Figure 2. An optimized hydrometallurgical process is expected to be widely employed in few high industrialized countries specially in China until 2025 due to the high yield rate, which has been industrialized by Retriev Technologies, the leading battery recycling company in North America [3].

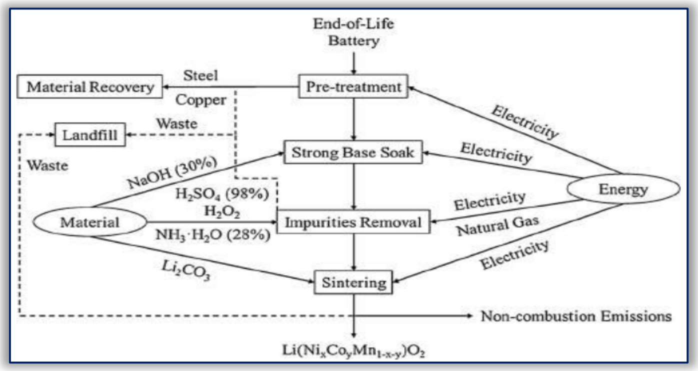

Figure 2. $Li(Ni_xCO_yMn_{1-x-y})O_2$ - NMC battery recycling process [3]

The recycling process for batteries for electric and hybrid vehicles, described on figure 2, includes a total of four phases: pretreatment, strong base soak, impurities removal and sintering. Pretreatment consists of cutting and crushing vehicle assemblies, with the separation of steel and copper particles and sprays, as well as in the collection of powders of said materials. Steel and copper parts and shavings are sent to other plants for further processing, while the powder of said materials is introduced into the next phase of the recycling process. Strong base soak aims to get rid of aluminum in the powder, which demands a huge amount of NaOH (30%) and gives up the opportunity to recycle aluminum scraps. After that, other impurities need to be removed by leaching, extraction and precipitation, with the consumption of much H_2SO_4 (98%), H_2O_2 and $NH_3 \cdot H_2O$ (28%). Sintering is the final phase in the process of recycling batteries, aiming to produce NMC, and some other materials such as Li_2CO3 are consumed [3,4].

Following the dismantling of vehicles, one of the key recycling stages for both electric and hybrid vehicles is the recycling of batteries, as the dominant source of energy for these types of vehicles. Metallic scraps can be subject to different recycling processes, including the mineral processing techniques, pyrometallurgical or hydrometallurgical treatment. The prod-ucts of the recycling process are metallic alloys or compounds, or solutions containing metal ions. Mineral processing techniques intends to separate materials according to different properties like density, conductivity, magnetic behavior, etc.[5]. This treatment is usually applied as a pretreatment to concentrate the metallic fraction, which will be conducted to a hydrometallurgical or a pyrometallurgical recycling process. Pyrometallurgical processes are usually associated with the production of steel, ferromanganese alloys or other metallic alloys.

Figure 3 is a schematic depiction of the Lithium-ion Batteries (LIB) recycling process. This type of battery contains chemically valuable, rare, but also toxic elements and materials, so their efficient, safe and mass recycling is imperative. Different methods of LIB batteries are used, through which various process operations, both mechanical and chemical and electromagnetic, are combined. The aforementioned processes and operations of the battery are initially pyrometallurgical, and then hydrometallurgically processed, so as to ensure gradual separation of rare and toxic elements [6,7]. Such processes are almost 100% closed, that is, they provide a pragmatic lack of GHG gas emissions, while simultaneously using the obtained gases for obtaining certain amounts of energy, that is, different chemicals and various compounds, which, besides that they do not emit into the environment (which would represent pollutants) they are valuable and commercially valuable compounds. By using these processes, nickel and cobalt are extracted and collected in a fairly pure state, while lithium and aluminum remain in the form of a compound in the cluster, so they require additional processing and separation processes.

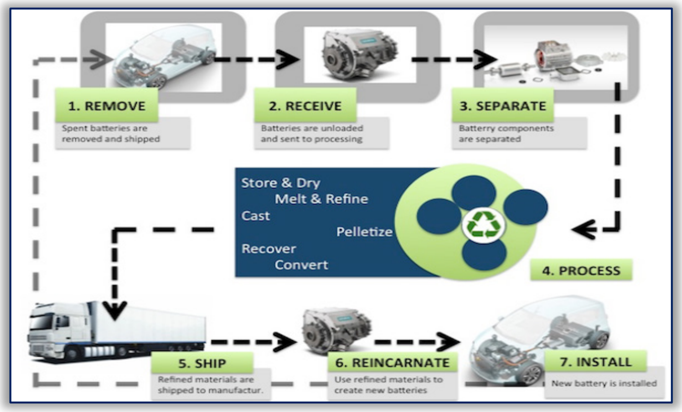

Figure 3. Industrialized Recycling Processes for EV LIBs [1, 6, 7]

Subprocesses 5 to 7 in Figure 3 represent the stages of the recycling process that are finally obtained, through separation and purification, elements and materials are packaged and delivered to the developers of assemblies and aggregates for new electric and hybrid vehicles. These recycled materials are primarily used for the production of the most valuable and most complex aggregates and vehicle assemblies, such as electric motors and generators, electric batteries, power electronics components, electronic components for vehicle control. Finally, the assembled assemblies and aggregates produced in the factories for assembly of ready-made electric vehicles.

Since each recycling process occurs within industry, there is little to no uncertainty in the recycling process and it is not a prediction of future use, capacity, or yield.

4. METODS OF RECYCLING

For the purpose of real and detailed presentation of GHG emissions the optimal model is complete grave-to-gate life cycle model is employed, where the reduction can be estimated based on the amount of recovered materials.

The process that is shown in Figure 4 is divided into three phases:

1) the first phase involves the disassembling of hybrid and electric vehicles, the recycling of vehicle assemblies without batteries and tires, and in particular the recycling of tires and vehicle batteries;
2) separating and purifying compounds and obtaining as pure elements as metal and non-metal;,
3) production of a vehicle, consisting of assembling individual aggregates and assemblies and their installation into a complete vehicle.

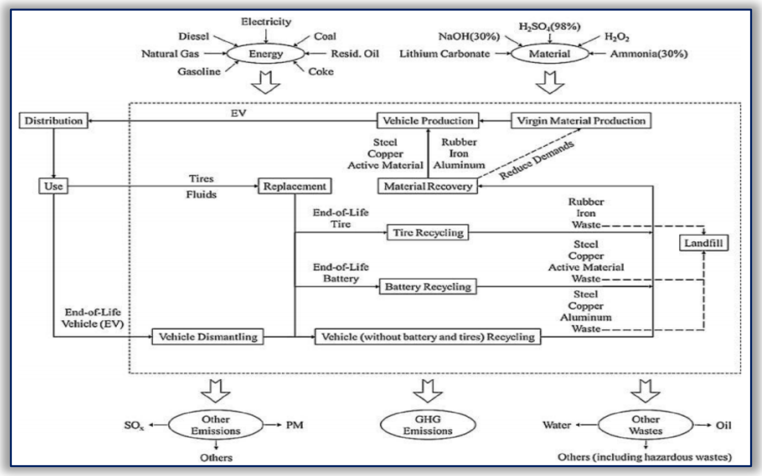

Figure 4. LCA model employed and system boundary [1]

Bearing in mind that the recycling process consumes considerably less energy than that precious elements and compounds are obtained from the ore, or directly from the nature, that is, the GHG emissions are significantly reduced. It should be emphasized that the current understanding of the recycling process implies that the final product will be elements and compounds that would be used as raw materials for further production of new assemblies, while a more modern understanding of recycling involves further use of recycled materials and the production of new assemblies and their installation in hybrid and electric vehicles.

Table 2. Energy/material consumption, non-combustion GHG emissions
and scrap production of different stages [1, 8]

Energy/material consumption, non-combustion GHG emissions and scrap production		Vehicle recycling	Battery recycling	Tire recycling
Energy consumption (MJ/t)	Coal	0.0	0.0	2,143.1
	Electricity	77.6	2,329.3	800.0
	Diesel	790.0	0.0	0.0
	Natural gas	0.0	5,018.8	0.0
Material consumption (kg/t)	Magnetite	6.5	0.0	0.0
	Salted solution	1.6	0.0	0.0
	H_2SO_4 (98%)	0.0	1,100.0	0.0
	NaOH (30%)	0.0	2,180.0	0.0
	$NH_3 \cdot H_2O$ (28%)	0.0	110.0	0.0
	Li_2CO_3	0.0	120.0	0.0
Non-combustion GHG emissions (kg CO_2 eq/t)		0.0	67.3	170.9
Scrap production (kg/t)	Steel	647.7	180.0	0.0
	Iron	0.0	0.0	230.0
	Aluminum	41.3	0.0	0.0
	Rubber	0.0	0.0	670.0
	Copper	31.0	100.0	0.0
	NMC	0.0	250.0	0.0
Sources		Belboom et al. (2016), Li et al. (2016); Enterprise investigation	Georgi-Maschler et al. (2012), Ordoñez et al. (2016), Xie et al. (2015); Enterprise investigation	Li et al. (2010)

In Table 2, based on the LCA model, has been presents the consumption of energy / material, non-combustible GHG gases and products per unit mass [t] is shown at the end of the life of electric vehicles, viewed through different phases of recycling, including disassembling, recycling of assemblies (without tires and batteries) especially recycle batteries and recycle the tire.

Data in this part are normalized based on the industrial data from Comet Traitement SA in Belgium while several post shredding treatments are not carried out due to the expectation for China in 2025 [1]. Figure 5 shows in detail the reduction of energy consumption and reduction of GHG gases at the end of the life of electric and hybrid vehicles.

Taking into account the previous research [8], GHG emissions are with the production of electric vehicles for which no recycled materials of 14.9 t CO_2 have been used, reduced to 9.8 t CO_2, using recycled materials in the production of assemblies, aggregates and complete electric and hybrid vehicles. This resulted in a reduction of 34% of GHG emissions.

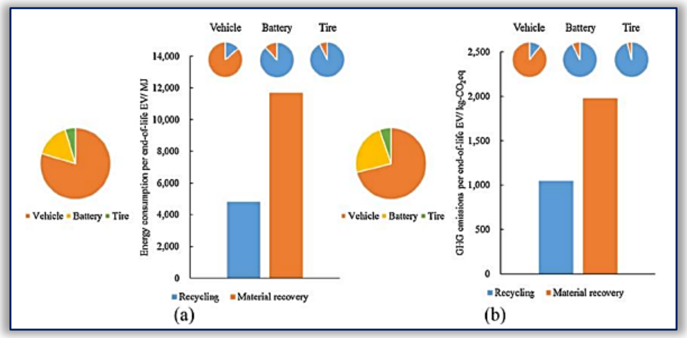

Figure 5. Composition for a) energy consumption and b) GHG emissions per end-of-life EV [8]

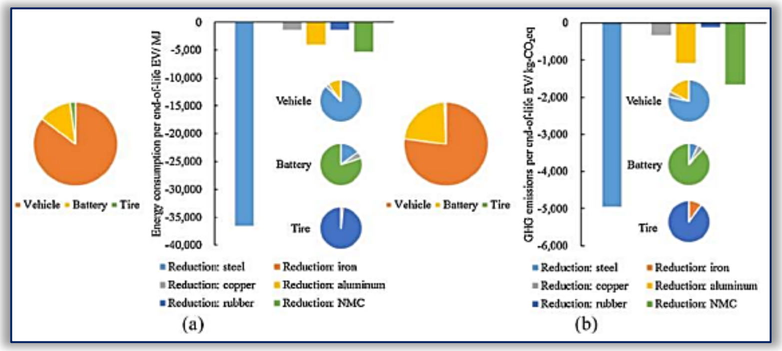

Figure 6. Composition for reduction of a) energy consumption and b) GHG emissions per end-of-life EV [8]

Although the current energy consumption, even GHG emissions, has seen significant growth in the use of recycled materials in the production of electric vehicle components, it is possible to achieve a reduction of 27.4 GJ of energy and 4.0 t CO2 emissions of GHG, as shown in Figure 6, which is a decrease by more than 85% of consumed energy and more than 78% of released GHG.

Looking at the effects of battery recycling, representing only about 9% of the total mass of electric and hybrid vehicles, one can conclude that the results outperform expectations. Specifically, about 4.1 GJ of energy and 1.2 t CO2 emissions are a reduction if recycled materials are used for the production of new NMC batteries, which represents a reduction of about 13% of the energy consumed and about 23% reduction of GHG emissions.

The tire recycling, as indicated in Table 2, is one of the most important segments of the overall recycling of the vehicle, and accordingly, this field is specifically explained in the paper.

Tires, if not properly disposed of, do not recycle and do not ensure their return to the production process, they are a source of very toxic waste. In addition, if the tires do not retract, or do not re-use raw materials from worn tires, this represents an extremely large loss of valuable raw materials.

In 2015 the European Union (Figure 7) has been processed by recycling nearly 5 000 000 tons of passenger and truck tires represents almost one third of annual output in 25 emerging countries [9]. Today, about 12% of the total amount of worn tires is subjected to recycling procedures, starting from their dismantling from the vehicle, through organized collection, pressing, removal of wires and cutting, to prepare for a detailed recycling procedure [10].

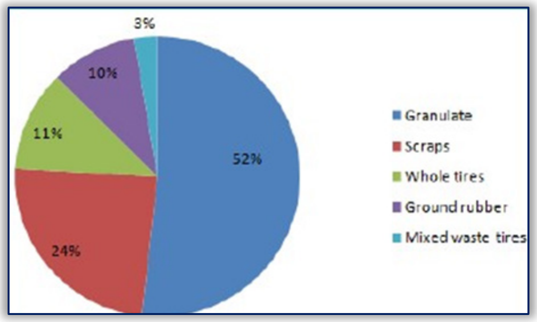

Figure 7. Material production of waste tires in the European Union, year 2015 [9]

Of the total amount of clogged tires, about 76% are recycled into one of three types of materials that can be further used in processed products, such as [11]:

» Scraps,
» Granulate,
» Ground rubber (size of 300 mm and ± 500 microns).

Fabrics from waste tires are material with high sorption capacity, flexibility and elasticity, excellent sound absorption and thermal insulation properties.

Components from waste tires have a different applicability as a new material in the automotive industry in the motor section, in wheel arches – noise control, mud flaps – corrosion property, resistance to water, snow, aggressive (in winter – gritted road), insulation hood – control noise, vibration capacity, fire resistance. In part of the passenger esp. in car interior, rubber car mats – extra edge protection against seepage of water into the base fabric, door panels – side bar (stainless material property) [9].

When considering the optimization of the recycling process in the future, it is necessary to take into account the tendencies of the ray and the application of new and improved materials, innovative technologies and conceptually completely new recycling procedures.

Figure 8 sums up current and future tendencies in the application of new design and conceptual solutions for hybrid and electric vehicles, the use of new technologies and advanced materials, which greatly affect future recycling processes as well as the increase in recycling percentage of total quantities of materials built into vehicles, as well as the degree of separation of clean materials, which can be used without any additional processing in the new production processes of hybrid and electric vehicles [12].

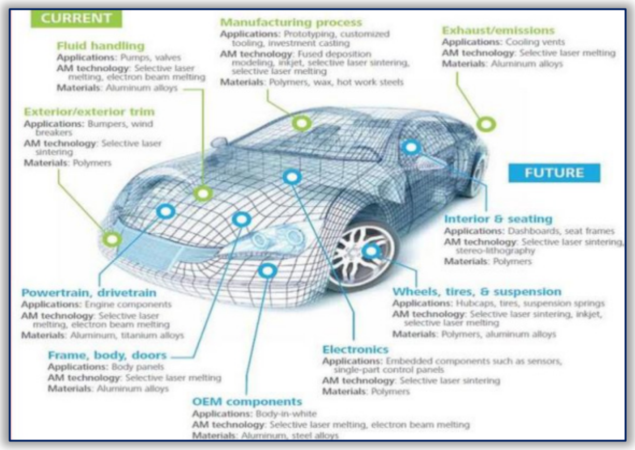

Figure 8. Current and future tendencies in the automotive industry [12]

5. CONCLUSIONS

The research and results presented in this paper clearly point to the fact that the particularly massive use of advertised materials in the production of assemblies, aggregates for electric vehicles, as well as electric and hybrid vehicles in large part contributes significantly to the reduction of GHG emissions, but indirectly also to the reduction of energy consumption in relation to classical production methods, i.e. solely from materials obtained from ores and directly from nature.

However, other ecological benefits are also indirectly achieved through the collection and recycling of nickel, cobalt and other potentially dangerous elements in the environment, which are larger or smaller in components (especially batteries) of hybrid and electric vehicles. Particularly significant savings are obtained by recycling aluminum and lithium, for which the extraction of ore from the natural environment requires a considerable amount of energy, but also the production of enormous amounts of harmful gases, which are not only polluted by air, but also water and soil.

With this approach, a "green" technology itself, ie the production and application of hybrid and electric vehicles, can become "even greener", using even cleaner technologies, which imply even less pollution of the environment, and on the other hand require even less energy shock for getting ready product.

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References

[1] Han H., Qinyu Q., Zongwei L., Fuquan Z., 2017. Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case. State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China.
[2] Li, W., Bai, H., Yin, J., Xu, H., 2016. Life cycle assessment of end-of-life vehicle recycling processes in China - take Corolla taxis for example. J. Clean. Prod. 117, pp 176–187.
[3] Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H., Rutz, M.V., 2012. Development of a recycling process for Li-ion batteries. J. Power Sources 207, pp 173–182.
[4] Xie, Y., Yu, H., Ou, Y., Li, C., 2015. Environmental impact assessment of recycling waste traction battery. Inorg. Chem. Ind. 47 (4), pp 43–46.
[5] J.A.S. Tenório, D.C. Oliveira, A.P. Chaves, Carbon-zinc batteries treatment by ore processing methods, in: Proceedings of the Global Symposium on Recycling Waste Treatment and Clean Technology (REWAS'99), vol. II, TMS, 1999, pp. 1153–1160
[6] Bernardes, A. M., Espinosa, D. C. R., and Tenório, J. S., 2004. Recycling of Batteries: A Review of Current Processes and Technologies, Journal of Power Sources, 130(1), pp 291-298.
[7] Espinosa, D. C. R., Bernardes, A. M., and Tenório, J. A. S., 2004, An Overview on the Current Processes for the Recycling of Batteries, Journal of Power Sources, 135(1), pp 311-319.
[8] Qiao, Q., Zhao, F., Liu, Z., Jiang, S., Hao, H., 2016. Comparative study on life cycle CO_2 emissions from the production of electric and conventional vehicles in China, 8th International Conference on Applied Energy, Beijing, China
[9] Behúnová, A., Knapčíková, L., Behún, M., 2016. Economic and environmental advantages of materials manufactured from waste tires, Tome X, 2017, Acta Technica Corviniensis, University Politehnica Timisoara, Faculty of Engineering Hunedoara, Romania, pp 129–132.
[10] Knapčíková L., Herzog M., Oravec, P.: Material characterization of composite materials from used tires, In: Výrobné inžinierstvo. č. 4 (2010), s. 31–34. – ISSN 1335–7972, www.tuke.sk/fvtpo/casopis.
[11] Knapčíková L, Pešek, L.: Kompozitný materiál z recyklovaných textílií, úžitkový vzor č. 6907: Vestník ÚPV SR č.: 052014 – Banská Bystrica : ÚPV SR – 2014.
[12] Todor M.P., Kiss, I.: Systematic approach on materials selection in the automotive industry for making vehicles lighter, safer and more fuel–efficient: Applied Engineering Letters – Vol. 1, No 4, 91-97, Kragujevac, Serbia, 2016.