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BATTERIES AS A TOOL AGAINST CLIMATE CHANGES

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Abstract: In order to prevent rising danger caused by climate changes, in recent decades an agreement on the level of United Nations was established, to reduce gradually the consumption of fossil fuels until its total termination. This agreement (United Nations Framework Convention on Climate Change (UNFCCC)) until 2018 was signed by a majority of countries in the world. One of the requirements was the transition to electrically powered automobiles, which in developed countries started roughly in 2010. The competition between fuel cells and batteries as driving tools became actual then, but in the key moment batteries mainfested themselves to be technologically superior. Already in 2018 the number of battery driven electric cars produced in leading developed countries was expressed in millions.

Following this new and significant role of batteries, the aim of this contribution is a) a short presentation of the principle of energy conversion in batteries and their energetic characteristics, b) the survey of the requirements to the reactants in chemical reaction of a battery, from which the troubles in their development may be derived, depending on the materials technology, c) the competitiveness of batteries to the fossil fuels in an energetic sense, and, d) the forecast what one may expect in near future from the competitive power of batteries within the scope of development of new materials.

Keywords: Advanced batteries, climate changes, competitiveness of batteries, electric cars, how a battery works.

1. PREFACE

The characteristic of the 20th century is the industrialization based on consumption of fossil fuels. In recent decades, scientists involved in climate research alerted on the global warming caused by rising concentration of greenhouse gases, primarily CO_2 in atmosphere. This problem is serious to such an extent that particular United Nations bodies were established to prevent climate changes. The UN advisory body called Intergovernmental Panel on Climate Change (IPCC) provides the reports on the scientific view about climate changes and their political and economic impacts, and suggests feasible responses. This body was established in 1988. by the World Meteorological Organisation (WMO) and endorsed by UN General Assembly. All members of the WMO and UN are eligible to participate in it. IPCC reports gather reliable scientific information from scientific journals and stimulate research in climate sciences. The diagram in Figure 1, originating from NASA measurements [1] is a part of one of reports, which indicate an exponential rise of global temperature after 1980-ies. To prevent the temperature changes of becoming irreversible, international treaty under the title The United Nations Framework Convention on Climate Change (UNFCCC) is opened for signature at the Earth Summit in Rio de Janeiro 1992. In 1994, the treaty was ratified by a significant number of countries, and from 1995 the convention parties organize annual meetings. In 1997, by the Kyoto Protocol, the developed countries accepted the obligations for the period 2008–2012 to reduce CO_2 emissions within accepted quotas. In 2010., in Cancun, the UN Climate Change Conference accepted an agreement to limit global warming to below 2.0 °C relative to the pre-industrial mean tempertaure, as well as to support all innovations leading to the reduction of greenhouse gases emmision [2]. In 2015., the Paris Agreement was adopted, which entered into force in November 2016., relating to the emission limits beyond 2020. It lowered the allowed global temperature increase up to 1.5 °C in relation to pre-industrial mean temperature.

The IPCC reports have crucial impact on the decisions within the UNFCCC. For example, the fifth IPCC's report was a scientific base of the UNFCCC's Paris agreement in 2015.

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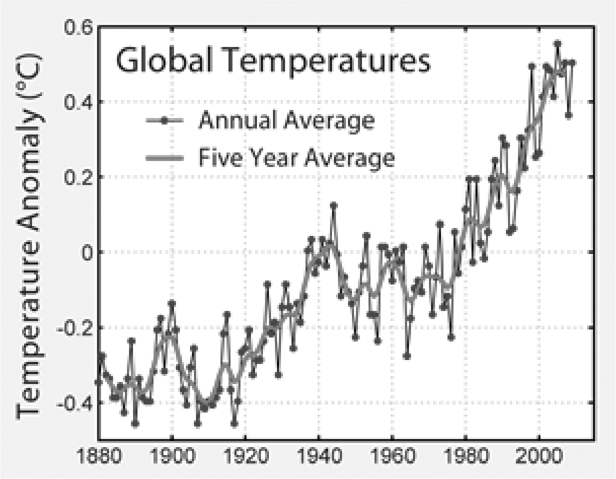

Figure 1. The increase of average (land and sea surface) global temperature during decades [1]

A part of the battle against climate changes is a political decision of developed countries, actualized particularly in 2010 in connection with the Cancun conference, to gradually replace oil powered cars by electric cars. In that time dilemma existed what of possible power sources to use to drive cars. Namely, since 1980, hydrogen/air fuel cells were intensively developed in hope to become a power source for electric cars. However, thanks to the discovery of Li-ion batteries, what happened in 1990, and their further development, in the key moment, the batteries displayed more advantages as power sources. Thus, already in 2010, electric cars powered by batteries appeared in ordinary traffic, and since then their number rose exponentially throughout the world.

Regarding this new and significant role of batteries, in the further text, the principle on which battery works, the problems in battery development, the competitiveness of batteries against liquid fossil fuels as power sources in automobiles, and a forecast of advances in battery development in near future, are considered.

2. HOW A BATTERY WORKS? BATTERY CHARACTERISTICS: CAPACITY AND ENERGY

Definition

Batteries are compact, portable chemical reactors able to transform the heat of a redox chemical reaction into electrical energy. The primary batteries is the name for battery types which can not be used after discharging. The secondary batteries are rechargeable and may be used for a long time. Their rechargeability is thanks to the reversiblility of underlying chemical reaction. They are advantageous from the scope of both economy and environmental protection, thus they are exclusively the subject of consideration in this article.

The general advantage of heat-to-electric energy conversion in batteries is a high conversion degree, close to 100%. Also, they do not polute the atmosphere during the use.

The dimensions of batteries are adapted to the consumer needs. Several grams to several decagrams weigh the bateries for portable electronic devices – mobile phones, cameras, tablets and lap-top computers (Figure 2). Several to tens kilograms weigh the batteries, usualy of prismatic form, aimed to start engines with internal combustion.

Figure 2. Batteries for small consumers: mobile and wireless phones, cameras, etc.

About the redox reactions

The redox reaction is a chemical reaction between reactants having reduction and oxidation abilities, which occurs by the tranport of electricity between them. The electricity transport is the main behavior that enables the heat-to-electric energy conversion, thus, this type of reaction is exclusively applied in batteries.

Figure 3. shows the scheme of electricity movement during an oxidoreduction reaction.

First step of redox reaction is the jump of electrons from reduction to oxidation reactant. From the stoichiometric laws it follows that, per one mole of reactants suffering the oxidation number change z, an amount of electricity equal to zF gets transferred by electrons. Here F is the Faraday constant, or a symbol for the amount of electricity carried by one mole of electrons, equal to 96500 coulombs (C), or 26,8 amper-hours (Ah). In this step, the electrified reaction products (ions) arise. The secondary step, taking place simultaneously, is the neutralization of electrified products, to maintain neutral state of matter. This step occurs by atraction of opositely electrified ambiental mobile ions. Thus it is mandatory to proceed the reaction in an electrolytically conducting medium. Final reaction products are obtained by completion of both reaction steps.

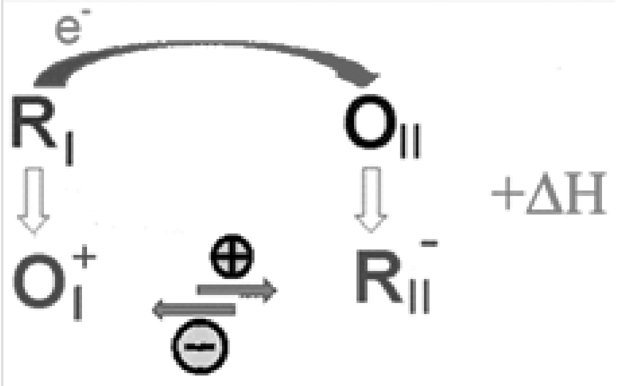

Figure 3. Scheme of the electricity movement in a redox reaction, for z = 1: R_I –reduction reactant, O_I^+ its reaction product, O_{II} is oxidation reactant, R_{II}^- its product. Ions move to opositely electrified products to neutralize them

A spontaneous flow of reaction assumes that the reactants transform themselves into more stable products, i.e., poorer in energy. Thus the reaction is accompanied by release of heat, ΔH joules per mole of the reactant. To determine it, it is practical to calculate with the reactant which participates in the reaction with the stoichiometric number equal to one.

To convert reaction heat into electric work, the flow of electricity (zx26,8 Ah per mole) should be arranged in a way to surmount any potential difference, said to be Є volts. Potential difference is zero if the reactants are mixed, since it may not appear within a unique body containing mobile charges, but it may be realised as a non-zero value if the reactants are separated, as arranged in a battery.

Construction of a battery

In a battery, reduction and oxidation reactants (called anode and cathode materials) are fixed on opposite sides of a metallic conductor, which are dipped into electrolyte solution. A resistor separates anode and cathode compartments. Resistor has the role of energy consumer. Simple ohmic resistor transfers the obtained electric energy back into heat, hovewer, if it is an electromotor, it converts electric energy into mechanical work. Ampermeter and voltmeter may, optionally, be connected into metallic part of battery, in order to control both the rate and the conversion degree.

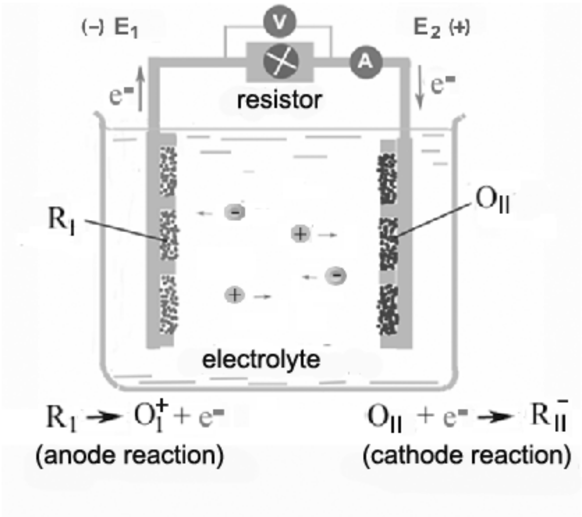

Figure 4. Scheme of battery construction [3]

If the electric circuit of the battery is closed, the tendency of redox reaction to occur spontaneously forces electrons to move from the reduction to the oxidation reactant through the metal conductor. Simultaneously, the ions in electrolyte by a two-way movement, neutralize reaction products of primary step, and enable a circular flow of direct current through the battery.

The tendency of reaction to occur keeps also permamently a higher concentration of electrons on the anode side, manifesting itself as a potential difference across the resistor. Potential difference (batttery voltage) has its maximum at infinite resistor resistance, which means also the highest conversion degree.

The part of heat converted to electric energy (w per mole of any of reactants), according to the physical laws of direct current, is equal to the product of transferred charge (z x 26.8 Ah/mol, called molar capacity) and voltage Є:

w = (z x 26.8) x Є Wh/mol [1]

At high resistor resistance, w ~ ΔH, i. e., conversion degree w/ ΔH ~ 1

If, oppositely, consumer resistance is zero, potential difference is zero and conversion degree is also zero, and during the battery work, the released reaction heat warms the battery body to the same level as if the reactants are mixed mutually.

Battery characteristics: capacity and energy

The battery capacity presents the amount of electricity which delivers a fully charged battery. This is the way to calculate it:

Battery capacity = number of moles of any reactant x molar capacity = $n_{a(c)}$ x (z x 26,8) Ah [2]

For its calculation, either oxidation or reduction reactant may be used, since they participate in the reaction in stoichiometric ratios, and thus must have the same molar capacities.

Since z is ordinarily 1 or 2, and only rarely 3, molar capacity depends slightly on reactant nature (i.e. on the position in Periodic system of elements). Thus, the battery capacity is mainly detemined by the number of moles of reactants, and consequently the dimensions of battery is proportional to the battery capacity. Capacity is the characteristic which is ordinarily anotated on the battery label (Figure 5).

The energy of a battery is the amount of electric energy which may be obtained from a fully charged battery. The way to calculate it is:

$$\text{Energy} = \text{battery capacity} \times \text{voltage} = \left(n_{a(c)} \times z \times 26{,}8\right) \times \varepsilon, \quad Wh \qquad [3]$$

Since, apart from capacity, voltage is the other characteristic usually annotated on the battery label, energy of battery may be calculated from the data read from the battery labels.

The theoretical energy density, which is important for comparison of usability of different batteries, may be calculated in the following way:

Figure 5. Sample of a battery label

$$\text{Theoretical energy density} = \frac{\text{energy of battery}}{\text{sum of reactant masses}} = \frac{n_{a(c)} \times Z \times 26{,}8 \times \varepsilon}{n_a M_a + n_c M_c} Wh/kg \qquad [4]$$

In the sum of reactant masses in denominator, the anodic and cathodic reactant participate with their stoichiometric amounts. This sum may contain also electrolyte molar mass as a third addend if it participates in the redox reaction (as is, for example, sulfuric acid in Pb-acid battery)

For practical use, much more significant is practical energy density, which may be calculated by the expression:

$$\text{Practical energy density} = \frac{\text{energy of battery}}{\text{total mass of battery}} = \frac{n_{a(c)} \times z \times 26{,}8 \times \varepsilon}{n_a M_a + n_c M_c + \Sigma M_{constr}} Wh/kg \qquad [5]$$

In the denominator, apart from sum of reactant masses, participates also the sum of masses of all construction parts. The sum of masses of construction parts may overrate several times the masses of reactants, which causes that practical energy density is up to several times lower than the theoretical value.

3. REASONS OF SLOW DEVELOPMENT OF NEW BATTERY TYPES, AND THE CONNECTION WITH THE HISTORY OF ELECTRIC CARS

An inspection into battery construction and in its working procedure allows to perceive the following mandatory requirements for the reactants of battery chemical reaction:

1. Reactants are oxidoreduction agents. Only redox reactions enable electricity movement which may be utilized to convert the heat of reaction into electric energy.
2. For a battery to be rechargeable, the reactions of reactants should be completely reversible,
3. The reactants and their products are solid materials of similar specific volume. This condition enables to reactant to keep fixed to metal support throughout any multiple charging/discharging procedure,
4. Reactants, products and construction materials are inert toward electrolyte. Namely, any chemical reaction between the reactants and electrolyte reduces the amount of reactants available to energy conversion, while reaction of construction materials with electrolyte may cause battery mechanical damage.

5. The reactants, electrolyte and construction materials are abundant and cheap. This is an important condition for a battery to be economic for production and adoptable to market.

Numerous requirements for the reactants of rechargeable batteries is the reason why each discovery of new battery types is rare and significant event in electrochemistry. This may be illustrated by few battery types widely adopted in practice:

1. Lead acid battery (Pb-PbO_2) is discovered in 1859. Its redox reaction is:

$$Pb + PbO_2 + 2\ H_2SO_4 = 2\ PbSO_4 + 2\ H_2O$$

Theoretical energy density is 169 Wh/kg, and after more than one century of advancement of construction materials, its practical energy density did not exceed ~35 Wh/kg,

2. Alkaline, nickel-cadmium (Ni-Cd) battery is discovered in 1900. Its redox reaction is:

$$Cd + 2Ni(OH)_3 = Cd(OH)_2 + 2Ni(OH)_2$$

Its theoretical energy density is 209 Wh/kg, while contemporary value of its practical energy density is ~40 Wh/kg

3. Most recently, Li-ion battery was discovered in 1990. Its redox reaction is:

$$LiC_6 + MeO_2 = 6\ C + LiMeO_2\ (Me = Co,Ni,Mn)$$

Theoretical energy density is 628 Wh/kg and practical energy density is >120 Wh/kg.

The jump in energy density of Li-ion battery is thanks to a smaller molar masses of reactants (M(**LiC_6) =** 79 g/mole) compared to lead acid battery (M(Pb) = 207 g/mole), as well as due to a larger voltage (3,7-4 V, against ~2 V for lead-acid battery). The reactants are the so called intercalation compounds of lithium, solid materials which have been intensively investigated since 1980, suffering negligible volume change on charging and discharging [4,5].

First commercial Li-ion battery was released on market by Sony Energytec Inc., in 1990. [6]. Its anode was graphite, which on charging transforms into layered intercalation compound LiC_6, and cathode was layered intercalate compound $LiCoO_2$ which on charging releases Li ions. The voltage of charged battery was close to 4 V. For this voltage, only organic electrolytes, resistant to electrolytic decomposition, may be used, and in this case it was a mixture of ethylene carbonate and propylene carbonate. Today, cathode is usually a layered compound of mixed oxides, CoO, NiO and MnO_2 in various molar ratios, assigned usually as CNM cathode [7,8].

First Li-ion batteries were very expensive, thus being suitable only for small and expensive consumers, however through decades, the price droped, and until 2010, they became suitable for massive use even in electric cars.

The history of electric cars

The idea of a battery powered (electric) car is more than one century old. Figure 6 shows a model of electric car designed by Porsche, exposed on the World exhibition of innovations in Paris in 1900. It was powered by Lead-acid batteries, then only available on the market. Although it was more comfortable for use from noisy oil powered engines, its disadvantage was short mobility range, caused by small energy density of batteries, thus it became uncompetitive against rapidly developed engines with internal combustion, particularly due to more and more abundant and cheap oil.

Figure 6. Model of electric car designed by Porsche, exposed on the World exhibition of innovations in Paris in 1900

The circumstances changed drastically at the beginning of the 21st century. The danger of climate changes required ultimately the reduction of fossil fuel consumption. Inside of this requirement is the transition to electric automobiles. Helpful event in that sense was the discovery of energetically rich Li-ion batteries. Thanks to its high energy density, the mass of batteries needed for an acceptable radius of movement became fairly lower than the automobile own mass. Since 2010, the number of electrical cars produced over the world increased exponentially, as the Figure 7 shows.

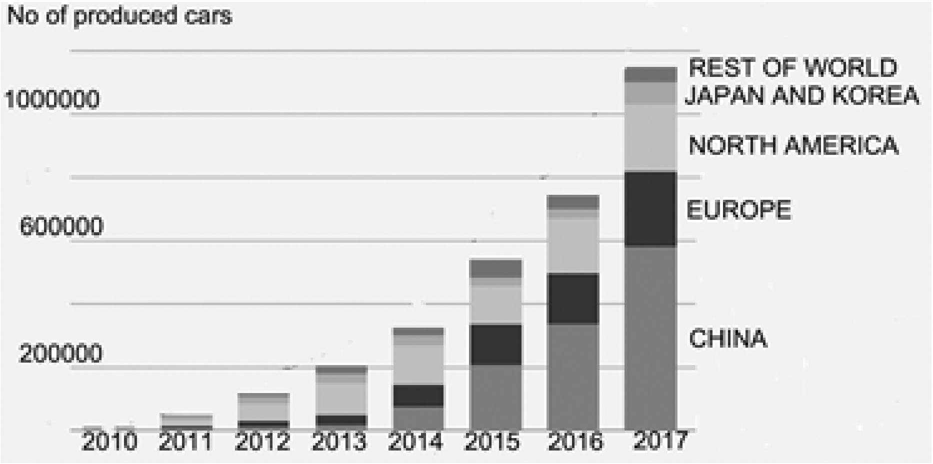

Figure 7. The number of electric cars produced in leading countries or regions worldwide, in the period 2011-2017 (Adapted from CarbonBrief [9])

The leading company for production of electric cars Tesla, uses the battery pack, consisting from more than 7000 Li-cell units, with the mass of 540 kg and a total energy content of 85 kw. These data allow to calculate that energy density of Li-ion battery used is 157 Wh/kg, which is higher than usually annotated for these batteries (~ 120 Wh/kg), and witnesses on the internal development of batteries. Figure 8. presents a corresponding model of electric car and its battery pack, adapted to be placed on the bottom of the car.

Figure 8. Tesla electric car and its battery pack (energy 85 kWh, мass 540 kg, practical energy density 157 Wh/kg) (Advertisement matter)

4. THE COMPETITIVENESS OF THE BATERIES TO THE LIQUID FOSSIL FUELS

In order to estimate the comptitivenes of the contemporary batteries to the liquid fossil fules in energetic sense, we may start with the energetic characteristic of liquid fossil fuel.

The heat of combustion of gasoline and diesel fuels, in average, amounts to 48000 kJ/kg. By multiplying with the coefficient for transformation to Wh/kg units one obtains:

48000 kJ/kg x (0.28 Wh/kJ) ~ 13400 Wh/kg

Note that this value is much higher than the analogue values for batteries, thanks to light elements: carbon and hydrogen, participating in these compounds.

Due to the limitations originating from the Second law of thermodinamics and due to the many movable parts suffering the friction (Figure 9), the conversion degree of heat into kinetic energy in internal combustion engine is relatively low, said ~ 25%.

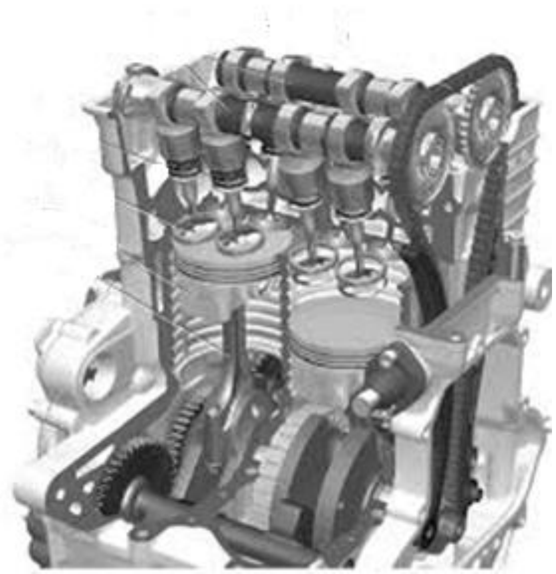

Figure 9. Cross section through a contemporary engine with internal combustion

Thus, 13400 x 0.25 ~ 3300 Wh/kg is energy density of fossil fuel actually utilized as the kinetic energy of a moving automobile.

We may note that with 35 kg of liquid fuel (i.e., equivalent to 50 liters) a contemporary car with its average mass of ~ 1500 kg, has an authonomy radius range of 500 km.

It is important to note that any mass of liquid fossil fuel develops nearly threefold mass of carbon dioxide. More precisely one reservoir of fuel of an average automobile, upon combustion, develops 35x3.09 ~108 kg of CO_2. One should note that due to a low conversion degree, only 25 % or ~ 27 kg of this emission is connected to actually utilized energy of fossil fuel, while 75% is connected to waste heat liberation.

A hypotetical ideally competitive battery, assuming 100 % conversion degree of heat to electric energy, should have energy density of ~3300 Wh/kg. Namely, 35 kg of such hypotetic batteries replace effectively 35 kg (one average reservoir) of liquid fossil fuel.

Let us to estimate competitiveness of some available battery types against hypotetical ideally competitive battery (having energy density equivalent to the energy density of oil):

For lead acid battery: 35 Wh/kg /3300 Wh/kg ~ 0.01

It means 100 x 35 ~ 3500 kg of lead acid batteries is equivalent energetically to one reservoir (35 kg) of oil. That mass is more than twice higher than an average car mass.

For Tesla battery the ratio is: 157 Wh/kg /3300 Wh/kg ~ 0.05, i.e., 20 x 35 ~ 700 kg Li-ion batteries are equivalent energetically to one reservoir (35 kg) of oil.

The last considered data show that energy density of contemporary batteries replaces only nearly 5% of the actually utilized energy density of liquid fossil fuel.

Why, in comparison to fosssil fuel, we use today 20 times poorer power source in contemporary electric cars?

The reason is in the anticipation that the damage for global economy caused by climate changes may become multiple times higher from todays damages if the consumption of fossil fuels continues at todays rate. One should note here that electric cars do not polute the atmosphere.

4. WHAT ADVANCEMENT IN BATTERY COMPETITIVENESS MAY BE EXPPECTED IN NEAR FUTURE?

On the diagram shown in Fig.10., one may see a survey of practical energy density of batteries which are already in use (bars 1-4), then of those being in final stage of development before practical use (bars 5-7), and of that being still in the stage of laboratory investigations (bar 8) [10]. The plateau of darker part of bars is the achieved energy density, while plateau of lighter part of bar is the energy density which may be achieved having in mind contemporary technological resources. The lowest energy density of 35 Wh/kg has a classical Pb-acid battery. The nickel-cadmium batteries, since discovery compete to the lead-acid batteries in all consumer areas, but are preferably used within small energy consumers. The nickel-metal hydride (Ni-MH) batery (bar 3], [11] commercialized in ~1980., are advanced batteries with somewhat higher energy density in comparison to classical batteries, however they can not withstand the competition of more recent, fast developing Li-ion batteries, and have today rather limited consumption space in small energy consumers, mostly in wireless phones.

Contemporary battery driven cars use Li-ion batteries presented by bar No 4., in the midle part of the diagram, with the energy density ranging 120-160 Wh/kg [10].

Li-ion battery did not achieve the theoretically highest energy density, thus it is now in the stage of development (bar 5, Future Li-ion batteries). The expectation to achieve higher energy density is based on the possibility of use of intercalation materials of reduced molar masses. Having in mind available elements in the Periodic table of elements, maximum energy density which may be achieved is about 300 Wh/kg. In future Li-ion batteries the graphite anode, being the limiting factor of capacity, is expected to be replaced by more capacitive materials, based on, for example, alloy forming materials, Sb [12], CoO[13,14] or Si [15]. The main technological problem of these materials is very high volume change on battery charging and discharging, which are attempted to be solved by using various composite materials.

The highest energy density may be achieved if the reduction reactant is pure metal from the range of light elements, while the oxidation reactant is oxygen from air, or sulphur (bars 6-8). For rechargeable batteries of this group the technological solutions are in different stages of finishing.

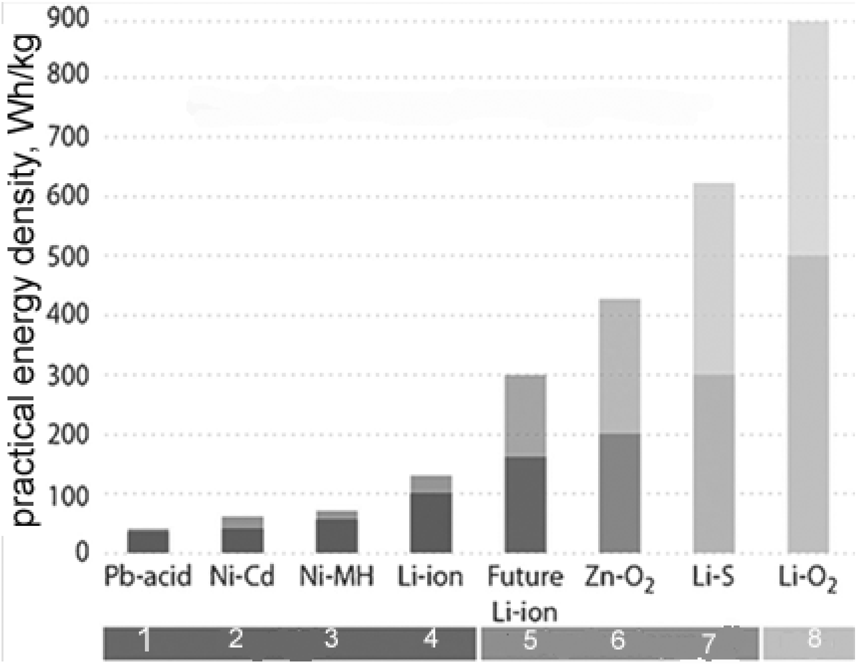

Figure 10. A survey of practical energy density of batteries being already in use (bars 1-4), being in final stage of development (bars 5-7), and being in stage of laboratory research (bar 8). Plateau of down placed darker part of bars denotes achieved energy density and plateau of top placed lighter part is the estimated achievable energy density [10]

Zn-air battery [16] is most close to a practical use. Lithium-sulfur battery has presently the problem with extremely low reactivity of sulfur, which is attempted to be solved by nanoparticulate sulfur dispersion on electronically conducting support [17]. Among the batteries with metal anode, the highest density is expected from the battery Li-air [18], amounting to 900 Wh/kg (bar 8). This battery, although very attractive, still experiences many technological problems, including suitable membrane permeable to Li ions but completely impermeable for oxygen, as well as the limited cyclability of lithium ions from the cathode compartment [19].

Each advancement in battery density field reduces the mass of battery pack needed for targetted mobility range of 500 km. The Table 1 contains practical energy density in left column, and the mass of battery pack for mobility range of 500 km in right column. As already considered, one needs 3500 kg of lead-acid batteries. The mass of contemporary Li-ion batteries needed for the same mobility range is less than 1000 kg. If Li-air batteries with the energy density 900 Ah/kg may actually be realized in a practically available form, the mass of batteries needed would be ~ 130 kg. An ideally competitive battery with the energy density of 3300 Ah/kg looks like unachievable with the materials available today for battery construction.

Table 1. Practical energy density (left) and corresponding mass of batteries for mobility range 500 km of an average car (right).

Energy density Wh/kg	Mass kg
3300 (ideal)	35
900 (Li-O_2)	130
120 (Li-ion)	>1000
35 (Pb-acid)	3500

The problem of energy content of batteries is only a part of problems acompanying the transition to electric cars. Other problems are:

– Low rate of battery charging in comparison to the rate of filling of gasoline reservoir

– Unresolved problem of recovery of batteries which lost the capacity

Finally, the electric cars do not solve the problems of atmosphere polution with CO_2 as long as the electric power for battery charging comes from thermal plants using coal. Their advantage will come to expression just when the renewable resources become exclusive resources of electric energy production.

5. CONCLUSIONS

The development of electric cars is in function of prevention of climate changes. It was actualized by a UN organisation decision to support technologies that prevent emission of greenhouse gases in atmosphere. In 2010, when mass production of electric cars started worldwide, the batteries of Li-ion type, discovered in 1990 were more suitable for that purpose than a long-time investigated H_2-air fuel cells, based on hydrogen energetics and technology.

The energy density of contemporary batteries replaces nearly 5% of the actually utilized energy density of liquid fossil fuel. However, the transition to electric cars is mandatory, having in mind that any mass of liquid fossil fuel libarates on combustion almost threefold mass of CO_2 in atmosphere, what means considareble danger of climate changes, which may appear by continuation of consumption of fossil fuels at todays rate. Furthermore, there are real expectations that energy density of further batteries may be enhanced to ~ 27 % of the utilized energy density of liquid fossil fuel.

The development of electric cars does not solve the problems of atmosphere polution with CO_2 as long as the electric power for battery charging comes from the thermal plants using coal. Their advantage will come to expression just when the renewable resources become exclusive resources of electric energy production.

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БАТЕРИЈЕ КАО СРЕДСТВО ПРОТИВ КЛИМАТСКИХ ПРОМЕНА

Сажетак: Како би се спречила растућа опасност узрокована климатским променама, у недавним декадама склопљен је споразум на нивоу Уједињених нација, како би се постепено смањила потрошња фосилних горива до потпуног престајања коришћења. Овај споразум (Оквирна конвенција о климатским променама Уједињених нација (UNFCCC)) до 2018. потписала је већина држава света. Један од захтева је био прелазак на аутомобиле на струју, што је у развијеним државама започело око 2010. године. Конкуренција између горива и батерија као средства за вожњу је тада постала актуелна, али у кључном тренутку батерије су се показале као технолошки супериорне. Већ у 2018. години број електричних возила која се возе на батерије, произведен у водећим развијеним земљама био је изражен у милионима.

Пратећи ову нову и значајну улогу батерија, циљ овог доприноса је а) кратко представљање принципа конверзије енергије у батерије и њихове енергетске карактеристике, б) анкета о захтевима реактаната у хемијској реакцији батерије, из којих проблеми у њиховом развоју могу да произлазе, у зависности од технологије материјала, в) конкуренција батерија и фосилних горива у енергетском смислу, и, г) прогноза онога што се може очекивати у блиској будућности од конкурентне снаге батерија унутар видокруга развоја нових материјала.

Кључне ријечи: напредне батерије, климатске промене, конкурентност батерија, електрични аутомобили, како батерија ради.

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