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Battery Electric Vehicles: Perspectives and Challenges

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Abstract. In the early decades of the car industry (1880-1920), battery electric vehicles (BEVs) got a remarkable popularity. Eventually, they fell into oblivion for nearly a century, leaving the stage to internal combustion vehicles (ICVs), which enabled long-distance driving thanks to the superior energy density of liquid fuels. The invention of the lithium-ion battery (LIB, 1991), characterized by unprecedented energy density and steeply decreasing costs, set the stage to reverse this century-long trend, making nowadays BEVs a competitive alternative to ICVs. In this paper, we analyze the perspectives of battery electric cars, quantitively assessing their performance in terms of energy efficiency and consumption versus ICV counterparts. An examination of material requirements for manufacturing each battery component is made, with focus on critical resources such as cobalt, dysprosium, lithium and graphite. Based on quantitative data, we conclude that the transition to electric powertrains for light-duty vehicles is not only desirable but also doable. However, this must be accomplished by following circular economy principles across the whole industrial chain, in the frame of a wider, radical transformation of the mobility system towards more sustainable models.

Keywords. Battery electric vehicles, lithium ion batteries, cobalt, dysprosium, critical materials, energy efficiency, circular economy.

THE RISE, FALL AND REBIRTH OF THE ELECTRIC CAR

The widespread notion that electric cars are a new technological concept is incorrect. The first battery-powered electric vehicle (EV) was made in 1834, *i.e.*, over 50 years before the first internal combustion vehicle (ICV) powered by gasoline went onroad.[1] Notably, the first examples of machines for personal transportation were based on steam engines and dates back to the very beginning of the 19th century. A century later, at the turn of the 20th century, the share of registered US cars was as follows: 40% powered by steam, 38% by electricity, 22% by gasoline (Figure 1).[1] Therefore, as weird as it may sound nowadays, the fight for predominance among the three car concepts was far from over in 1900, when refined oil products were still scarcely available, electricity was a luxury for (some) city dwellers, and roads were far from being developed and paved outside the main urban centers.

Figure 1. From left to right, examples of electric, steam and internal combustion engine cars of the early 20th century (1906, 1908, 1925, respectively).

In the early 20th century, cars were only used by wealthy people within metropolitan areas, where distances were very short. This is why electric cars were still an attractive option. Moreover, EVs were silent, did not produce any smoke or smell and – most remarkably – did not require hand crank to be turned on. However, within a few years, the situation dramatically changed in favor of ICVs,[2] whose dominance in road transportation was poised to last for over one century. The main drivers for the triumph of ICVs were (i) the invention of the electric starter in 1912, (ii) the start of the industrial production of the Ford Model T in 1908 (though Henry Ford continued to use his luxury electric car); (iii) the oil boom in Texas that made gasoline increasingly available at affordable prices, (iv) the development of road networks that required cars with increasingly long mileage.[2] The last EV of the pioneering times was produced in Detroit in 1926[1] and the idea was (ephemerally) resurrected only in the 1970s in the aftermath of the first oil crisis. Waves of interest occurred in the last part of the 20th century, but times were not mature, primarily because battery technologies (typically based on lead-acid systems) were not capable of providing acceptable mileage at an affordable price and overall weight.

In 1997 Toyota released Prius, the first hybrid car (Figure 2).[3] It combined an ICE with electric propulsion, which enabled a decrease of fuel consumption in urban settings. Nowadays, hybrid cars are the preferred choice for taxi drivers in many cities worldwide. The success of Prius and of some other hybrid models (almost exclusively from Japanese firms) marked the slow rebirth of electric mobility. The first Prius used a nickel-metal hydride (NiMH) battery pack.[4]

The technological game changer that made at last possible the dream of Thomas Edison – the pioneer of the electric transportation – is the rechargeable lithium-ion battery (LIB), which was introduced in the market by Sony corporation in 1991 to power laptops.[5,6] The progressive introduction of portable devices on a large scale (mp3 players, mobile phones, etc.) and also of systems requiring bigger battery packs (home appliances, bikes) offered a formidable opportunity to boost the development of LIBs and widely expand the market. This trend was timely pinpointed by two American engineers, Martin Eberhard and Mark Tarpenning, who realized that LIBs could be the long-awaited solution to enable battery vehicles with long ranges. They founded Tesla Motors in 2003 and were soon joined by Elon Musk, a flamboyant South African immigrant and entrepreneur, who became the CEO and product architect of the company. Since then, Tesla has become one of the most noteworthy, controversial and debated companies in the world. Whatever will be its future destiny it will be historically remembered as the company which challenged the most gigantic industrial conglomerate of human industry – oil & automotive – and forced it to change its century-old trajectory.[7]

There are three types of cars equipped with a battery pack: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). HEV batteries are charged only by the thermal engine or via regenerative braking, whereas in PHEV these processes can be integrated by direct charging on the electric grid. BEV have only an electric motor and can be powered exclusively by electricity. This article will primarily deal with BEVs, often indicated simply as electric vehicles (EVs).

THE KEY COMPONENTS OF BATTERY ELECTRIC VEHICLES

BEVs are easier to assemble and cheaper to maintain than ICVs simply because they contain a much smaller number of moving parts.[8] Hybrid, instead, are by far the most complex and materials intensive automobiles, as

Figure 2. The slow rebirth of electric vehicles: the first hybrid Toyota Prius (1997, top) and the Tesla Roadster (2008, bottom).

they contain both electric and traditional components. Key constituents of BEVs are: the battery, the electric machine, the power electronics and the charging device.[9] A schematic representation of the key components of an electric car are depicted in Figure 3.

Battery. It determines the key technical attributes of an EV, such as driving range and also performance. In the past, EVs were equipped with lead-acid or nickel hydride batteries, but nowadays lithium ion batteries (LIBs, see also next paragraph) are by far the dominant technology and their role is not expected to fade even in the medium-long term, due to the unique (electro)chemical and physical properties of lithium.[6] The most important parameters that define the quality of a battery are the mass and volume energy densities, the former being expressed in MJ/kg (or more often in Wh/kg and indicated as "specific energy") and the latter in MJ/L or Wh/L;[10] the volume energy density is particularly relevant for vehicles, due to obvious space constraints. In Figure 4 are depicted energy densities of some types of batteries, along with those of the liquid fuels used in transportation. It must be emphasized that data in Figure 4 refer to *cells*, but car batteries operate as *packs*. These include the control circuitry that warrants the car performance under any conditions and the robust casing that protects the cells (vide infra). Therefore, at pack level, the battery energy density is smaller by 30-50% compared to bare cells. On the long term, the accessory parts of the battery appear to be the main limit for increasing energy density. The energy density of the most performing LIBs for EVs are presently close to 250 Wh/kg (Tesla Model 3), or 710 Wh/L.[11] This value unfavorably compares with gasoline or diesel fuels, which is nearly 15-fold higher at ca. 10,000 Wh/L. However, this comparison is partly misleading because the energy packed in the storage unit must be converted into mechanical movement. For this job an electrical motor is 3-4 times more efficient than a combustion engine and, at the same time, is substantially lighter. Therefore, power densities should be normalized accordingly.[12] A 75 kWh lithium ion battery pack (Tesla Model 3) weights about 478 kg, whereas an equivalent ICE car requires the burning of only 25 kg of gasoline to deliver the same energy to the wheels.[4] However, it must be emphasized that an EV is a closed

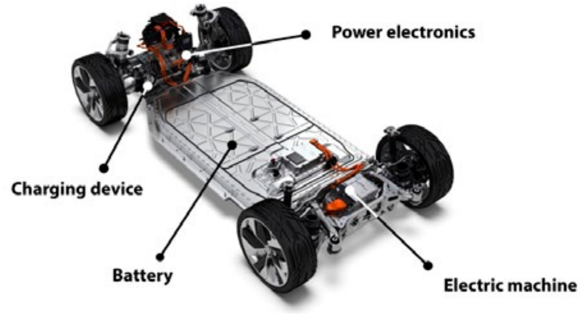

Figure 3. The key components of a battery electric vehicle (BEV).

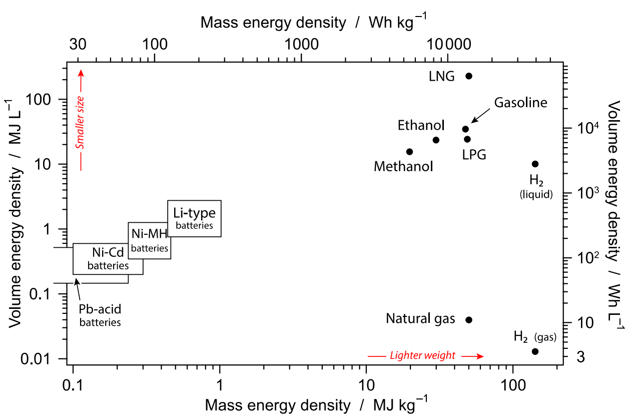

Figure 4. Volume and mass energy densities of some selected batteries and liquid fuels. Both MJ and Wh are reported in the diagram as energy units (on opposite sides), as both are largely diffused in the literature and technical documents.

system which exchanges only (electric) energy with the external environment, whereas ICVs are open systems undergoing a constant inbound flow of fuels and an outbound flux of gaseous chemicals at tailpipe. After 250,000 km, an average diesel car running at 18 km/L, has burnt 13,900 L of fuel, i.e., over 10 tons corresponding to about 8 times the weight of the whole ICE car and over 20 times the weight of a 75 kWh EV battery. When the electricity is produced by solar panels (an increasingly frequent case) the flux of matter that moves an electric car is reduced to zero across the entire supply chain. In other words, comparisons of energy density and material intensity of batteries vs. traditional fuels is less straightforward than it may appear at first sight.

Electric machine. This term defines the combination of the electric motor, converting the electrical in mechanical energy, and the power generator coupled to it, which recovers kinetic energy from braking and deceleration and convert it into electricity for recharging the battery. Electric machines are characterized by an high starting torque (up to 1,000 Nm), high efficiency (up to over 90% battery-to-wheels), robustness, negligible noise, long life and low maintenance costs. Electric machines can run with both direct (DC) and alternating (AC) current. Traditionally, series wound DC motors have been used, but today modern BEVs can also be powered by AC. The alternating current generates a rotating magnetic field that causes rotational movement inside the motor (made up by a stator and a rotor) via electromagnetic induction. In turn, the motor is coupled to a gearbox that brings the power directly to the wheels; the speed of the vehicle depends on the Pulse Width Modulation (PWM) frequency of the power converter. In principle, in a BEV, the electric motor can be directly incorporated into the wheel (as e.g., in the Michelin Active Wheel), removing the need for a complex and intrinsically inefficient transmission system of ICVs that converts the linear and noisy motion of cylinders into the circular motion of the wheels.

Power electronics. The power electronic module oversees all the functions that control the efficiency and economy of the vehicle, such as torque and efficiency of the motor, and regeneration of the battery charge. The main function is to convert the DC output of the battery into an AC feed for the motor through an inverter (or viceversa during recuperation). It also controls the different levels of voltage, depending on the power demand and specific device to run. It is also very important for the charging process.

Charging device. It is the interface between the vehicle and the electric grid. Modern electric cars can be typically charged both with AC and DC. The AC charging mode is controlled via an onboard system which operates during slow garage-based operations (2-3 kW, standard socket) or in small-medium size recharging stations up to 22 kW. If one wants to charge faster, the AC/DC converter needs to be bigger and heavier, taking up more space and increasing the complexity and cost of the vehicle. Therefore, off-board DC fast-charging systems are typically used to charge the battery with higher power (≥ 50 kW).[4] Fast DC charging stations up to 300 kW are now being introduced by some companies. This poses relevant challenges for the long-term integrity of the battery (a very efficient cooling systems is required) and for the electric grid as a whole. In fact, with a high market penetration of BEVs, the stability of the grid may in principle be endangered not only by extensive networks of high-power fast charging stations with high peak demands,[13] but also by uncoordinated EV charging at the residential level at low-medium power.[14] Accordingly, the diffusion of the electric car must be accompanied by an upgrade and strengthening of the electric grid, i.e., the so-called smart grid.[15] In this scenario, a large share of electric vehicles should be ideally charged around midday, when the peak of photovoltaic production occurs. This can be facilitated by a larger diffusion of parking lots equipped with charging stations at workplaces.

THE CORE OF BEVS: THE LITHIUM ION BATTERY

The basic idea of this device (whose concept dates back to 1970s)[6] is the reversible, alternate intercalation of Li^+ in a lithium oxide material at the cathode and in graphite at the anode, upon redox processes. J. B. Goodenough, M. S. Whittingham and A. Yoshino were awarded the Nobel Prize in Chemistry 2019 for the development of lithium-ion batteries.

Lithium is the smallest and lightest metal ion, hence LIBs exhibit intrinsically high mass energy density and are particularly suitable for fast recharging. Moreover, it has excellent cycling performance and exhibits one of the highest electrochemical potential among metals, which enables devices with high voltage. A LIB is made of anode, cathode, separator, electrolyte and two metallic current collectors at each terminal; it is schematically depicted in Figure 5.

Upon battery charging, the Li^+ ions are forced to move away from the cathode (where cobalt/nichel oxidation occurs) and nest inside the graphite layers (which gets reduced) of the anode; upon discharging, they go back to the cathode at their equilibrium position. In

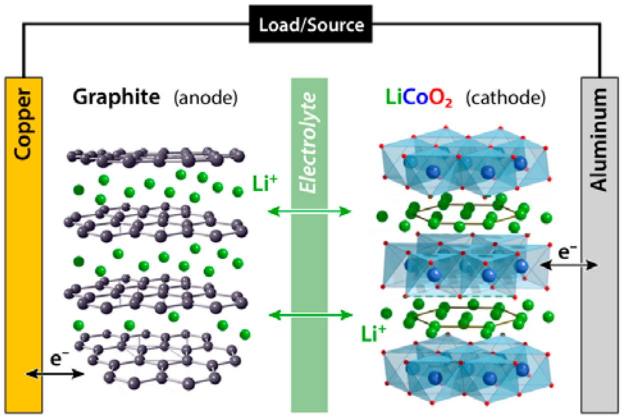

Figure 5. Scheme of a lithium ion battery, where Co^{4+}/Co^{3+} half reaction occurs at the cathode and redox-promoted intercalation of lithium in graphite takes place at the anode.

parallel, electrons move back and forth along the external circuit and are conveyed to the Al and Cu terminals on the cathode and anode side, respectively. Upon battery discharge, the electric current powers the external device. When shuttling between electrodes, Li^+ ions passes through a plastic polymer separator that prevents the flow of electrons inside the battery.

The cathode of LIBs is made of layered oxides of general formula $LiMO_2$, where M indicates some combination of Co, Ni, Al, and Mn; nowadays anodes are made of carbonaceous materials, particularly natural and artificial graphites.[16] Non-layered cathodes can be made of less precious Li oxide materials (e.g., $LiFePO_4$), but their energy density is not comparable with layered systems and cannot be used in highly performing LIBs. The electrolyte is typically a lithium salt in an organic solvent or gel. The replacement of the latter media with solid matrices would be a substantial breakthrough of the LIB technology, particularly in terms of durability and safety.[17]

The features of the three main families of LIBs currently on the market are reported in Table 1. Cobalt is omnipresent, due to the unique electronic configuration of Co^{3+} with 6d electrons in a low spin state, which makes it particularly small and capable of affording batteries with high energy density. Big efforts are being made to reduce as much as possible the cobalt content, due to supply concerns (vide infra). For instance, the Nichel-Manganese-Cobalt batteries (NMC) have progressively evolved as, for instance, NMC111, NMC622 and then NMC811, where the numbers designate the specific ratio of each metal.[18]

The element requirements of some common electrodes (in kg/kWh) are reported in Table 2.[18] From these data it can be inferred that a medium sized 40 kWh battery NMC 111 contains in the cathode about 5.5 kg of Lithium (without considering the electrolyte), 15.7 kg of Ni, 14.7 kg of Mn and 15.8 kg of Co (to be reduced to 8.6 and 3.8 kg with NMC 622 and NMC811, respectively). A battery of a 40 kWh BEV also contains nearly 50 kg of graphite, irrespective of the cathode composition. Efforts to increase the energy density of batteries are now also addressed to the improvement of the standard graphite anode, with focus of silicon-based materials.[20] These solutions are still far from large-scale market applications.

Real-life batteries for electric vehicles are made of hundreds or thousands of individual cells having the structure depicted in Figure 5 and connected in a series and parallel combination. These cells may have three different shapes: cylindrical, prismatic and pouch, the latter being characterized by very small thickness (< 1 cm). Different car manufacturers adopt different types of cells and related assemblies (Figure 6).

Tesla uses cylindrical cells slightly longer and wider than conventional AA cells for home appliances, profiting from the large manufacturing experience of its part-

Table 1. Key parameters and applications of the three main families of LIBs.[19]

Name	Battery type		
	Lithium Cobalt Oxide (LCO)	Lithium Nickel Cobalt Aluminum Oxide (NCA)	Lithium Nickel Manganese Cobalt Oxide (NMC)
Cathode	$LiCoO_2$	$LiNiCoAlO_2$	$LiNiMnCoO_2$
Voltage [V]	3.7 – 3.9	3.65	3.8 – 4.0
Mass energy density [Wh kg^{-1}]	150 – 240	200 – 300	150 – 220
Cycle life	500 – 1000	500	1000 – 2000
Thermal runaway [°C]	150	150	210
Applications	Mobile phones, tablets, laptops, cameras.	Medical devices, electric powertrains, industrial.	E-bikes, medical devices, electric vehicles, industrial.

Table 2. Li, Co, Ni, Mn, Al requirements for common battery cathodes (kg/kWh).[18]

	Li	Co	Ni	Mn	C
LCO	0.113	0.959	–	–	
NCA	0.112	0.143	0.759	–	
NMC111	0.139	0.394	0.392	0.367	≈ 1.2
NMC622	0.126	0.214	0.641	0.200	
NMC811	0.111	0.094	0.750	0.088	

ner Panasonic, with whom it has developed the so called Gigafactory 1 in the Nevada desert. The enormous facility is planned to be energy self-reliant through a combination of photovoltaic, wind and geothermal energy. The projected capacity for 2020 amounts to 35 GWh/y of automobile cells and 50 GWh/y of battery packs for stationary backup of renewable power facilities, but it is not yet evident if these targets will be fully met. The idea is to demonstrate cradle-to-cradle handling of

Figure 6. Individual cells for BEVs and their final assembly in the pack: Tesla (cylindrical, top) and Nissan Leaf (puch, bottom).

Lithium ion batteries, all the way from raw materials to manufacturing and then recycling. The battery pack of the long-range Tesla Model 3 (75 kWh) contains 4416 cylindric batteries (70 mm length, 21 mm diameter; 66 g) arranged in 96 blocks of 46 parallel connected cells. The Nissan leaf 2018 (40 kWh), has a battery pack made of 24 modules, each containing 8 pouch NMC cells. Each of these 296 cells weights 914 g and have a size of 261x216x8 mm. All the battery packs in BEVs are protected by robust metallic and plastic enclosures that protect the cells from external elements (e.g., dust, moisture, rain, debris) and must withstand severe crash tests to warrant the safety of passengers in case of accidents.[21] Last but not least, BEVs are equipped with a battery management system (BMS) which warrants integrity and best performance, for instance by avoiding damages due to anomalies in temperature or electricity supply.

Nowadays battery packs range typically from 20 up to 90 kWh; the driving range is rated between 150 and 500 km,[16] but strongly depends on the weight of the vehicle, style of driving, speed and, quite remarkably, outside temperature.[22] At 0 °C the mileage of an EV is shortened by about 30% and even more in harsher winter conditions, this is related to a lower intrinsic efficiency of the device at low temperature and to the energy needed to warm up the car interior. Also hot temperatures have detrimental effects for similar (and opposite) reasons, but to a substantially lesser extent. As far as temperature is concerned, one may say that LIBs are like human beings: they perform best in the range 15-30 °C.[22] (4) Average consumptions of EVs are about 12-14 kWh/100 km in mild and warm seasons and 15-17 kWh/100 km in cold weather.

Present targets for BEVs to become fully competitive with conventional thermal cars concern:

(i) *Faster charging capabilities* in order to achieve 80% state of charge within 5-20 min. This target will become more challenging if the average battery capacity will grow bigger. For example, to charge a 60 kWh battery (350-400 km range) in 20 min would require at least 180 kW of charging power and a very efficient on-board temperature control management of the cells. Nowadays standard fast charging stations are normally rated 50 kW. It must be emphasized again that the diffusion of fast charging stations requires a more rational management of electricity peak demand, to be ideally matched with the daily and seasonal production peaks of renewable electricity.

(ii) *Higher battery energy density* at about 240 Wh/kg and 500 Wh/L at pack level, in order to routinely reach driving ranges of 500 km.[16] This is technically possible already, but only for models which, at present, are economically accessible to a limited fraction of consumers.

(iii) *Price decrease* down to 125 \$/kWh at pack level to become fully competitive with ICVs at the car showroom. Present battery costs are placed at 100–170 \$/kWh and 220–250 \$/kWh at the cell and pack level, respectively.[16]

Regarding future perspectives, research on next generation batteries targets the development of new sensors to monitor complex reactions in the device, so as to enable self-healing and enhance battery performance and lifetime.[23]

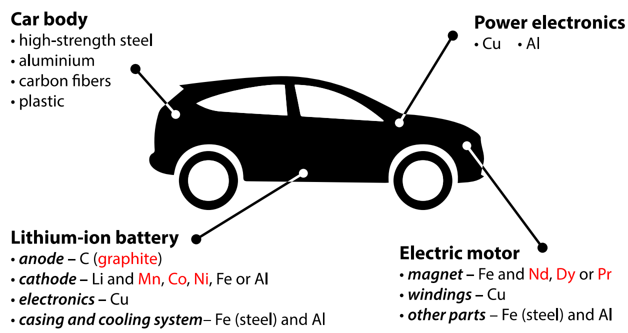

Figure 7. Most relevant materials used in different parts of battery electric vehicles. Those defined as critical are highlighted in red.

CRITICAL RAW MATERIALS IN BEVS

Since 2011 the European Commission has compiled a list of "critical raw materials" (CRM); the latest list has been issued in 2017 and contains 27 materials or classes of materials such as Platinum Group Metals (PGM) or Rare Earth Elements (REE).[24] Materials are defined critical after a thorough screening that quantitatively assesses (i) importance for the EU economy in terms of end-use applications and added value and (ii) risk of supply disruption for the EU.

Due to the ever-increasing number of road vehicles worldwide, the huge size of the market and the extensive use of materials of different sorts in automobiles (a light-weight duty vehicle weights between 1 and 3 tons) the car industry is the object of intensive studies to assess its materials sustainability.[25] This issue is even more important nowadays, because this industrial sector is undergoing a technological shift from thermal to electric traction.

The body and some auxiliary parts of BEVs and ICVs are virtually identical. The electric machine is much lighter than the conventional combustion engine, but this advantage is counterbalanced by the heavy battery pack, which can exceed 600 kg for the largest capacities (85-100 kWh).[26] The weight of battery packs is almost linearly correlated with overall capacity, when the same cell technology is examined. On the other hand, ICVs have a much larger number of parts, which impacts the mass of the automobile. All in all, BEVs equipped with lithium ion batteries and ICVs of comparable size have a similar weight, but BEVs are more material intensive than conventional thermal cars. In other words, they contain substantial amounts of more "sophisticated" materials (particularly metals) some of which are considered critical.[27] In Figure 7, major raw materials utilized in electric cars are schematically indicated.[27]

As far as material criticality is concerned, battery is by far the most sensitive part of BEVs, both in terms of number of materials involved and quantity utilized.[18,27] As pointed out above, the battery pack of a BEV contain some tens of kilograms of metals – in particular Li, Co, Ni, Mn and Al (cathodes, electrolyte) – and graphite materials (anode). In batteries, Cu is only used as anode collector (along with Al on the cathode) in rather limited quantities. However, Cu is a strategic metal for the electric mobility system as a whole, being widely employed in car circuitry and wiring, all the way to the electric grid.

Among the materials listed in Figure 7, Co, Li, Dy are the most critical in terms of potential availability risks, whereas graphite is critical because the production is highly concentrated in one country (China). Let us briefly examine each of them.

• *Lithium.* At present, lithium is the most difficult component to replace in BEVs. Its mass, volume and electrochemical properties suggest that the role of lithium in this sector can be reduced only going beyond metal-based batteries, an unlikely scenario for the foreseeable future.

In 2017, about two thirds of lithium was extracted from hard rocks,[28] which are crushed to allow the separation and concentrations of lithium minerals and then chemically processed (e.g., by leaching) to obtain lithium hydroxide, carbonate or chloride. An easier, cheaper, but longer process is extracting lithium dissolved in highly concentrated underground saltwater solutions called continental brines. Such brines are brought to the surface by drilling wells and then moved through a series of surface ponds to concentrate the lithium salts and remove impurities (Figure 8). The last step is chemical treatment to make the final marketable product, such as dry lithium carbonate.[28] Extraction from brine was started in the salt lakes of the Atacama desert in

Figure 8. Lithium brine ponds in the Lithium Triangle, South America (bottom right map).

Chile in 1980s. This technique is now dominant in the so-called "Lithium Triangle", the region between Chile, Bolivia and Argentina where the concomitance of geological, orographic and climate conditions have created several lakes very rich in lithium brines (Figure 8). The largest lithium reserve in the world is the Salar de Uyuni in Bolivia, for which extraction plans are conflicting with the need to preserve a place of unique environmental value and are challenged by the presence of high concentrations of magnesium, which needs to be separated.[29] It has to be emphasized that lithium extraction from brines, though relatively easy, is a lengthy process that cannot quickly respond to the steep rises in demand that are expected in the years to come.[27]

According to the US Geological Survey (USGS), Australia (from hard rocks) and Chile (from brines) currently dominate lithium production with 60% and 31% of global output in 2018, respectively.[30] The production of this highly valuable metal has been on a steep rise in recent years (+ 23% in 2018), due to enhanced demand for all types of electric vehicles. The largest known untapped resources (i.e., identified deposits) are concentrated in the Lithium Triangle, but their upgrade to reserves (i.e., technically and economically exploitable stocks) is still uncertain in Bolivia and Argentina.[28] The search for new lithium reserves is a relatively recent trend, hence it is reasonable to expect the discovery of relevant deposits in new geographic areas such as Afghanistan, where effective exploitation may be extremely challenging for a variety of technical and political issues.[31]

In 2018, over 80 million new cars were sold. On the other hand, we can approximately assume that an average BEV contains about 10 kg of lithium in the battery.[32] Therefore, if all the cars presently sold worldwide were BEVs, the annual lithium demand would be 800,000 tons. This is about 10 times the current world production,[30] half of which goes to the battery market, the rest being used in ceramics, glass, lubricants and other minor applications.[28] These data also suggest that the present production of lithium for the manufacturing of batteries (about 40,000 tons/y) can in principle sustain only a 5% share of EV in the present global annual car market.

The substantial increase in resource and reserve estimates in recent years does not indicate risks of lithium shortages up to the medium term (10-20 years).[18] Recently, there have been a supply deficit for refined products and an oversupply of mined minerals. Spot prices of lithium carbonate have fallen 60% from early 2018 to mid-2019, but long-term contract prices (over 75% of lithium trade globally) were rather stable in the same period. Forecasting on the longer term on such a complex and evolving market is difficult. Price trends depends on multiple factors such as the evolution of the market in road vehicles,[8,33] the availability of new lithium reserves and, last but not least, the establishment of recycling practices in a circular economy perspective. At present, lithium recovery is technically possible through a variety of pyrolytic, hydrothermal as well as pyro- and hydrometallurgic methods.[27] Despite some companies have implemented industrial processes for recycling LIBs,[34] the recovery and recycling of lithium from batteries remains scarcely attractive at the present cost of virgin mineral products.[18] The economic attractiveness of recycling will improve when the number of end-of-life EVs will substantially increase.

LIBs in cars are considered exhausted when they can recharge at 80% of the initial rate, a level allowing excellent performance in some second-life applications such as accumulators for renewable electric generation facilities powered by intermittent sources (wind, photovoltaics). Some companies have implemented this practice in flagship sites such as the Amsterdam stadium (3 MW),[35] showing that car LIBs can fruitfully serve well beyond the performance guaranteed by car manufacturers which is between 150000 and 200000 km. Longer mileages can be achieved by a thorough daily management, especially in the recharging phase.[36] For instance, it is advisable to not keep them above 80% or below 20% of their capacity for very long times. This means that batteries of higher capacity (> 60 KWh) can in principle last longer, as the number charge/discharge cycles across their lifetime tends to be lower.

• *Cobalt.* Cobalt is considered the most serious potential obstacle for the expansion of the LIB market for electric mobility.[18] As already pointed out, cobalt is the best choice among transition metals to get laminated cathodes with very high energy density; so far, it could be only partially substituted with Ni or Mn. In the last decade (2009-2018) the world mine production of cobalt has increased by 125%, from 62 to 140 kton/year;[37] in comparison Ni production has increased by "only" 64%, (from 1.4 to 2.3 Mt).[38] By assuming 10 million BEV cars sold yearly by 2025 (about 10% of the global car market) – with an average battery pack of 75 kWh (about 400 km driving range) and under the assumption of a mixed cathode chemistry relative to the present technologies – the global demand for cobalt in LIBs would increase up to almost 600% (from 50 to 330 kt, 2016-2025).[18] At present, it is not evident if supply can keep up with such a steep demand, in the absence of substantial technological advancements to reduce the use of cobalt in LIBs, even if demand trend will be less disrupting, as projected by other studies.[39]

Besides impending constraints in material availability, cobalt is critical for other aspects. First of all, most of it is obtained as a byproduct of the extraction of Ni and Cu (about 60% of the world cobalt production comes from copper ores),[40] which means that its production is dictated by the market trends of its parent "attractor metals", potentially generating uncertainty and price volatility.[41] Moreover, cobalt production is concentrated (around 60%) in a politically unstable country such as the Democratic Republic of Congo (DRC), where violation of human rights in small uncontrolled mines is well documented.[42] To give an idea of the economic value of cobalt, it is interesting to note that one of the largest mines in Congo (Mutanda) produces about 250 kt/y of Cu and 25 kton/y of Co, but the latter generates about 40% of the revenues.[18] Cobalt refining is also a matter of concern because most of it is done in China. The trade flow of Ni-Co and Cu-Co ores from DRC and other countries to China is a multibillion affair that feeds the Chinese manufacturers of LIB cathodes.[18] This is one of the (many) strategic activities behind the ongoing "trade wars" between China and the USA.

The benefits and concepts related to the reuse and recycling of LIBs discussed for lithium fully applies – and even more strongly so – to the more critical cobalt. Indeed, at present, LIB recycling is much more attractive for cobalt than lithium due to its higher economic and material value. At any rate, the extensive use of LIBs is a relatively recent trend, therefore large-scale recycling can be effectively accomplished not earlier than 2025, with EU possibly obtaining about 10% of its Co supply for the EV sector from end-of-life batteries in 2030.[39]

• *Graphite.* The dominant material for LIBs anodes is graphite, sometimes added with small amounts of silicon oxides. Both synthetic graphites (SGs) and natural graphites (NGs) are normally utilized, with an almost equal market share. NGs tend to be less performing, but they are about 50% cheaper than SGs.[16] NGs occurs in several forms (amorphous, flake and vein) and its quality is dictated by the carbon content and the grain size; battery grade NG must have a very high carbon content (> 99.95%) and particles sizes in the range 10-25 μm for optimal operations.[43] Availability of natural graphite is not a matter of concern in itself because the annual world demand is around 1 Mt and estimated world reserves are currently placed at 300 Mt.[44] New extraction projects are under development in several parts of the world, particularly in Africa (Tanzania, Mozambique), North America and Australia; reserves in Europe appear to be very limited.[43] Presently, the issue with natural graphites is that over 60% are produced in China (the rest primarily in Brazil and India), which makes this anode material the most geographically concentrated component of LIBs in terms of supply, even more than cobalt.[18,45] However, less than 10% of graphite is used for batteries, the primary application being refractories, due to its high temperature stability and chemical inertness, and steel making.[43] The share of graphites used in LIB manufacturing is expected to increase dramatically in the next decade.[45]

• *Dysprosium.* The most widely used motors in electric vehicles are based on permanent magnets (PM) which are made of the neodymium-iron-boron (NdFeB) alloy,[46] primarily in a $Nd_2Fe_{14}B$ tetragonal crystalline structure. At present, NdFeB is the dominant high-performance permanent magnet material due to its superior magnetic flux output per unit volume, which is almost ten times as much compared to ferrite. Besides electric motors, NdFeB is used in several applications such as wind turbines, computer drives and headphones. The NdFeB alloy is made in different variants, with minor concentrations of other rare earths (dysprosium, praseodymium, terbium) or transition metals (copper, cobalt, niobium) capable of optimizing the alloy's properties for specific applications. Dysprosium is used to enhance the performance of NdFeB magnets at high temperatures (up to about 7% in weight), such as those reached inside electric motors.[47] About 90% of BEVs presently sold have permanent magnet motors, whereas induction motors, which do not require rare earth elements (REE), cover most of the rest. PM motors are up to 15% more efficient and the combined weight of metals used in PM motors is also 15% smaller than induction motors, despite the presence of REE. The latter account for a tiny percentage of the overall motor weight, which is mainly dictated by laminated steel and copper.[47]

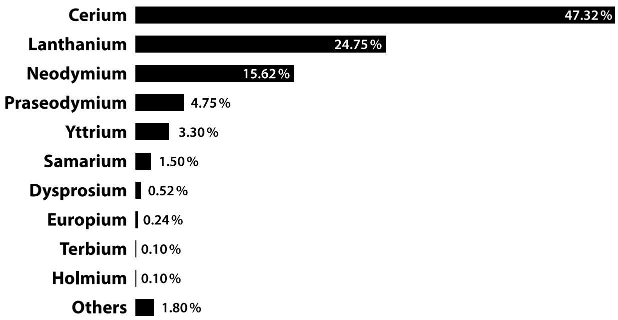

Figure 9. Production of rare earth oxides in 2017.[52]

REE are not rare on the Earth's crust, but they are rarely found at concentrations making extraction viable from the technical and economic point of view. Accordingly, rare earth mines are very few worldwide and prices are highly volatile. Dysprosium makes less than 1% of the global production of rare earth oxides, while neodymium is about 16% and is substantially cheaper (Figure 9).[48,49] This physical and economic constraint has prompted technological improvements leading to a decrease in the use of dysprosium by 50% (from about 120 to 60 g) in the average EV.[47] This allowed a stabilization of the global demand of dysprosium oxide, which is almost completely covered by China. In the years to come, a large expansion of the EV market is expected and, in spite of an enhanced efficiency in the use of dysprosium in permanent magnets, it is expected that its demand will increase to such an extent that China alone will no longer be able to cover it with legal production (illegal mining of REE in China is common).[47]A number of new mining projects of rare earths are under development in several countries, including Australia, Canada, Chile, Namibia and Greenland.[47] Therefore, a relieve on the supply of dysprosium and, more generally, of rare earth elements is expected, also in light of the increasing efforts aiming at recycling REE[41] and replacing the most rare ones in new magnet formulations.[50,51]

EFFICIENCY, ELECTRICITY, CONSUMPTION AND ENVIRONMENTAL IMPACT OF BATTERY ELECTRIC VEHICLES

Level 1 – Tank-to-wheel vs. battery-to-wheel and the overall electricity consumption of BEVs

The average consumption of a modern 150 hp car is around 6 liters of gasoline for 100 km, which corresponds to about 60 kWh in terms of thermal energy content of the fuel. An equally rated electric car (e.g., Nissan Leaf 2018) runs at least 250 km with its fully charged nominal 40 kWh Ni-Mn-Co lithium ion battery (actual: 38 kWh). In a nutshell, the energy consumption of the gasoline car is 0.60 kWh/km, i.e., four times higher than a BEV (0.15 kWh/km). If one considers losses due to battery charging and discharging (5-20%, depending on specific conditions of temperature, current intensity, etc.) a BEV is still over three times more efficient than an ICV of comparable power.

Assuming a yearly mileage of 15,000 km, a medium-size EV (0.15 kWh/km) consumes 2,250 kWh/y, i.e., less than the average EU household (3,500 kWh/y). It has been assessed that if 80% of EU cars were electric by 2050, the EU electricity demand would increase by only about 10%.[53] The desirable scenario of an overall decrease of the number of cars in the EU in the next decades would make electricity demand for personal car transportation nearly insignificant. Let us put these consumption numbers in a specific national context. In Italy there are 37 million cars, running an average 12,000 km/y. If they were all electric – assuming 0.18 kWh/km by including charging/discharging losses – they would require 80 TWh/y of electricity. Italy already produces over 110 TWh/y only by renewable sources (hydro, PV, wind, biomass, geothermal). Therefore, by increasing 70% only renewable electricity production with respect to current levels, all Italian cars could in principle be powered by renewables. The target is very ambitious but not unrealistic in a 20-year time window, particularly in the perspective of a very likely climate crisis that may foster drastic political decisions and, hopefully, bring about a more moderate use of individual transportation. It must be emphasized that a strong expansion of the EV market in the next 20 years would be fully sustainable in terms of electricity demand, but might find bottlenecks regarding the availability of critical materials such as cobalt (see above).

Level 2 – The influence of the electricity production mix on greenhouse gas (GHG) emissions of BEVs

This issue has been examined in many studies, and there is a general consensus that greenhouse gas emissions (primarily CO_2) associated with the use of BEVs are lower compared to ICVs, when the electricity production stage is factored in.[27] In Figure 10 are reported the results of a recent study where GHG emissions of gasoline and diesel cars vs. BEVs are thoroughly analyzed, in relation to the electricity mix of every EU country and taking into account upstream emissions (extraction, transport, refining of fossil fuels) and cross-border electricity trade among different countries.[54]

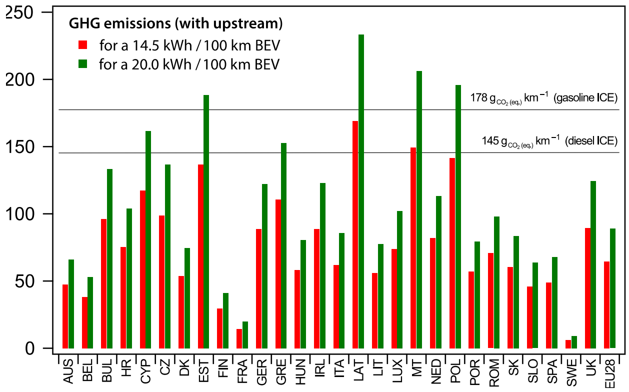

Figure 10. Greenhouse gas (GHG) emissions of electric vehicles in the countries of the European Union vs. gasoline and diesel cars, taking into account the electricity generation mix and cross-border electricity exchange.[54]

Small/Medium-size BEVs (14.5 kWh/ 100 km) entail a lower GHG emissions than gasoline ICVs in every EU country and perform worse vs. diesel only in two countries (Latvia and Malta) in which electricity production is strongly based on coal and oil (Malta is now switching to gas). On the other hand, the GHG emission of BEVs is much lower than ICVs in countries with a strongly decarbonized electricity portfolio such as Sweden, France, Finland, Austria and Denmark, which primarily rely on nuclear, hydro, wind and biomass. It is noteworthy the good performance of BEVs in Italy, a big exporting industrial economy with a renewable electricity production close to 40%.

It must be emphasized that all of these data can be considered a superior limit, as they do not take into account a simple fact. At least in this initial stage, BEV owners are typically more environmentally concerned than the average citizen and often feed their cars with self-produced PV electricity or sign contracts with utilities that sell renewable electricity packages. Such a bargaining power, which of course cannot be exerted at the gasoline pump with ICVs, can speed up the “greening” of the electric system in a bottom-up fashion.

Level 3 – Overall life-cycle assessment of battery electric vehicles

Assessing the environmental impact of BEVs over the entire lifecycle is a complex exercise that depends on several factors, such as the size of the vehicle considered, the electricity production mix, the location of the mineral resources for batteries and whether the comparison is made with diesel or gasoline cars. The European Environment Agency has recently released an excellent report on the state of the art in the field, where details on impacts assessed at the different stages of the industrial chain are reported: raw materials extraction, production, use, end-of-life.[27] The component that makes the biggest difference between BEVs and ICVs is of course the battery. It has been consistently reported that the extraction of battery materials has a substantial impact in terms of human, freshwater and terrestrial ecotoxicity, as well as freshwater eutrophication. In this domain, the comparison with ICVs may be presently unfavourable[55] and the single most important factor leading to this result is the use of electricity produced from fossil fuels in raw materials extraction and battery manufacturing.[27] Besides the use of renewable electricity at every stage of LIB production, use and disposal, other relevant factors that can improve the life-cycle environmental performance of BEVs vs. ICVs are (i) using them for at least 150,000 km and (ii) better transparency of car firms through the implementation of traceability protocols along the whole raw materials supply chain, so as to constantly monitor social and environmental impacts.

Finally, putting the BEV industrial supply chain in the context of circular economy is crucial for the end-of-life management.[27] To this end, legislations around the world must promote as much as possible the implementation of Extended Producer Responsibility (EPR) practices, which make product manufacturers responsible for the entire life-cycle of their products and especially for the take-back, recycling and final disposal. In the last decades, several governance mechanisms have been introduced on waste disposal and mineral recycling processes for electronics and batteries. Recycling practices related to BEVs are already and will continue to be shaped by these national and international regulations, which will become stricter as electric mobility will expand.[56]

The number of BEV to recycle is presently insignificant, but companies and legislators must be ready for the first wave of end-of-life BEVs which will occur in the 2020s.

CONCLUSION

After one century of undisputed dominance of the internal combustion engine, the road transportation sector is slowly undergoing an epochal transformation towards electric powertrains. This trend is dictated by two main factors: the quest for enhancing the energy efficiency of vehicles and the need of improving air quality in urban areas for the sake of public health. Another factor that may foster the market expansion of EVs is the supply and/or price of oil in the long term. At present, oil is cheap and plentiful,[57] but it is increasingly obtained from unconventional resources[58] (e.g., shale rocks, tar sands, conventional wells in extreme environments), which are characterized by stronger carbon footprints, heavy environmental impacts, questionable economic returns, poor energy return on energy invested (EROI).[59] On the other hand, the constant increase of renewable electricity production and the possibility to deploy vehicle fleets which are intrinsically less dissipative (batteries are far easier to recycle than CO_2) can ultimately be a major driver for the transformation of the car sector.

There is debate on which extent electrification will permeate the way of moving persons and goods in the next decades. In our opinion, BEV will be dominant for personal transportation (cars, SUVs, motorbikes, bikes) because the ubiquity of the recharging infrastructure (i.e., the electric grid) is a formidable asset versus potential competitors lacking an energy distribution base (e.g., hydrogen).[60] On the contrary, we believe that battery-based transportation will be far less relevant for trucks and buses, due to the huge material demand this would imply for manufacturing batteries. Since heavy duty vehicles are often collected in large parking lots and run more predictable routes, it is reasonable to expect that they may be preferentially electrified via fuel cells,[61] fed by hydrogen or liquid fuels produced in large centralized facilities. In this regard, it is needless to say that an even more rational solution for freight transport is shifting as much as possible to railways, which are largely existing and often underutilized in several countries.

Lithium ion battery is the key enabling technology for the development of road electric transportation, with a number of different chemistries now available for the cathode, but less practical solutions for the anode, beyond graphite materials. It can be reasonably expected that no practical alternatives to LIBs will be found in the next decade and perhaps even beyond, also because the huge ongoing investments in LIBs manufacturing make it harder for potential alternatives (e.g., lithium-sulphur, lithium-air or sodium/magnesium based batteries)[62] to become economically or technically competitive.[16] Unfortunately, the energy sector is afflicted by frequent claims of "revolutionary" inventions or discoveries, with scientists sometimes too bold in communicating results to the general public, without properly highlighting the limits of their work for commercially viable applications.[63]

The road transportation sector claims about 50% of the world oil supply and emits about 18% of global CO_2 emissions,[64] therefore the electrification of road vehicles is a key milestone of the global energy transition, because almost 30% of the world electricity supply is *already* generated by renewable WWS technologies (Water, Wind, Solar)[65] and will grow further in the years to come, due to massive investments worldwide, with China as leader.[66] However, in order to make this process truly beneficial for society, it is necessary that the global industrial supply chain of LIBs – all the way from raw materials extraction (concentrated in South America, Africa and Oceania) to battery manufacturing (primarily in China, Japan and South Korea) to usage (mainly in North America, Europe, China, Japan) – is made environmentally and economically sustainable.

Regarding physical availability of materials, cobalt represents a real risk, whereas lithium appears to be of lower concern. At any rate, integral recycling of LIBs at the industrial scale is becoming mandatory because it is presently projected that there will be 140 million EVs on the road by 2030 (10-15% of the global share), with 11 million tons of LIBs reaching their end-of-life service throughout the next decade.[67] The biggest obstacle in this direction is the fact that batteries are manufactured in several forms, sizes, and chemistries, hence a variety of disassembly/recycling protocols needs to be established, increasing technical and economic costs. Ultimately, failure in addressing the recycling issue could endanger the expansion itself of the BEV market, as availability of some virgin raw materials (particularly cobalt) could turn out to be an insurmountable physical limit, also in view of the rise of another potentially huge market such as backup battery packs for intermittent renewable technologies.

In principle, electric vehicles might be an integral part of smart electric grids, serving as two-way electricity dispatchers on demand (V2G, i.e., vehicle-to-grid concept)[68] thus helping to shelve peak demand. This approach has several pros and cons, for instance the car owner could make a profit of his/her "mobile storage system", but the lifetime of the battery would be negatively impacted. The rational of this idea is compelling: 97% of their lifetime vehicles are idle. However, an effective implementation of V2G require substantial advancements at the grid and battery level.

Presently, the car battery industry is focusing on three priorities to be fully competitive with traditional thermal cars: a price of 125 $/kWh for LIB packs,[16] higher energy densities (up to 500 Wh/L, pack level)[16] to extend driving ranges beyond 500 km, and the consolidation of fast charging networks. A relevant issue to address is the modernization of the commercial network of car companies, which is unprepared (if not unwilling) to offer electric models to customers.[69]

It must be emphasized that the final objective of the electric revolution should not be the replication of the presently inefficient and unsustainable system heavily based on individual mobility, with an increasing urban population trapped in traffic jams, albeit "electric". The great transition to be possibly accomplished within the next 30 years primarily concerns the development of public, mass, light and smart transportation, which entails buses/metros, railways, bike lanes, shared mobility, autonomous driving. The desirable expansion of the BEV market is only one of the ingredients to achieve a radical change of the transportation system towards new, rational and resource efficient paradigms that make cities designed for people and not for automobiles.

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