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Electric vehicles: solution or new problem?

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Abstract Since electric vehicles (EVs) have been recognized as a technology that reduces local air pollution while improving transport energy security, they have been promoted in many countries. Yet, mainly due to their high costs, especially in the case of pure battery electric vehicles, and a lack of proper infrastructure, the use of EVs is still very limited. In this paper, some of the major barriers and the future challenges are discussed. The current problems are mainly attributed to two categories: (1) the battery performances and costs, as well as battery production including issue of material availability and (2) environmental benefits of EVs depending on the sources used for the electricity generation and their carbon intensity. The major conclusions are that (1) research and development with respect to batteries has by far the highest priority and (2) it has to be ensured that the electricity used in EVs is generated largely from renewable energy sources.

Keywords Battery · Costs · Emissions · Lithium

1 Introduction

Currently, the transport sector is responsible for about one quarter of the total greenhouse gas (GHG) emissions and about 33% of the final energy consumption in the EU-28 (SPB 2016). Due to the increasing GHG emissions and local air pollution, interest in electrification of mobility is rapidly growing.

Because of their zero emissions at the point of use, battery electric vehicles are considered as an environmentally friendly technology. They can significantly contribute to the reduction in local air pollution and possibly also to reduction in GHG emissions in the transport sector. In addition, an increase in energy supply security reducing the dependency from the imported fossil fuels could result from a switch to electric vehicles. Due to

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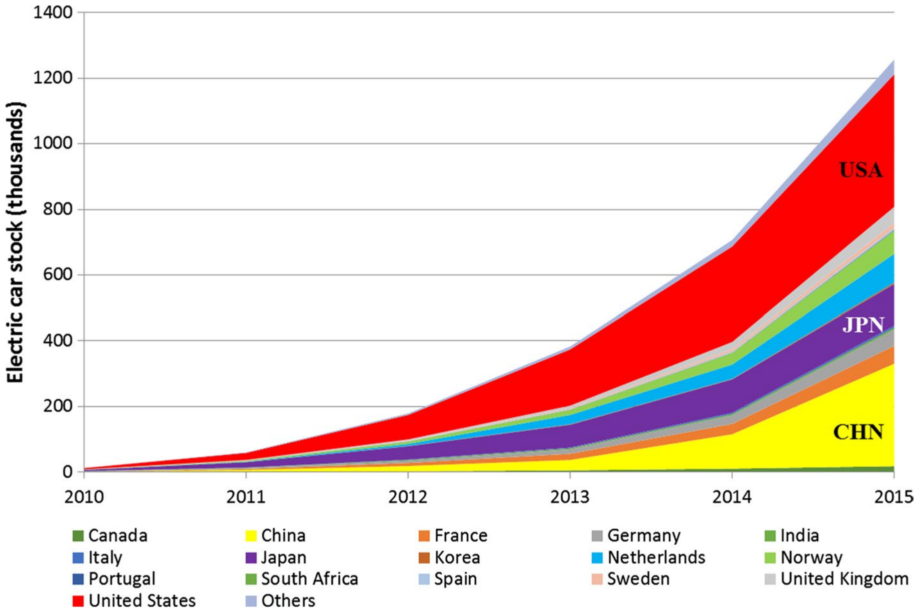

Fig. 1 Development of the global stock of rechargeable EVs. (Data source: IEA 2016)

different kinds of supporting policies and measures implemented in many countries worldwide, the number of electric vehicles is continuously increasing; see Fig. 1. However, the share of EVs in total vehicle stock is just about 0.1%. The market share of EVs is highest in Norway and the Netherlands, 23% and nearly 10%, respectively (IEA 2016).

The major reasons for the slow penetration of EVs are high purchase prices, limited driving range and longer charging time compared to conventional cars, as well as insufficient charging infrastructure. Yet, significant improvements, especially with respect to batteries, have been achieved over the last decade so that the future market penetration of EVs could be accelerated (IEA 2016). According to the Paris Declaration on Electro-Mobility and Climate Change and Call to Action, the goal is to have worldwide more than 100 million EVs and 400 million two and three-wheelers by 2030 (PD 2015).

However, an increasing electrification of mobility needs first a sound analysis on how environmentally benign and sustainable electric vehicles really are. This requires a comprehensive analysis of their environmental benefits in the whole energy supply chain as well as an investigation on the long-term availability of materials (e.g., lithium) needed for the production of electric vehicle batteries. The increasing use of lithium in batteries for EVs has already raised concerns about future lithium supply and availability. There are speculations that the dependence on the OPEC oil cartel will be replaced by a new lithium cartel based in South America, where most lithium resources are concentrated. The appropriate recycling of lithium-ion batteries could mitigate this problem. However, their recycling is complicated, energy intensive and not yet established (Gaines 2014).

The core objective of this paper is to analyze these issues and to provide a sound assessment of whether EVs contribute significantly to reducing GHG emissions or whether rather new problems are created. Actually, the major problems are related either to the battery or to the way electricity is generated. Regarding the battery, two categories of problems are relevant: operations dynamic performance and production of battery.

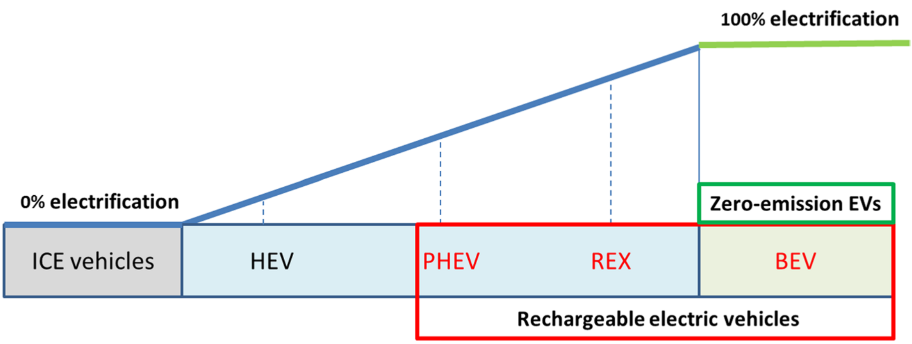

Fig. 2 Level of electrification of electric vehicles. (Reproduced with permission from Ajanovic and Haas 2016)

2 Impact of battery on mobility costs

In spite of supporting policies implemented worldwide, the number of EVs is still very low due to few obstacles. The major one are high costs of EVs, which are dependent on EVs type, as well as car- and battery size.

Different types of EVs—Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV), Plug-In Hybrid Electric Vehicles (PHEV), Range Extenders Electric Vehicles (REX)—with different levels of electrification are analyzed in this paper; see Fig. 2. Fuel cell electric vehicles (FCV) powered by hydrogen, which are specific type of EVs, are not considered in this paper. Due to their high costs and requirements for new infrastructure, they could be of interest in the long term. A comprehensive description of different types of electric vehicles including FCV is provided by Ajanovic (2015).

Although HEV are currently mostly used, due to similarity to conventional internal combustion engine (ICE) vehicles, their contribution to the reduction in environmental problems is very limited. For the future, of the special interest are rechargeable EVs—PHEV, REX and BEV—that have the higher level of electrification. This means that these vehicles have the longer electric driving range but also larger batteries and higher costs. Particularly important are BEVs while they have zero emissions at the point of use. Due to this characteristic, they could contribute significantly to the reduction in the local air pollution. This issue is of very relevant for polluted urban areas (e.g., Beijing and Shanghai).

To increase the cost competitiveness of EVs in comparison with conventional ICE vehicles is very important to accelerate their market penetration. Economic assessment of EVs is pretty good documented in the literature (e.g., McKinsey & Company 2011; Tseng et al. 2013; Plötz et al. 2013; Ajanovic and Haas 2015). Basic cost structure of the mobility with different types of EVs in comparison with conventional gasoline and diesel vehicles is shown in Fig. 3. These costs are dependent on vehicles kilometers driven per year that could be different from region to region. For example, average annual mileage in Austria is approximately 15,000 km, and in the City of Vienna ca. 7000 km (Jellinek 2015). Similar data are documented also for the EU countries (ACEA 2017). In this paper is assumed that due to limited driving range and charging infrastructure, BEVs are currently used mostly in cities for short distances (8000 km per year). For hybrid and conventional cars, the higher number of specific kilometers driven is taken into account, up to 15,000 km per year.

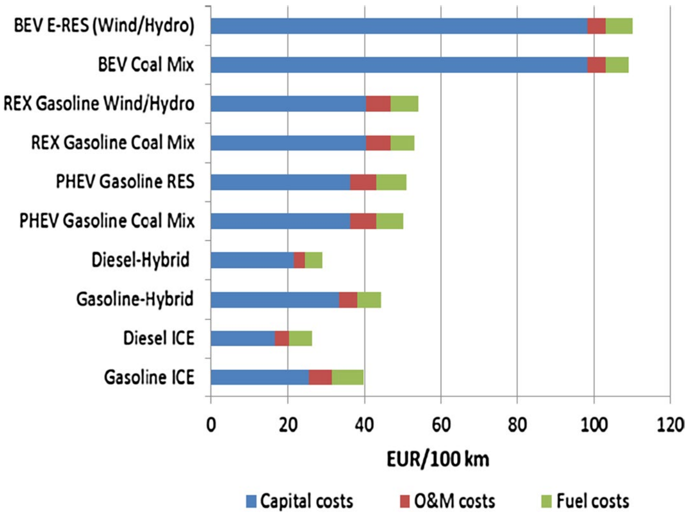

Fig. 3 Mobility costs of electric vehicles (car size 80 kW)

Total mobility costs (TMC) are dependent on vehicle costs (VC), capital recovery factor (α), the specific number of vehicle kilometers (vkm) driven per year, fuel/energy price (P), fuel/energy intensity of cars (FI) per kilometer driven, and operating and maintenance costs ($C_{\text{o\&m}}$) which are calculated as average over total kilometers driven. They are calculated as:

$$\text{TMC} = \frac{\text{VC} \cdot \alpha}{\text{vkm}} + P \cdot \text{FI} + \frac{C_{\text{o\&m}}}{\text{vkm}}$$

Vehicle costs are very dependent on the car size as well as capacity of the battery used inside (Ajanovic 2015). The majority of battery electric vehicles have batteries with capacity between 22 and 60 kWh. However, there are also examples with higher (e.g., Tesla Model S up to 100 kWh, BYD e6 up to 82 kWh) or lower (e.g., Renault Twizy 6 kWh) battery capacity.

Battery capacity used in PHEVs is much lower, mostly between 4.5 and 10 kWh. In HEVs, mostly used batteries have capacity between 1.3 and 1.6 kWh; see Fig. 4.

To make EVs more competitive with conventional cars, EV manufactures are offering EVs in different car-size categories. However, with the increased power delivered by battery packs[1] comes to a corresponding increase in battery weight.

The battery capacity is related to the electric driving range of EVs. The total energy of the pack is always higher than usable energy. The oversized battery should be able to meet power requirements, to reduce safety risks, maximize the battery life as well as to deliver same driving range during the whole lifetime. A new battery is typically charged to 80% and discharged to 30%. As the battery fades, the bandwidth may expand to keep the same driving range; see Fig. 5. Once the full capacity range is needed, the entire cycle is applied.

[1] A battery pack is a set of batteries or individual battery cells. This term is usually used in reference to EVs. Note that a cell is a single unit that converts chemical energy into electrical energy, and a battery is a collection of cells.

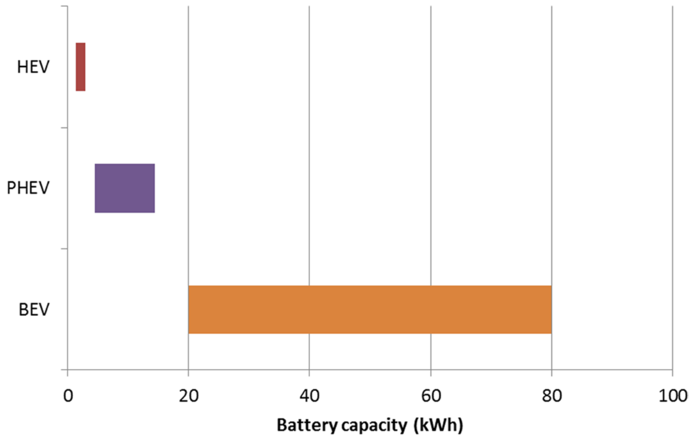

Fig. 4 Battery capacity for different types of EVs

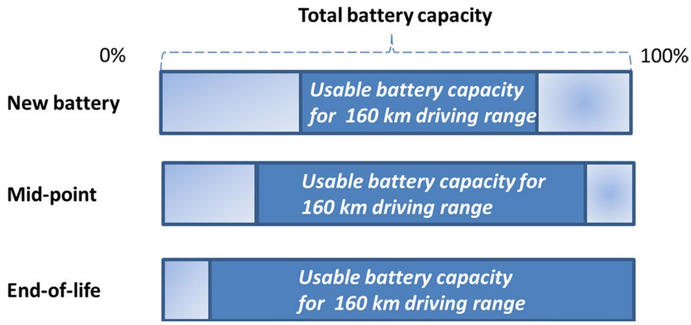

Fig. 5 Driving range as a function of battery capacity. (Data source: BU 2016)

This will cause stress and accelerate the aging of the battery as well as shorten the driving ranges considerably (BU 2016).

The difference between physical and used battery capacity is illustrated in Fig. 5. For example, to have 23 kWh usable energy with which about 160 km range could be delivered, total battery energy must be 29 kWh.

As described above the total mobility costs are dependent on the capital recovery factor (α), which is further dependent on the interest rate and depreciation of vehicles as well as battery.

Regarding the battery, it is important to state that there is a difference between 'calendar life' and 'cycle life'. Even if it is not used, a battery cell aged over time results in capacity loss. Overall age is the number of years a battery can be expected to remain useful. Most EV batteries have guaranteed 'calendar life' for 8–10 years or 160,000 km (BU 2016). However, the current battery lifetime is determined under test conditions, and the aging process can be accelerated by different climates and usage patterns.

Battery lifetime is also dependent on battery use, especially the number of charge/discharge cycles. Cycle stability is the number of times a battery can be fully charged and discharged before being degraded to 80% of its original capacity (Reid/Julve 2016). Typically, when used in cars, the end of battery life is defined as the point when the battery capacity is lower than or equal to 80% of its original capacity.

Cycle life has often a strong relationship with depth of discharge (DOD)—the deeper the DOD, the shorter the cycle life. A typical DOD window is 80% for BEV packs and 70% for PHEV (Cluzel and Douglas 2012). To extend lifetime of a battery, EV manufactures oversize the battery pack with the goal to avoid a full DOD window of the pack and to overcome expected degradation.

Battery life is critical for the economics of EVs both in terms of total cost of ownership but also in terms of the environmental impact (Cluzel and Douglas 2012; Notter et al. 2010). Both would be significantly affected in the case of battery replacement before the vehicle end of life.

In the future with the expected increasing energy density of batteries (see IEA 2016), as well as broader availability of charging infrastructure (including also possibilities for fast charging), the number of specific kilometers driven of EVs could be much higher, making BEVs more attractive and more cost-competitive with conventional cars.

As can be seen clearly from Fig. 3 total mobility costs are dominated by capital costs of vehicles. In the case of BEV, these costs are largely determined by costs of battery. Share of battery costs in total car price is approximately between 25 and 55%. As documented by Nykvist and Nilsson (2015) battery costs have significantly decreased over the last few years, from about 1300 US$/kWh in 2006 to about 420 US$/kWh in 2014. However, further decrease of battery costs is necessary to make EVs cost-competitive with conventional cars.

3 Features of different types of batteries

The battery is an essential part of electric vehicles. Battery electric vehicles are powered by a high-voltage, deep-cycle electric vehicle battery. Electric vehicle batteries are characterized by their relatively high power-to-weight ratio (in comparison to starter battery[2]), energy-to-weight ratio and energy density. However, EVs usually have also a basic starter battery, which allows use of standard automotive accessories which are designed to run on 12 V. This battery is not designed for deep discharge, and a full discharge can reduce the battery's lifespan (Johnson 2016). Such batteries are used also in ICE vehicles with the main purpose to start the engine. Usually they are lead–acid type, but in some vehicles, a lithium-ion battery is used as an option to save weight (Wert 2009).

In order to increase consumer acceptance and stimulate the introduction of EVs, it is essential that batteries meet certain performance requirements. The most important battery performances are storage capacity (kWh), specific energy (Wh/kg), specific power (W/kg), calendar and cycle life, self-discharge rate (%), conversion efficiency (%), and safety.

Most of the battery performances are dependent on the type of battery used. Mostly used rechargeable batteries in EVs are lead–acid (Pb–acid), nickel metal hydride (NiMH), molten salt battery (NaAICI4) and lithium-ion.

The major properties of different types of rechargeable batteries are shown in Table 1. Every type of battery has some advantages and disadvantages.

[2] The starter battery is nearly always lead–acid battery.

Table 1 Major properties of different types of rechargeable batteries. (Reproduced with permission from EUROBAT et al. 2014; Gondelach 2010; Cluzel and Douglas 2012)

	Lead-based	NiMH	NaNiCI2	Li-ion
Power density (W/kg)	180–500	150–1200	180	300–1800
Energy density (Wh/kg)	30–50	30–80	120–125	70–125
Energy density (Wh/L)	60–120	50–300	185–300	85–275
Self-discharge rate (% per month)	~3	~15–20	No self-discharge at cell level	~2–5
Optimal ambient *T* range (°C)	0 to +40	−10 to +45	−40 to +60 at battery level	−10 to +25
Operating ambient *T* range (°C)	−30 to +75	−10 to +45	270–350 at cell level	−10 to +55
Max operational lifetime (years)	3–8	8–10 (for HEV and active cooling)		~10
Number of cycles	500–4500	1350–2000	1000	1000–3500
Cost (EUR/kWh)	50–270	400–1400	500–700	300–1200
Energy efficiency (%)	70–82	60–70	92.5	80–90

Lead–acid batteries are the oldest type of rechargeable battery. These batteries can be used as automobile engine starter batteries as well as deep-cycle batteries. However, no lead acid battery should be discharged below 50% of its capacity, as it shortens the battery's lifetime (Barre 1997). Some early electric vehicles have used lead–acid batteries due to their mature technology, high availability, and low cost. However, like all batteries, they have significantly lower energy density than liquid fuels, 30–50 Wh/kg and efficiency between 70 and 82%. They have very low energy-to-weight and energy-to-volume ratio what mean that lead acid batteries take up significant amounts of space within vehicles and add significant amounts of weight. Due to these characteristics as well as a shorter life than the vehicle itself, typically needing replacement every 3 years (Morad et al. 2016), lead–acid batteries have small portion in the final electric vehicle stock.

Nickel–metal hydride batteries (NiMH) are considered as a relatively mature technology. Compared to lead–acid batteries, they have lower efficiency (60–70%) in charging and discharging, but they have higher energy density, 30–80 Wh/kg. Major weaknesses of these batteries are poor efficiency, high self-discharge and poor performance in cold weather. Their advantage is long life, about 160,000 km, when used properly. NiMH batteries have proved good performances when used in hybrids vehicles (Kalhammer et al. 2007; Shiau et al. 2009). This battery is mostly used in PHEV. However, their relatively low energy density (Wh/L) and specific energy (Wh/kg) imply large, heavy batteries for extended electric travel. Applications include hybrid vehicles such as the Toyota Prius, the Toyota RAV4-EV all-electric plug-in electric car, and consumer electronics.

The sodium nickel chloride (NaNiCl), or so-called zebra battery, is a relatively mature technology. The major advantages of this battery are the following: It has a good energy density of about 120 Wh/kg, can last for a few thousand charge cycles, and is nontoxic. Major weakness is poor power density and the requirement to heat battery for use. The normal operating temperature of these batteries is in the range between 270 and 350 °C, and this can lead to the problems with thermal management and safety. Moreover, there are also significant thermal losses when the battery is not in use.

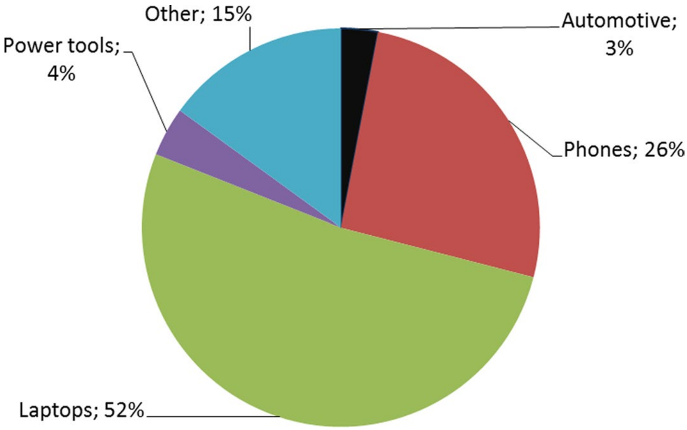

Fig. 6 Applications of rechargeable lithium-ion cells. (Data source: Avicenne 2011)

Currently, EVs rely predominately on lithium-ion batteries, although their maturity is moderate. This battery has a relatively high energy density, usually between 70 and 125 Wh/kg, good power density, and 80–90% charge/discharge efficiency.

The weaknesses of traditional lithium-ion batteries include short cycle lives (hundreds to a few thousand charge cycles) and significant degradation with age. Moreover, traditional lithium-ion batteries can pose a fire safety risk if punctured or charged improperly and heaters can be necessary in some climates to warm them (Mikolajczak et al. 2011). This battery has also high costs.

Lithium-ion batteries have widespread use in consumer electronics (e.g., mobile phones), and their use in transport applications (e.g., the Tesla Roadster electric car and in Prius conversions to a plug-in hybrid) is recent; see Fig. 6.

Lithium batteries have been already evaluated as a good option especially for PHEVs and BEVs (Axsen et al. 2008; Burke 2007; Kalhammer et al. 2007; Karden et al. 2007; Shiau et al. 2009; BCG 2010). The mostly used lithium battery technologies for automotive applications are lithium–nickel–cobalt–aluminum (NCA), lithium–nickel–manganese–cobalt (NMC), lithium–manganese spinel (LMO), lithium titanate (LTO), and lithium–iron phosphate (LFP). Each of these combinations has different characteristics regarding performance (peak power at low temperature, state-of-charge measurement, and thermal management), cost, safety, specific energy and power, as well as lifetime (see Fig. 7).

Currently, no single technology is perfect in all six dimensions. All existing lithium-ion chemistries have some pros and cons. Therefore, it is needed to find compromises with regard to battery characteristics, costs and safety. Yet, safety is an absolute condition for commercialization. This means that safety enhancements may even demand sacrifices in battery performance and cost (Gerssen-Gondelach and Faaij 2012; ARPA-E 2009; Anderman 2010).

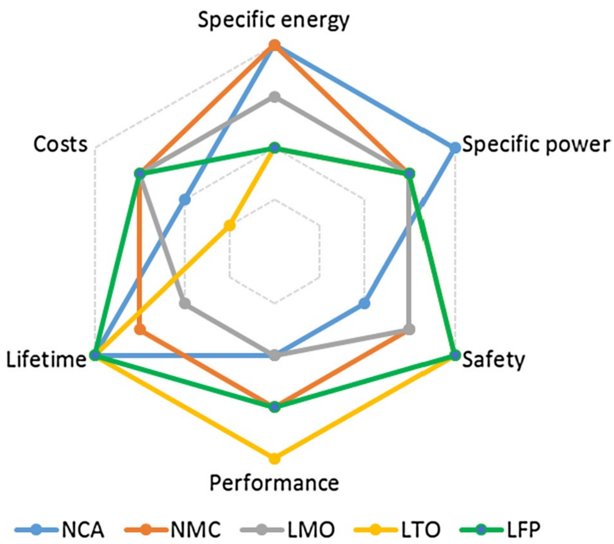

Fig. 7 Trade-offs between the five principal lithium-ion battery technologies. (Data source: BCG 2010)

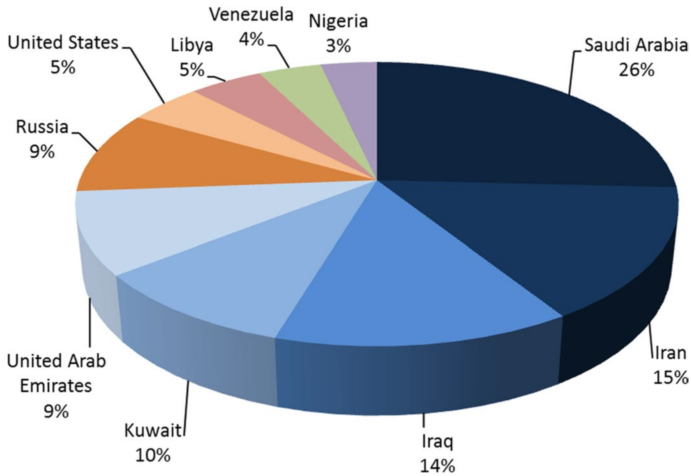

Fig. 8 Countries with largest conventional oil reserves. (Data source: Statista 2017a)

4 Supply security: oil versus lithium

The transport sector, especial road transport, is currently almost completely based on fossil fuels, namely gasoline and diesel. Huge dependency on imported fossil fuel is one of the negative aspects of our transport system. The largest quantities of petroleum are located in just a few world's regions. The largest amount is in the Middle East, about 74%; see Fig. 8.

With electrification, energy diversification in the transport sector could be significantly increased and energy import dependency from the few oil-producing countries reduced.

However, an increasing use of EVs raises some new questions. One is regarding availability of materials needed for battery production. As stated above, currently, in EVs most

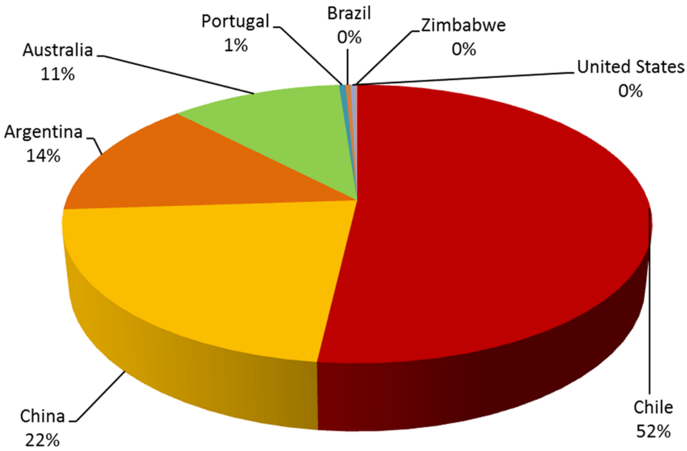

Fig. 9 World lithium reserves by country. (Data source: Statista 2017b)

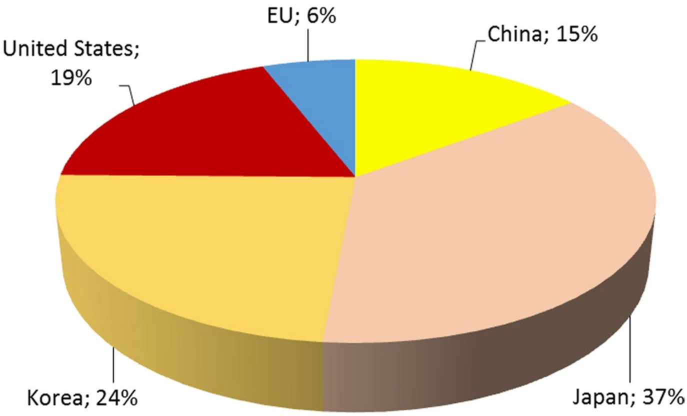

Fig. 10 Share of production of lithium-ion batteries in 2014. (Data source: CEMAC 2016)

common batteries are lithium-ion batteries. The fundamental material for their production is lithium. Most lithium reserves are located in South American countries, about 66%, followed by China (22%) and Australia (11%); see Fig. 9.

However, the production of lithium-ion batteries is largely located in Asia (76%), USA (19%) and the EU (6%), see Fig. 10.

This fact leads to thoughts that with the increasing demand for lithium, dependency on imported oil from Middle East could be replaced by dependency on lithium from South America. Lithium supply could become a new problem, depending on monopolistic behavior and geopolitical relations (Angerer 2009). In addition, its availability is influenced also by demand from other sectors (Tahil 2007).

In fact, the amount of lithium used in batteries is relatively small, about 0.15 kg/kWh. For a typical EV battery capacity (25 kWh), the percentage of lithium used in the total battery mass is between 1.2 and 2.4%. It is obvious that for a battery pack, a significant amount of additional materials is needed, such as nickel, cobalt, aluminum, manganese. Projections on material availability for EV batteries are shown in Table 2. In the third

Table 2 Demand for raw materials versus world reserves. (*Sources*: Gondelach 2010; Angerer 2009; Andersson and Rade 2001; Gaines and Nelson 2010; U.S. Geological Survey 2010)

Li-ion battery	Demand (kg/kWh)	Demand for 1.6 billion EVs (1000 tons)	World reserves (1000 tons)	World reserve base (1000 tons)
Lithium	0.15	6000	9900	11,000
Nickel	1.2	48,000	71,000	150,000
Cobalt	1.2	48,000	6600	13,000
Manganese	1.2	48,000	540	5,200,000
Phosphate	0.8	32,000	16,000	n/a
Aluminum	0.04	1600	n/a	n/a
Iron/steel	0.4	16,000	77,000	n/a

column, the demand of material for the production of 1.6 billion EVs is documented. Note that these are alternative numbers and do not add up.

According to the IEA[3] scenario in which IPCC[4] CO_2 reduction goals should be met, the cumulative amount of rechargeable electric vehicles produced by 2050 would be 1.6 billion (Gaines and Nelson 2010). Assuming all EVs would have a typical battery capacity of 25 kWh, and all batteries are expected to contain the same chemistry, the total material demand until 2050 is shown in Table 1 (Gondelach 2010). Although the world reserves of lithium are big enough for the future demand, there could be a shortage of some other materials.

As discussed Gondelach (2010), if all lithium batteries were based on cobalt, manganese or phosphate, material availability would be a significant problem. The reserves of these materials would not be able to meet the demand. On the other hand, their world reserve base is stated to be very high (Gaines and Nelson 2010).

However, it is not likely that all batteries will be based on the same structure of materials. But, as stressed in the literature, due to increasing demand for the various materials, to ensure their future availability, recycling will be necessary (Angerer 2009; Gaines and Nelson 2010). For example, using recovered cobalt and nickel for lithium battery results in a 51% saving of natural resources (Dewulf et al. 2010).

Due to the EC directive 91/157/EEC, in the EU, a very good system for collecting and recycling of lead acid batteries has already been established (EC 1991). Recycling rates are estimated to be more than 90%. However, unlike lead-based batteries, lithium batteries do not present significant environmental concerns beyond fire safety and landfill utilization. There is some concern with nickel metal hydride batteries commonly used in current generation of hybrids, but these batteries are highly recyclable (Duleep et al. 2011). We can assume that the new lithium battery technology will have similar collection and disposal procedures as well as similarly high levels of recycling. There are already some companies working on the recycling of the lithium batteries coming primarily from portable electronics equipment (Duleep et al. 2011).

[3] International Energy Agency.

[4] Intergovernmental Panel on Climate Change.

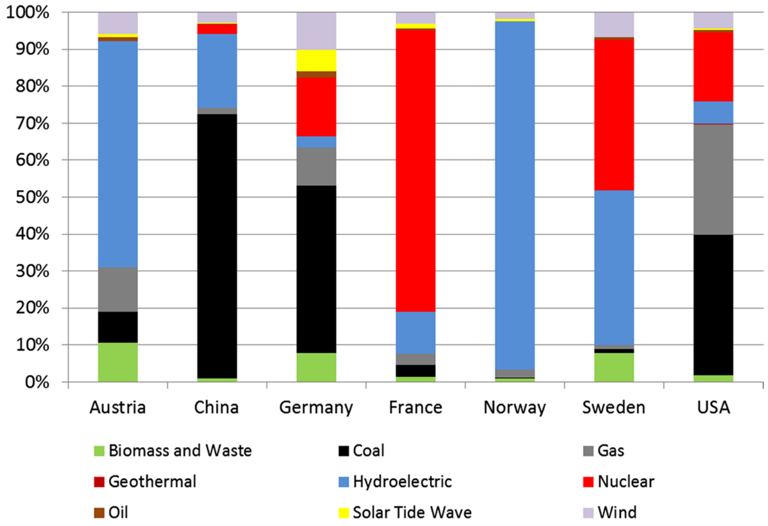

Fig. 11 Energy mix in 2014 by country. (Data source: TSP 2014)

However, current battery recycling methods are energy intensive. Emissions after treatment and transportation/handling costs are also high. Industry claims that approximate cost for battery recycling is \$1000 to \$2000 per ton (Duleep et al. 2011). This mean that the metal recovery alone cannot pay for recycling costs. Due to this, in some regions, subsidy in the form of tax is added to each manufactured cell. Some battery types, such as lead and nickel-based batteries, are nearly profitable from metal recovery, so subsidies are minimal. The lithium battery receives among the highest subsidies since the cells generally contain little retrievable metal (Duleep et al. 2011).

5 Environmental issues

To assess full environmental impact of different types of automotive technologies, we need to consider all emissions that occur in the whole energy supply chain.

Total GHG emissions of vehicles are very dependent on energy used in cars. The total carbon intensity of grid electricity is dependent on the emissions caused during fuel upstream production, fuel combustion at power plants, and the electricity losses in transmission and distribution. It can be very different from country to country depending on energy mix used in electricity production. Energy mix is very different across the countries; see Fig. 11. For example, energy mix in Norway encompass huge amount of renewable energy sources (RES), and energy mix in China is dominated by coal.

If the same type of BEV is charged by electricity mix in different countries, total CO_2 emissions per kilometer driven are very different; see Fig. 12. It is obvious that in countries with high use of RES, EVs could significantly reduce GHG emissions. In some countries (e.g., China), EVs could contribute just to the reduction in the local air pollution.

In the EU's Energy and Climate Change Packages for 2020 and 2030 increasing use of RES in electricity generation is one of the three major targets. Increasing share of RES in electricity mix makes EVs more environmentally friendly and therefore more attractive.

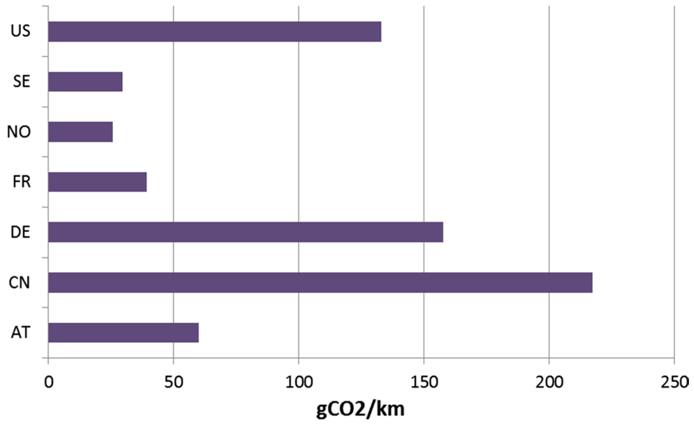

Fig. 12 Total emissions of the same BEV in different countries

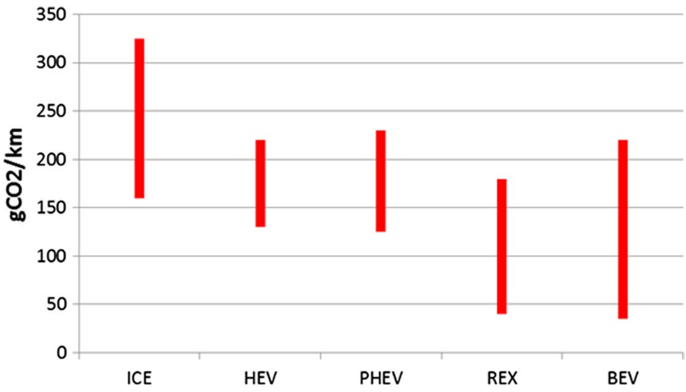

Fig. 13 CO_2 emissions per km driven for various types of EV in comparison with conventional cars

Depending on assumption regarding car- and battery size as well as the number of specific kilometers driven per year, total emissions could be different. The range from different analyses (Ajanovic 2015; Helms et al. 2010; Lucas et al. 2012; Ma et al. 2012; Patterson et al. 2011; Samaras and Meisterling 2008; Zamel and Li 2006; Odeh et al. 2013) is shown in Fig. 13. In spite of a broad range, it is obvious that EVs, especially BEVs, could contribute to the reduction in GHG emissions from the transport sector, especially in countries with higher share of RES in electricity generation.

6 Conclusions

The crucial aspect for the future penetration of EVs is the development of the battery performances, as well as the reduction in their costs. Although battery performances have been significantly improved, further efforts are still necessary to increase their lifetime and the number of charge/discharge cycles as well as the usable battery capacity over the whole life span of the battery.

With respect to the costs, remarkable reductions have been already achieved over the last decade, and for the next years, further cost cuts are very likely, mainly, because of increasing demand for EVs and more intensified competition between battery manufacturers. However, it is still not clear whether in the future different types of batteries will compete with each other or whether finally only one type will turn out to be most favorable.

Another important issue currently discussed is the availability of materials for electric vehicles production. It could happen that due to the switch from gasoline and diesel cars to EVs we will change the dependency from oil-producing countries to lithium producing countries, which are mainly concentrated in South America. However, with the increasing demand for EVs we are convinced that new and cheaper technological solutions will emerge in the future, mainly due to competition.

Electric vehicles could contribute to the reduction in some problems in the transport sector, especially to the reduction in local air pollution. However, their contribution to the reduction in GHG emissions is very dependent on the electricity mix used in EVs. Electric vehicles could bring about environmental benefits only in countries with a very high share of RES in electricity generation.

One of the largest challenges for the future will be to provide clean carbon-free sources for electricity generation. While this is a minor problem in countries with large shares of renewables as Norway, Austria or Sweden, in most other countries which largely use coal for electricity generation (e.g., China, Turkey, Greece), it may cause a severe barrier. Currently, in many countries, the CO_2 emissions per kWh of electricity generated are very high, leading to the effect that virtually no reduction in GHG emissions is brought about by EVs. Future policy designs should ensure high environmental benefits of EVs. Hence, it has to be ensured that either all electricity generated additionally comes from renewable sources or that certified green electricity is used in the EVs.

Finally, not all current problems in the transport sector can be solved merely by switching to new automotive technologies. We need also new mobility behavior.

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