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# "Electric vehicle battery second life applications in stationary storage – feasibility analysis in Europe"

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# ABSTRACT

The current environmental and social challenges in transport and energy sectors imply the radical transformation towards the use of clean technologies. Electric mobility has been regarded as the most promising solution to decarbonise transport. At the same time, in order to increase the renewable energy use, new technologies to store the intermittent renewable energy are needed urgently.

With a rapid uptake of electric powertrains, the vast and continuously increasing amount of used batteries will reach their end of life in the coming decades. These batteries could be either recycled or re-used for other purposes.

This master thesis aimed at evaluating the feasibility for the electric vehicle batteries to be further used in stationary energy storage applications after they have become unsuitable for their use in the electric vehicle, so-called battery "second life" concept.

A literature and desk review reveals that political and social environments encourage the second life concept; environmental benefits and technological feasibility aspects are still unclear and heavily depend on further research results; however, economical and legal aspects are currently the blocking factors for second life to become a reality for large scale deployment.

Value proposition and profitability were considered as the main deciding factors for the second life concept feasibility. Driven by the public actor, the value added of the second life battery could be measured in terms of potentially generating environmental benefits which are however demonstrated only under certain conditions and assumptions. Nevertheless, the concept of second life batteries will most probably not be further brought to large scale markets due to marginal potential economic benefits and the complex business environment.

Since the recycling is the only alternative for second life, it represents the main competition for the second life. In this regard the calculation was made for the amount of raw materials embedded in the batteries at the end of their first use in the electric vehicles.

It was forecasted that almost three million electric vehicles will be sold in Europe by 2020, which correspond to an accumulated battery capacity of 77.5 GWh to be potentially available for second use in 2030 (after 10 years of service in first life). These batteries, if recycled, could represent up to 60% of metal needs for the new car batteries in 2030. Moreover, the value of metals embedded in the electric vehicle battery in 2015 could rise by 60% in 2025.

*Keywords:* second life batteries, electric mobility, renewable energy storage, battery recycling, lithium-ion.

# L'ABSTRACT

Les défis environnementaux et sociaux actuels dans les secteurs des transports et de l'énergie impliquent une transformation radicale vers l'utilisation des technologies propres. La mobilité électrique est considérée comme la solution la plus prometteuse pour la dé-carbonisation des transports. Parallèlement, pour accroître l'utilisation des énergies renouvelables, il est urgent de mettre au point de nouvelles technologies permettant de stocker les énergies renouvelables intermittentes.

Avec l'adoption rapide des motopropulseurs électriques, la quantité croissante de batteries usagées atteindra leur fin de vie au cours des prochaines décennies. Ces batteries pourraient être recyclées ou réutilisées à d'autres fins.

Cette thèse vise à évaluer la faisabilité pour les batteries de véhicules électriques usagées d'être encore utilisées dans des applications de stockage d'énergie stationnaire après qu'elles soient devenues impropres à l'utilisation dans le véhicule électrique - le concept de "seconde vie".

La revue de la littérature et la recherche documentaire révèle que les environnements politiques et sociaux encouragent le concept de seconde vie; les avantages environnementaux et les aspects de faisabilité technologique ne sont toujours pas évidents et dépendent fortement de résultats de recherche supplémentaires; cependant, les aspects économiques et juridiques sont actuellement les facteurs de blocage pour que la seconde vie devienne une réalité pour un déploiement à grande échelle.

La proposition de valeur et la rentabilité ont été considérées comme les principaux facteurs décisifs pour la faisabilité du concept de seconde vie. Sous l'impulsion de l'acteur public, la valeur ajoutée de la batterie de seconde vie pourrait être mesurée en termes d'avantages potentiels pour l'environnement, lesquels ne sont toutefois démontrés que sous certaines conditions. Néanmoins, le concept de batteries de seconde vie ne sera probablement plus appliqué aux marchés de grande envergure en raison des avantages économiques potentiels marginaux et de la complexité de l'environnement économique.

Le recyclage étant la seule alternative à la seconde vie, est le principal concurrent de la seconde vie. A cet égard, le calcul a été effectué pour estimer la quantité de matières premières incorporées dans les batteries à la fin de leur utilisation dans les véhicules électriques.

Selon les prévisions, près de trois millions de véhicules électriques seront vendus en Europe d'ici 2020, ce qui correspond à une capacité de batterie cumulée de 77,5 GWh potentiellement disponible pour une deuxième utilisation en 2030 (après 10 ans de service dans la première vie). Ces batteries, si elles étaient recyclées, pourraient représenter jusqu'à 60% des besoins en métal des nouvelles batteries de voiture en 2030. En outre, la valeur des métaux incorporés dans la batterie du véhicule électrique en 2015 pourrait augmenter de 60% en 2025.

*Mots-clés:* batteries de seconde vie, mobilité électrique, stockage d'énergie renouvelable, recyclage de batteries, lithium-ion.

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**BEV –** battery electric vehicle

**EV** - electric vehicle

**GWP** - Global Warming Potential

**HEV** - hybrid electric vehicle

**ICE** - internal combustion engine

**ICT** - Information Communication Technologies

**JRC** - Joint Research Center

**kg** - kilogram

**LCA** - Life-cycle assessment

**LCO** - lithium cobalt oxide

**LCOS** - levelized cost of storage

**LFP** - lithium iron phosphate

**Li-ion** - lithium ion

**LMO** - lithium manganese oxide

**LTO** - lithium titanate

**NCA** - lithium nickel cobalt aluminium oxide

**NMC** - lithium nickel manganese oxide

**NO2** - nitrogen dioxide

**OEM** - original equipment manufacturer

**PESTEL analysis** - Political, Economic, Social, Technological, Environmental, Legal factor analysis

**PHEV** - plug-in hybrid electric vehicle

**PM**- particle matter

**PV** - photovoltaics

**R&I –** research and innovation

**SET Plan** - Integrated Strategic Energy Technology Plan

**SOx** - sulphur oxides

**T/MT** - tonne, mega tonne

**UK** - United Kingdom

**US** - United States

**Wh/kWh/MWh/GWh** - watt-hour, kilo-/mega-/giga watt-hour

# INTRODUCTION

Transport accounts for about 25% of all greenhouse gas emissions in Europe, and road sector is responsible for about 70% of this pollution.[1] The current dependence of transport modes on internal combustion engines (ICEs) based on fossil fuels creates severe problems for society and the environment. Transport reliance on ICEs notably contributes to the poor air quality in many European countries. Around 90% of people living in European cities are exposed to pollutants at concentrations higher than the levels reasoned harmful to health: according to the European Environment Agency, more than 488.000 EU citizens' premature deaths per year are attributed to exposure to harmful emissions ($PM_{2.5}$, $NO_2$ and $O_3$).[2]

The rise of traffic would further increase emissions, making transport the largest contributor of $CO_2$ emission in the EU and directly endangering the fulfilment of Europe's COP21 objectives of limiting global temperature rise.[3]

Overcoming transport reliance on fossil fuels can only be achieved through new technologies supporting the introduction of alternative powertrains based on clean and renewable energies. This can be achieved through either hydrogen/fuel cells or electric batteries.

At the same time about 42% of electricity in Europe is currently produced from fossil fuels. Decarbonising energy supply means the efficient transition to renewable energy sources and requires the storage of energy which is intermittent. Besides traditional mechanical storage, new technologies, such as electrochemical energy storage (batteries), are rapidly emerging also in the energy storage systems (ESS).

COP21 objectives, in particular limiting global warming to 2°C of temperature increase and drastically reducing carbon emissions, can only be met if a profound transformation of both the transport system and the energy sectors is achieved.

In 2015 the world reached the threshold of 1 million electric vehicles (EVs) on the road, but just a year later in 2016 this number surpassed 2 million units, indicating rapid market evolution.[4] In 2017 global EV sale reached 1.2 million units, a 58% increase from 2016. Experts predict a continuous exponential increase of the market for electrified vehicles.[5]

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[1] EUROPEAN COMMISSION. (2017). "COM(2017) 675 final. Delivering on low-emission mobility." <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0675>

[2] EUROPEAN ENVIRONMENT AGENCY. (2017) "Air quality in Europe report 2017." p.9 <https://www.eea.europa.eu/publications/air-quality-in-europe-2017/at_download/file>

[3] UNITED NATIONS. (2018). "The Paris Agreement" <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

[4] INTERNATIONAL ENERGY AGENCY. (2017). "Global EV Outlook 2017." *IEA Publications.* June, 2017. <https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf>

[5] THE ELECTRIC VEHICLE WORLD SALES DATABASE. (2017). "Global Plug-in Vehicle Sales for 2017 – Final Results." *EV-Volumes.com.* <http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/>

Along with the rapid uptake of the EV and in order to guarantee the supply of these vehicles, batteries, which are the most important component of the EV, will have to be developed and manufactured in large quantities. Currently the most deployed battery technology is the Lithium-ion (Li-ion) battery which is used in almost all EVs available on the market. As a consequence, a large stock of batteries no longer suitable for EV applications will be generated in a couple of decades.

A lifetime of an electric car battery is varying from 5 – 20 years, depending on the usage and charging intensity. Once an electric vehicle battery is no longer suitable for the mobility applications (falls to 80% of initial charge capacity), it can either be recycled or used in stationary energy storage applications – so called second life applications.

There are currently several demonstration projects ongoing which are using second life batteries for solar or wind energy storage for residential use, for grid stabilisation, for fast charging or for storing back-up power. Conclusions are now published on technical feasibility, however, less information is available on the environmental and economic impact of the second life concept.

However, since the issue of using second life EV battery will not arise before a couple of decades, the attention to this problem is only increasing slowly, and still remains relatively low. Nonetheless, in order to be prepared for the upcoming challenges, a clear strategy and methodology supporting circular lifecycle of the battery has to be developed across the whole value chain at the present moment.

A clear bottleneck for such strategy development is the uncertainty about batteries second life business case and the economic viability of such a concept. Nevertheless, business models emerging are concentrated on profits, without integrating environmental aspects in the core of the business (Jiao & Evans, 2016). Moreover, the assessment of environmental benefits of battery second life is not straightforward, if compared to the recycling alternative. Knowledge about the applications and reuse of EV batteries is still very limited due to the lack of experience and availability of second life batteries at the moment.

Therefore the **research question** of this master thesis is: *What is the viability and added value of battery second life concept, in particular in terms of generating environmental and economic benefits?*

The **hypothesis** underlying the research questions is: *EV battery second life applications will trigger new sustainable business models by 2030.*

**Methodology**

In general, a feasibility analysis is considered as a strategic analytical planning tool, conducted in the pre-business plan phase (Castrogiovanni, 1996). It includes data and information collection and analysis before the decision is made, and consequently helps to formulate decisions based on the conclusions made from the analysis (Currie, 2009).

A feasibility analysis also demonstrates how a business would operate under a certain set of assumptions — the technological and the financial aspects – and how sensitive it is to changes in these assumptions (Matson 2004). By gathering and analysing all relevant information, such approach can describe strengths and weaknesses of a concept, estimate the resources needed and objectively evaluate its prospects for success (Justis, 1979).

The general feasibility analysis is made primarily for investment decisions, however, in the current master thesis another motivation – sustainability – is considered on equal footing. If the concept is applied by a public actor, the return on investments is not the main motivation, but rather the environmental benefits.

In order to assess the feasibility of second life battery concept, in the **first chapter** of the master thesis an electric vehicle and stationary storage **technologies and market trends** are analysed, along with the **projections on the future demand** for batteries and related materials. A specific attention was made to **forecasting metal prices** used in batteries.

In the **second chapter**, the motivations and risks linked to second life concept are assessed. The proposed approach starts with a literature review for PESTEL analysis, for **stakeholder analysis** and for assessing second life battery **value proposition** with regards to levelised cost of storage (LCOS). An analysis was carried out to **compare recycling alternative** to second life.

In the **third chapter** a practical application analysis was performed. Firstly, it consisted of making a **repository of pilot projects** already ongoing which are looking at the integration of used EV battery into the small scale industrial stationary storage, and also at emerging **business models.** Secondly, an in-depth analysis was made on **estimating** the total amount of **batteries in MWh** and the total amount of related **materials in kg** to be embedded in EV in Europe by 2030. This allowed to estimate the amount of batteries which will be available for second life and the amount of related materials by 2030. Then, **a price forecast** was made for materials embedded in the future second life batteries in a view to evaluate the recycling alternative.

Finally, **conclusions and recommendations** are summarized in the last chapter of this master thesis.

**Limitations**

The scope of the current analysis is limited to battery electric and plug-in hybrid passenger cars in Europe.

# 1. LI-ION BATTERY DEMAND ANALYSIS AND PROJECTIONS

## 1.1. Battery technologies

Battery developments started in early 19th century, when scientist Volta invented the first battery in 1800.[1] Since then many technologies and battery applications were tested, and research continues to improve battery performance and discover new chemistries to store energy.

The development and manufacturing of batteries is a complex process including many aspects of research along the whole value chain – from battery cell materials and cell components, battery cell and pack manufacturing, assembly and packaging, to battery management and recycling issues. Battery packs are composed of battery modules, which in turn, are composed of battery cells (in which electrochemical reactions take place).

A battery cell consists of a container, positive and negative electrodes, a separator, electrolyte and conductive current collectors. The example of a lithium-ion battery cell structure is provided in the Figure 1 below (after Goodenough, 2013).

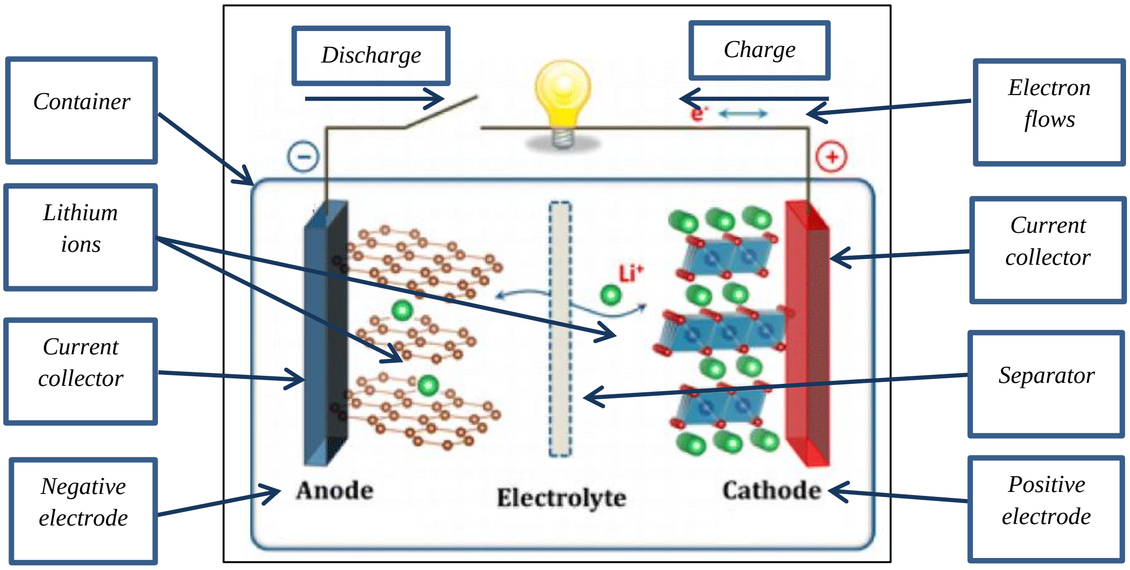


**Figure 1. Lithium-ion battery cell composition**

Main components of the battery cell are described below: [2]

The battery cell **container** is the plastic case, metal can, or foil pouch covering the cell – depending on the cell geometry/type, casing might be soft (for pounch cells) or hard (for cylindrical and prismatic cells). Important aspects are also vent and sealing of the case.

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[1] BATTERY FACTS. (2001). "Alessandro Volta (1745-1827)" *Batteryfacts.co.uk.* February 1, 2001. <http://www.batteryfacts.co.uk/BatteryHistory/Volta.html>

[2] O'HARA, T. & WESSELMARK, M. (2012). "Battery technologies: A general overview & focus on Lithium-Ion." *Intertek.* May 1, 2012. <http://www.ehcar.net/library/rapport/rapport207.pdf>

There are two electrodes – anode and cathode. In the **anode** (the negative electrode, a reductant) the cell's oxidation reactions happen, as a result generating electrons to the external circuit. The **cathode** (the positive electrode, an oxidant) is where the cell's reduction reaction takes place, consuming electrons from the external circuit.

The **separator** creates a physical barrier between the cathode and the anode, preventing the electrodes from touching, but at the same time allowing electrical charge to flow freely between them.

The **electrolyte** is the liquid or in some technologies gel or solid substance allowing the ionic conduction inside the battery between the anode and cathode.

The **conductive current collectors** are the carrier metal substrates holding the anode/cathode active ingredients. They conduct the charge to the outside of the battery and through the electricity consumption load unit. In lithium-ion batteries these are most commonly copper foil for the anode, and aluminum foil for the cathode.

Flow of electrons in an electrical circuit between two poles creates electricity. The battery discharges, when during the chemical reaction in the negative anode electrode atoms of Lithium lose one of their electrons, which travel along the circuit between the two poles (from negative to positive) of the battery to drive the electrical load (Tahil, 2010). At the same time a new positively charged (since it has lost one of its electrons) Lithium atom is created, called a Lithium-ion. Since its original neutral charge has been unbalanced, it travels across the electrolyte and separator towards the cathode to recombine with the electrons they originally lost (Tahil, 2010). During the charging the reactions are reversed.

Regarding battery chemistries, currently there are several battery types used, they differ by their structure and chemical composition, depending on the purpose. A broad overview of existing technologies is presented in table 1 below.

The distinction must be made between car lead-acid and lithium-ion batteries. While lead-acid batteries can be found in every car since they provide high current for the car starter motor, the Li-ion battery in the EV provides power for propulsion. This thesis only considers the car Li-ion batteries.

**Table 1. Brief overview of battery technologies**[1]

| | Purpose | Anode | Cathode | Electrolyte | Re-ch? |
|---|---|---|---|---|---|
| **Zinc-carbon battery** | AAA, AA, C and D dry cell | Zinc (Zn) | Manganese dioxide ($MnO_2$) | ammonium chloride ($NH_4Cl$) or zinc chloride ($ZnCl_2$) | No |
| **Alkaline battery** | AA, C and D dry cell | Zinc (Zn) powder | manganese dioxide ($MnO_2$) mixture | potassium hydroxide (KOH) (alkaline substance) | No |
| **Lead-acid battery** | Car battery | Lead (Pb) (Lead grid filled with spongy lead) | Lead dioxide ($PbO_2$) | sulfuric acid solution | Yes |
| **Lithium-ion (Li-ion) battery** | Cell phones, digital cameras, electric vehicles | Carbon (mostly graphite), also titanate, silicon alloys | Lithium Metal-alloy Oxide, many variations. E.g. $LiMn_2O_4$; $LiFePO_4$; $LiNiMnCoO_2$; $LiNiCoAlO_2$ … | sulfuric acid solution, in development gel and solid state (ceramic, glass or polymer) | Yes |
| *Many other technologies also exist, for example, flow batteries, nickel based batteries, gel lead acid batteries, but are not regarded in scope of this thesis* | | | | | |

As indicated in the table above, there are numerous technologies for the cathode materials in Li-ion batteries. While several thousand combinations of electrode materials have been investigated, less than 50 have been commercialised.[2] These different chemistries define the performance indicators of the battery – mainly the battery energy and the power, but as well lifetime, costs, safety and performance as shown in the Figure 2 below.

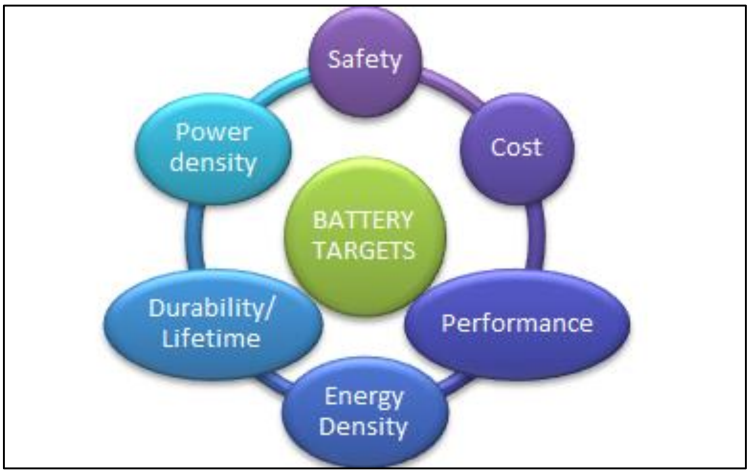


**Figure 2. Driving factors for Lithium-ion battery technology developments**[3]

[1] BRAIN, M., BRYANT C. & PUMPHREY C. (2000). "How Batteries Work." *How stuff works.* April 1, 2000. <https://electronics.howstuffworks.com/everyday-tech/battery3.htm>
[2] WINTER, M. (2017). "Lithium-ion Batteries and Beyond." *Total Battery Consulting.* Chapter I, p.6
[3] Author's work using WINTER, M. Lithium-ion Batteries and Beyond. *Total Battery Consulting.* 2017. Chapter I, p.56

**Energy density** is the batteries capacity of storing energy per kilogram of its weight (Wh/kg), of one litre of volume (Wh/l). **Power density** is the capacity of battery to deliver power per kilogram (W/kg) or litre (W/l). **Safety** describes the reliability towards the technology (e.g. the possibility of catching fire). **Lifetime** can be described either by cycle stability (number of times a battery can be fully charged and discharged) or by overall age (number of years the battery can remain useful for its purpose). Lifetime is especially important for the scope of this thesis, since it is one of the crucial factors for second life usage. **Performance** describes its behaviour under different condition (e.g. during very high or low ambient temperatures). **Costs** are expressed in € per kWh, and are usually used for battery pack.[1]

Often, these characteristics conflict with each other (higher battery power compromises safety, or highly energy dense chemistries are expensive), therefore extensive research is done on Li-ion battery technologies to optimize performances.

For the moment the current Li-ion batteries are optimised mostly by modifying the cathode chemical composition. The table below gives an overview of most common Li-ion battery cell chemistries for cathode.

**Table 2. Most common Li-ion battery technologies – cathode chemistry configurations[2]**

| Chemical Name | Material | Abbreviation | Applications |
|---|---|---|---|
| Lithium cobalt oxide | $LiCoO_2$ | LCO | Cell phones, laptops, cameras |
| Lithium manganese oxide | $LiMn_2O_4$ | LMO | Power tools, EVs, medical, hobbyist |
| Lithium iron phosphate | $LiFePO_4$ | LFP | Power tools, EVs, medical, hobbyist |
| Lithium nickel manganese cobalt oxide | $LiNiMnCo0_2$ | NMC | Power tools, EVs, medical, hobbyist |
| Lithium nickel cobalt aluminum oxide | $LiNiCoAlO_2$ | NCA | EVs, grid storage |
| Lithium titanate | $Li_4Ti_5O_{12}$ | LTO | EVs, grid storage |

The abovementioned cathode cell chemistries have different characteristics of the driving factors. Regarding the suitability to EVs, the table below shows the advantages and bottlenecks for each cell chemistry – dark/light green is representing advantages, yellow - acceptable performance, orange – minor disadvantages, and red – unacceptable characteristics.

As shown in the table, there are already several battery technologies existent which could satisfy EVs requirements and are used for both electrified (hybrid – HEV, plug-in hybrid – PHEV) and fully electric vehicles. In particular, the NMC technology is very interesting,

[1] DINGER, A., MARTIN, R., MOSQUET, X., RABL, M., RIZOULIS, D., RUSSO, M. & STICHER, G. (2010). "Batteries for electric cars." The Boston Consulting Group. p.3-5 <https://www.bcg.com/documents/file36615.pdf>

[2] BATTERY UNIVERSITY. (2017). "Types of Lithium-ion." *Batteryuniversity.com.* November 15, 2017. http://batteryuniversity.com/learn/article/types_of_lithium_ion

and even more if improved with silicon alloy anode and nickel rich cathode. Some combinations are performing well on all factors, except the energy density, such as LFP and LMOS. It means that the gravimetric or volumetric energy density of battery is low.

**Table 3. Cell chemistries: state of the art characteristics and future trends**[1]

| Cell chemistry | Energy | Power | Lifetime | Low temperature capability | Safety | Maturity |
|---|---|---|---|---|---|---|
| NMC | + | o | ++ | - | - | + |
| NCA | + | + | + | - | -- | + |
| LFP | -- | + | ++ | - | ++ | + |
| LMOS | -- | + | - | - | + | o |
| SiO/Ni-rich NMC | ++ | o | o | - | o | o |
| LTO/NMC | o | + | + | o | o | +/o |
| LTO/NMC | -- | ++ | ++ | + | + | + |
| Si alloy/Ni-rich NMC | ++ | o | - | - | o | o |
| Si/HV spinel | ++ | o | -- | - | o | - |

Another overview is given by Boston Consulting group below. The figure 3 shows the most common technologies and their performance characteristics. Since the publication some improvements have been made in the technology, nevertheless, the overall advantages and bottlenecks remain.

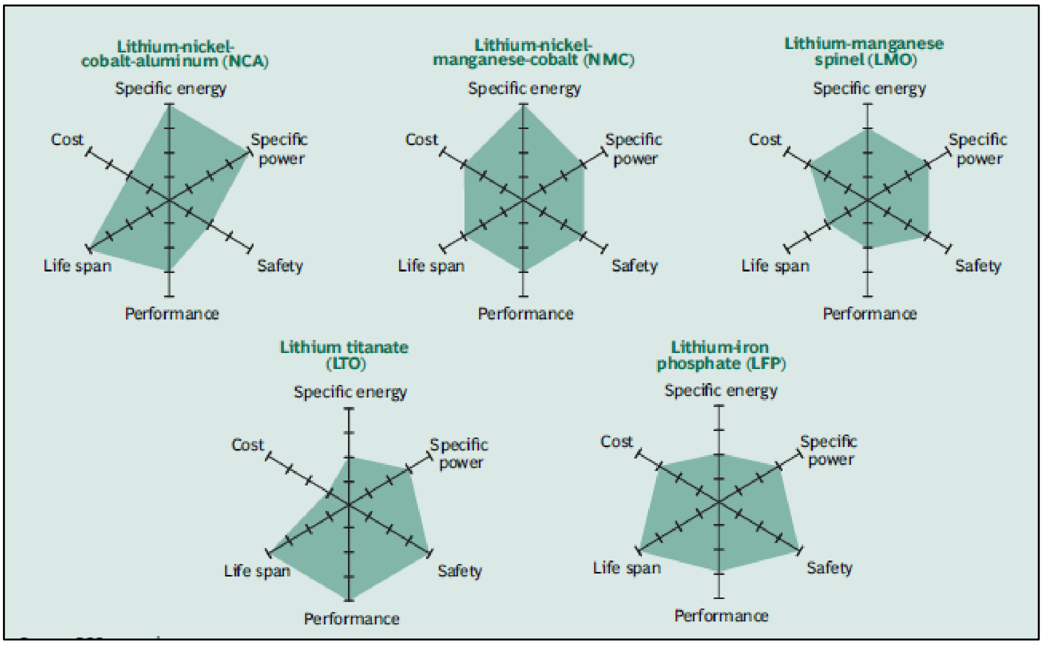


**Figure 3. Key performance indicators for five principal Li-ion battery technologies.**[1]

[1] AFFENZELLER, J. (2017). "Setting the scene: Current challenges and future technologies." *Presentation during the Horizon Prize Innovative Batteries Workshop.* May 12, 2017. Brussels.

Based on the strategy for the vehicle positioning and marketing, the manufacturer can choose the most appropriate battery. For example, he might choose a battery with high power and lower cycle life and proceed with regular battery change, or on the contrary - a long lifetime battery with moderate performance.

For what concerns second life applications, a longer use of the battery is expected, therefore technologies with good performance in the life span criteria are appropriate, e.g. NCA, LTO and LFP.

The figure 4 below summarizes the Li-ion cell chemistries used in different modules of EVs from 2008-2016. Some Models have changed the cell type since 2016, for instance, VW have changed to Samsung batteries for the e-Golf.[2]

| Cell Maker | SOP | Chemistry | Capacity | Configuration | Used in: | |
|---|---|---|---|---|---|---|
| | Year | Anode/Cathode | Ah | | Company | Model |
| Li Energy Japan | 2008 | G/LMO-NMC | 50 | Prismatic | MMC | i-MiEV |
| AESC | 2010 | G/LMO-NCA | 33 | Pouch | Nissan | Leaf |
| LG | 2012 | G/LMO-NMC | 16 | Pouch | Ford | Focus |
| A123Systems | 2012 | G/LFP | 20 | Pouch | Chevy | Spark |
| Panasonic | 2012 | G/NCA | 3.1 | Cylindrical | Tesla | Model S |
| LG | 2012 | G/LMO-NMC | 36 | Pouch | Renault | Zoe |
| Litech | 2013 | G/NMC | 52 | Pouch | Daimler | Smart |
| Toshiba | 2013 | LTO-NMC | 20 | Prismatic | Honda | Fit |
| Samsung | 2013 | G/LMO-NMC | 63 | Prismatic | CFA | 500 |
| SK Innovation | 2014 | G/NMC | 38 | Pouch | Kia | Soul |
| Samsung | 2015 | G/LMO-NMC | 63 | Prismatic | BMW | i3 |
| Panasonic | 2015 | G/NMC | 25 | Prismatic | VW | e-Golf |
| AESC | 2015 | G/LMO-NCA | 40 | Pouch | Nissan | Leaf |
| Panasonic | 2015 | Gr-Si/NCA | 3.4 | Cylindrical | Tesla | Model X |
| LG | 2016 | Gr/NMC | 56 | Pouch | Chevy | Bolt |

**Figure 4. Li-ion cells employed in EVs 2008-2016[3]**

It can be observed that the most common technology is NMC, together with LMO. This is confirmed in table 3 and figure 3 which shows the outstanding advantages of NMC in comparison with other technologies.

In order to evaluate the possible future technologies for EV batteries, it is necessary to evaluate future trends. It is considered that the improved Li-ion technology will stay the

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[1] DINGER, A., MARTIN, R., MOSQUET, X., RABL, M., RIZOULIS, D., RUSSO, M. & STICHER, G. (2010). "Batteries for electric cars." The Boston Consulting Group. p.3 <https://www.bcg.com/documents/file36615.pdf>

[2] ITERS NEWS. (2016). "Samsung SDI signs a deal to supply prismatic EV battery for Volkswagen" *Iternews.com.* December 6, 2016. <http://itersnews.com/?p=104707>

[3] WINTER, M. (2016). "The xEV Industry Insider Report." *Total Battery Consulting.* December 2016. Chapter II, p.33

technology of choice for the forthcoming years – in short to medium term, developments in high-voltage and/or high capacity cathodes, high-voltage electrolytes, silicon containing anodes, additives for both low and high temperatures would bring more realistic advancements rather than potentially developing rapidly new technologies.[1] This is also confirmed by the conclusions of a workshop organised by the European Commission on future research needs in batteries[2], where recommendations were made to continue research and development on current Li-ion technologies, while at the same time working on next-generation Li-ion technologies. The non Li-ion technologies are considered for longer term research.

The Figure 5 below shows the classification of the Li-ion cell technologies by "generations". Currently, those are generation 2a and 2b used in the EVs placed on the market.

| Cell generation | Cell chemistry | |
|---|---|---|
| Generation 5 | • Li/O₂ (lithium-air) | |
| Generation 4 | • All-solid-state with lithium anode<br>• Conversion materials (primarily lithium-sulphur) | > 2025 ? |
| Generation 3b | • Cathode: HE-NCM, HVS (high-voltage spinel)<br>• Anode: silicon/carbon | ~ 2025 |
| Generation 3a | • Cathode: NCM622 to NCM811<br>• Anode: carbon (graphite) + silicon component (5-10%) | ~ 2020 |
| Generation 2b | • Cathode: NCM523 to NCM622<br>• Anode: carbon | current |
| Generation 2a | • Cathode: NCM111<br>• Anode: 100% carbon | current |
| Generation 1 | • Cathode: LFP, NCA<br>• Anode: 100% carbon | current |

**Figure 5. Classification of Li-ion cell chemistries[3]**

The values in the NMC representation stand for the proportions of the chemical elements used in the cathode. For example, NCM622 means that 60% is nickel, 20% is cobalt and 20% is manganese. Therefore generation 3a chemistry NCM811 means that the proportions of nickel have been increased by 20%, and that the proportions of cobalt and manganese have been decreased by 20% each.

This is mainly done to ensure higher capacity while maintaining costs and reducing weight and pack size. For example, as presented in the figure 6 below, a 60 kWh pack based on

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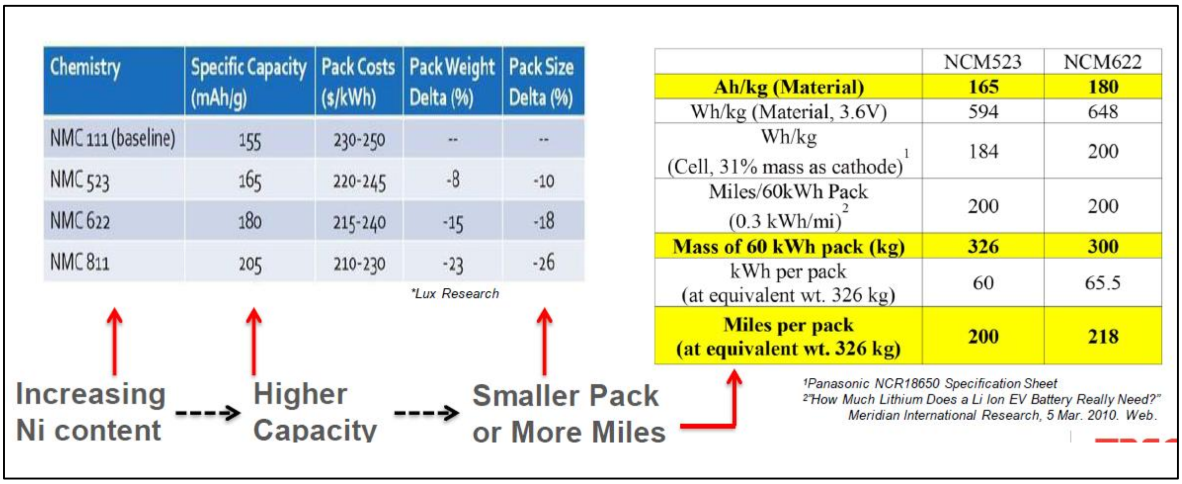
[1] WINTER, M. (2016). "The xEV Industry Insider Report." *Total Battery Consulting.* December 2016. Chapter II, p.33 , Chaper IV, p.8

[2] MEEUS, M., (2018). "Final report. European Battery Cell R&I Workshop." *European Commission.* February 12, 2018. <http://europa.eu/!ft46wu> p. 3

[3] NATIONALE PLATTFORM ELEKTROMOBILITÄT. (2016). "Roadmap integrierte Zell-und Batterieproduktion Deutschland". January, 2016 as mentioned in Lebedeva, Di Persio & Boon-Brett (2016)

NCM523 weights 326 kg, whereas it is decreased at NCM622 which weights 300 kg. It is an important improvement since battery weight for EV is a crucial aspect. At the equivalent weight of 326 kg, the NCM523 battery can guarantee 200 miles (capacity of 60 kWh per pack), whereas with the same battery weight NCM622 technology can ensure 218 miles (65.5kWh). Further research is currently done to move towards NMC811 which will improve the performance even more.



| Chemistry | Specific Capacity (mAh/g) | Pack Costs ($/kWh) | Pack Weight Delta (%) | Pack Size Delta (%) |
|---|---|---|---|---|
| NMC 111 (baseline) | 155 | 230-250 | -- | -- |
| NMC 523 | 165 | 220-245 | -8 | -10 |
| NMC 622 | 180 | 215-240 | -15 | -18 |
| NMC 811 | 205 | 210-230 | -23 | -26 |

| | NCM523 | NCM622 |
|---|---|---|
| **Ah/kg (Material)** | **165** | **180** |
| Wh/kg (Material, 3.6V) | 594 | 648 |
| Wh/kg (Cell, 31% mass as cathode)[1] | 184 | 200 |
| Miles/60kWh Pack (0.3 kWh/mi)[2] | 200 | 200 |
| **Mass of 60 kWh pack (kg)** | **326** | **300** |
| kWh per pack (at equivalent wt. 326 kg) | 60 | 65.5 |
| **Miles per pack (at equivalent wt. 326 kg)** | **200** | **218** |



**Figure 6. Different chemistries and corresponding EV characteristics**[1]

This is an important result to be considered when estimating the amount of resources needed in Chapter 3.

As a preliminary conclusion and as a baseline for the future investigation in this thesis, Li-ion NMC technology has still potential to improve its technological performances even though it is already state of the art. At the same time when further research will bring the current technology to its boundaries, research on next generations Li-ion technologies and post Li-ion batteries is essential.

[1] YAKOVLEVA M. (2017). "From raw material to next generation advanced batteries." *FMC.* Presentation at AABC Europe conference. January 30, 2017.

## 1.2. Battery technologies for electric vehicles

### 1.2.1. Electric vehicle technology

The first passenger vehicles developed in 1830s were electric and used non-rechargeable batteries. However, a true disruption of private transportation was experienced when by the end of 19th century a rechargeable battery was developed, which triggered the use of private and shared (taxis) cars. After 1910s the internal combustion engines outperformed batteries by their energy density and a fast refill, as well as cost and thus a number of electric vehicles decreased (Larminie, 2003).

Nowadays, the EVs are preferred upon conventional vehicles due to their sustainability and breakthrough improvements in the batteries. There is currently a wide range of EVs available on the market with different levels of electrification. The figure below shows the degrees of electrification and battery types used in these vehicles.

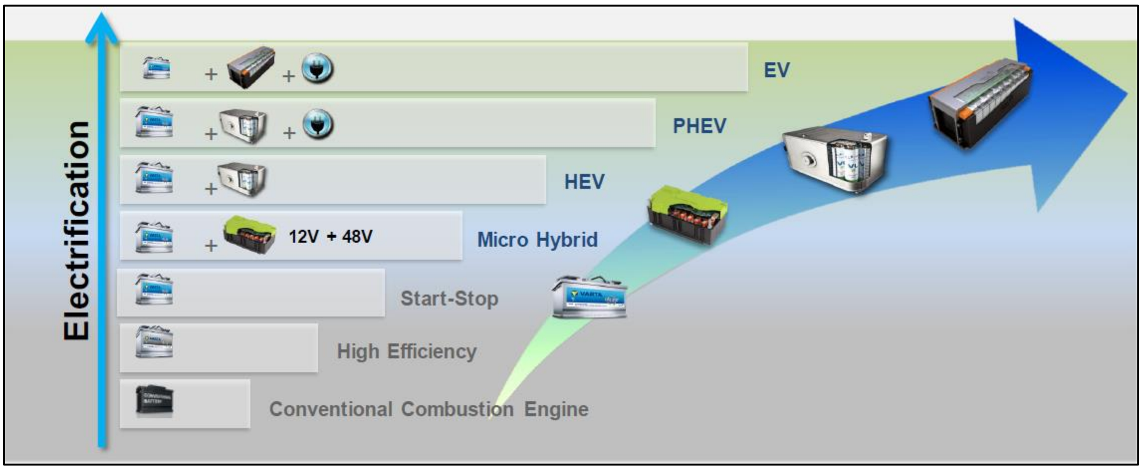



**Figure 7. Degrees of electrification and battery use in EVs**[1]

Some start-stop functions are supported by a small lead-acid or flooded battery. Next level are Micro hybrid and Hybrid electric vehicles (HEV) whose battery is used to regenerate energy from braking (lead-acid or li-ion) or even allow a certain range of electric driving (nickel-metal hydride or li-ion). Plug-in hybrids (PHEV) are vehicles whose battery can be charged from external power sources and are used with a combination of combustion engine. Full battery electric vehicle (BEV) uses battery as the sole source of energy.

Since PHEV and BEV use a li-ion battery of a considerable size and energy density, only these types of vehicles will be considered in this thesis. EV notion is used to combine both, PHEV and BEV.

[1] EUROBAT. (2014). "E-Mobility Battery R&D Roadmap 2030." *Eurobat.org.* April 29, 2014 <https://eurobat.org/sites/default/files/151027_eurobat_battery_rd_roadmap_introduction_-_final.pdf>

### 1.2.2. Drivers and enablers for electric vehicle adoption

Although the average end user interest towards EVs is between moderate to high, there are considerable socio-technical barriers preventing the rapid uptake of EVs. Major challenge is the battery technology, battery costs and charging infrastructure, along with consumer acceptance as the main social aspect (Egbue & Long, 2012).

On the consumer acceptance side, Jabłońska (2013) summarizes that consumer anxiety arises mainly on economic aspects and social features related to EV usage and service. Economic aspects are mainly purchasing and service costs (Rezvani et al., 2015), and social features are mainly linked to recharging time and infrastructure availability. A third aspect, integrating economic and social feature, is range anxiety, which is considered to be the biggest concern of all (Egbue & Long, 2012).

Different opinions exist about the influence of sustainability and environmental benefits of EVs on the consumer choice (Rezvani et al.; 2015, Egbue & Long, 2012). The importance of user awareness and knowledge rising is emphasized when trying to overcome the social barriers (Rezvani et al., 2015).

All above-mentioned social features largely depend on batteries, which determine range, costs and safety of the electric vehicle.[1] Battery cell technology and main underlying disadvantages are described in the section 1.1.

To address weaknesses, some innovative solutions such as fast charging and battery swap are trying to overcome these technical barriers, but currently require heavy investments in infrastructure (Jiao & Evans, 2016). Moreover both need further standardization across the whole battery assembly value chain to make these options technically and economically feasible.

The future of EV shares will be determined by technological, macroeconomic and political/legal conditions (Proff & Kilian, 2012).

Technology, mainly on batteries, is rapidly improving. R&I (research and innovation) generated knowledge and understanding on materials, chemistry, engineering and nanotechnologies bring remarkable results in improving battery key performance indicators[2].

International competitiveness pressures are high and will trigger new investments in R&I (Proff & Kilian, 2012). Many global automakers have announced the new EV model

[1] EUROPEAN COMMISSION. (2017). "Batteries - a major opportunity for a sustainable society" *Publications Office of the European Union, Luxembourg* <https://publications.europa.eu/en/publication-detail/-/publication/d9f3bd80-cb49-11e7-a5d5-01aa75ed71a1/language-en/format-PDF/source-69927140>

[2] idem

milestones and targets for the future, at the same time having 165 EV models on the market already.[1] Figure below summarizes OEM announcements as of May 2018.

**Table 4. List of OEMs announcements on electric car plans, as of May 2018[2]**

| Automaker group | Announced investment[a] | Electric models[b] | Annual global electric sales (shares)[c] |
|---|---|---|---|
| Nissan-Renault-Mitsubishi | • $9 billion over 2018-2022 (in China only) | • 12 electric models by 2022 | 3 million (30%) by 2022 |
| Volkswagen Group | • $40 billion manufacturing plant by 2022<br>• $60 billion battery procurement | • 80 electric models by 2025<br>• 300 electric models by 2030 | 2-3 million (20%- 25%) by 2025 |
| Toyota | • (not available) | • All vehicles hybrid, battery, or fuel cell electric by 2025 | 2 million (25%) by 2025 |
| Chongqing Changan | • $15 billion by 2025 | • 21 electric models by 2025<br>• 12 plug-in hybrid models by 2025 | 1.7 million (100%) by 2025 |
| BAIC | • $1.5 billion by 2022<br>• $1.9 billion (with Daimler) | • (not available) | 1.3 million (100%) by 2025 |
| Geely | • (not available) | • All models hybrid or electric by 2019 (Volvo) | 1.1 million (90%) by 2020 |
| General Motors | • (not available) | • 20 electric models by 2023 | 1 million (12%) by 2026 |
| Tesla | • $4-5 billion battery manufacturing | • 3-4 electric models (S, X, 3, Y) | 0.5 million (100%) by 2020 |
| Mercedes | • $12 billion manufacturing plant<br>• $1.2 billion battery manufacturing | • 10 electric models by 2025<br>• 50 electrified models by 2025 | 0.4-0.6 million (15%-25%) by 2025 |
| BMW | • $2.4-3.6 billion procurement by 2025 | • 12 electric models by 2025<br>• 13 plug-in hybrid models by 2025 | 0.4-0.6 million (15%-25%) by 2025 |
| Ford | • $11 billion manufacturing plant by 2022 | • 16 electric models by 2022<br>• 24 plug-in hybrid models by 2022 | (not available) |
| Great Wall | • $2-8 billion over 10 years | • (not available) | (not available) |
| Jaguar | • (not available) | • All models hybrid or electric by 2020 | |
| Infiniti | • (not available) | • All new models plug-hybrid or electric by 2021 | (not available) |

In addition to abovementioned announcements, Volvo has committed to electrify all cars by 2019, General Motors to launch 20 electric models by 2023. PSA launched a platform to release 4 new EVs and 7 PHEVs starting next year.[3] In addition, many strategic decisions and plans have not been announced yet therefore investments can be even higher.

Regarding political/legal conditions, the EV deployment is driven by governmental policies, such as financial incentives, non-financial benefits, developing charging infrastructure and the presence of local production facilities, which have strong positive impacts on EV shares in the country (Sierzchula et al., 2014). More precisely it is the consumer perception towards these policies that matters (Rezvani et al., 2015). Recent

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[1] FROST AND SULLIVAN. (2018). "Global Electric Vehicle Market Outlook, 2018 – Summary" *Frost.com* March 27, 2018. <http://www.frost.com/sublib/display-report.do?id=MDAB-01-00-00-00&bdata=bnVsbEB%2BQEJhY2tAfkAxNTI1ODc4MjYzNDE0>

[2] LUTSEY N., GRANT M., WAPPELHORST S. & ZHOU H. (2018). "Power play: How governments are spurring the electric vehicle industry." *The International Council on Clean Transportation (ICCT).* May, 2018. <https://www.theicct.org/sites/default/files/publications/EV_Government_WhitePaper_20180514.pdf>

[3] LAMBERT F. (2018). "PSA Group (Peugeot-Citroën-DS-Opel) creates new EV division ahead of launching its first electric cars." *Electrek.co* April 9, 2018. <https://electrek.co/2018/04/09/peugeot-citroen-psa-new-ev-division/>

Global EV market outlook 2018 predicts that governmental financial support is no longer needed to regularise price of EVs.[1]

Strong environmental policies are being taken in place to limit the use of polluting internal combustion engine cars. New European Regulations impose stricter $CO_2$ targets for passenger cars and heavy duty vehicles[2]. More and more cities around the world ban diesel cars in order to protect public health. In parallel with low emissions zones, polluting diesels are already not or soon will not be permitted to enter such major European cities as Madrid, Rome, Athens, Dusseldorf, Paris and others.[3]

Governmental policy towards research is also considered as a main instrument to reduce cost and improve performance.[4]

### 1.2.3. Electric vehicle current market and future projections

Considering that globally there were more than 1 billion cars on the road in 2016[5], the percentage of electric cars was still very small – only 0.2% of the total car stock. However, with 1.2 million new EV sold in 2017, and with more than 1.6 million to be likely sold in 2018,[1] the EV have proven their potential to be competitive with conventional vehicles. By the end of 2017 the EV stock on the road was more than 3.2 million vehicles, and it is estimated that by the end of 2018 it will reach 4.8 million.[4,1]

The figure below shows that the **total number of EVs** on the road has constantly increased in all markets. With the launch of the first modern series of electric cars around 2000s (Tesla Roadster in 2008; Nissan Leaf, BYD in 2000) the remarkable threshold of one million electric car stock was surpassed six years later, in 2015. However, just one year later in 2016 it already reached 2 million.

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[1] FROST AND SULLIVAN. (2018). "Global Electric Vehicle Market Outlook, 2018 – Summary" *Frost.com* March 27, 2018. <http://www.frost.com/sublib/display-report.do?id=MDAB-01-00-00-00&bdata=bnVsbEB%2BQEJhY2tAfkAxNTI1ODc4MjYzNDE0>

[2] EUROPEAN COMMISSION. (2017). "Europe on the Move: Commission takes action for clean, competitive and connected mobility" *ec.europa.eu* May 31, 2017. <https://ec.europa.eu/transport/modes/road/news/2017-05-31-europe-on-the-move_en>

[3] TRANSPORT AND ENVIRONMENT. (2018). "Diesel bans in cities still letting dirty new diesels off the hook – analysis." *transportenvironment.org.* March 14, 2018. <https://www.transportenvironment.org/press/diesel-bans-cities-still-letting-dirty-new-diesels-hook-analysis>

[4] INTERNATIONAL ENERGY AGENCY. (2017). "Global EV Outlook 2017." *IEA Publications.* June, 2017. <https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf>

[5] INTERNATIONAL ORGANIZATION OF MOTOR VEHICLE MANUFACTURERS. (2018). Production Statistics/Vehicles in use. < http://www.oica.net/>

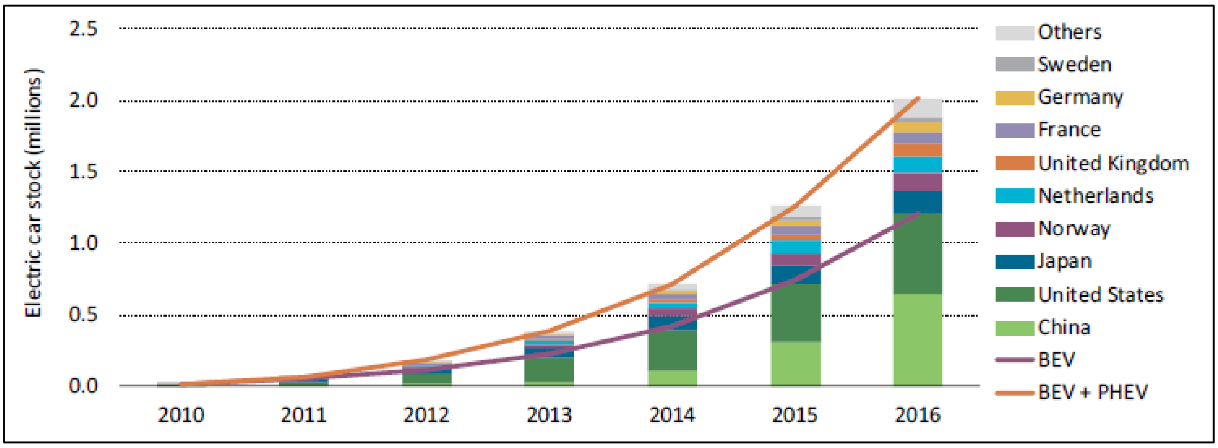


**Figure 8. Global electric vehicle car stock, in millions of units, 2010 - 2016**[1]

In 2016 out of 2 million EV, 32% (649 thousand) were on roads in China and 28% (564 thousand) in the United States. The top six European countries EV stock represents 26% of the global market (518 thousand).

China is also the world leader in EV **annual sales** representing 45% of the total number of EVs sold yearly (336 thousand cars in 2016). European countries follow with 26% (196 thousand). The figure below shows electric car sales, the market share of country's fleet and BEV and PHEV sales shares in selected countries.

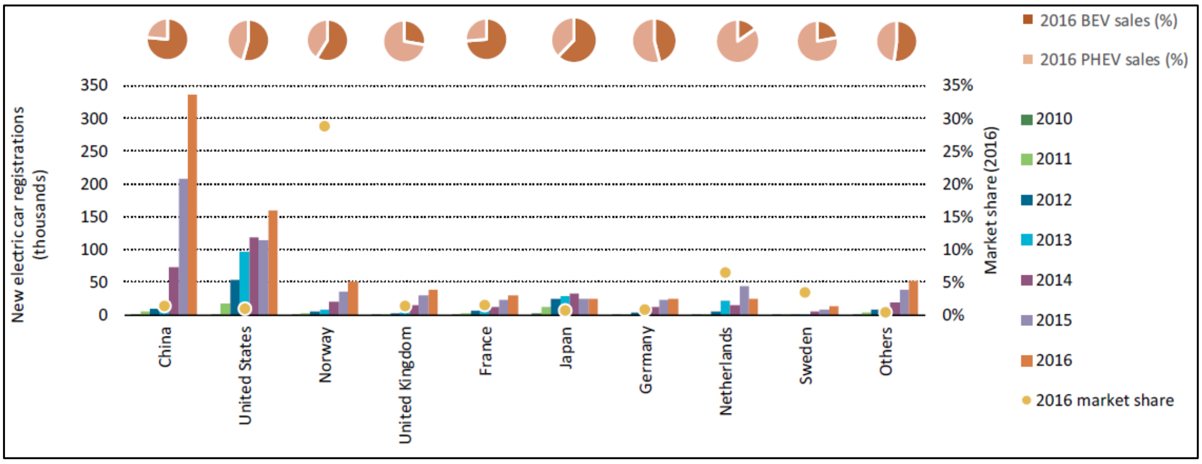


**Figure 9. Electric car sales, market share of country's fleet and BEV and PHEV sales shares in selected countries, 2010-2016**[2]

In absolute numbers main markets for EV sales are China and US, however, the most rapid growth is in China (almost double from US), moreover, experiencing on average 50% increase year-to-year. Compared to 2015, in 2016 China faced an increase of 62% in the EV stock, and the United States + 40%. It is important to notice that most of these vehicles

[1] INTERNATIONAL ENERGY AGENCY. (2017). "Global EV Outlook 2017." *IEA Publications.* June, 2017. <https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf>

[2] idem

(more than 75%) are fully battery EVs. It is a result of extensive financial and non-financial incentives in China.

European countries, however, have demonstrated record relative numbers – Norway is a global leader and reached 29% EV sales, followed by the Netherlands with 6.4% and Sweden 3.4%. Meanwhile, in China and US these numbers are close to 1.5%.

Regarding the future, there exists a number of projections with a quite large distribution fork. Figure 10 below represents an example of a future market forecast by Bloomberg.

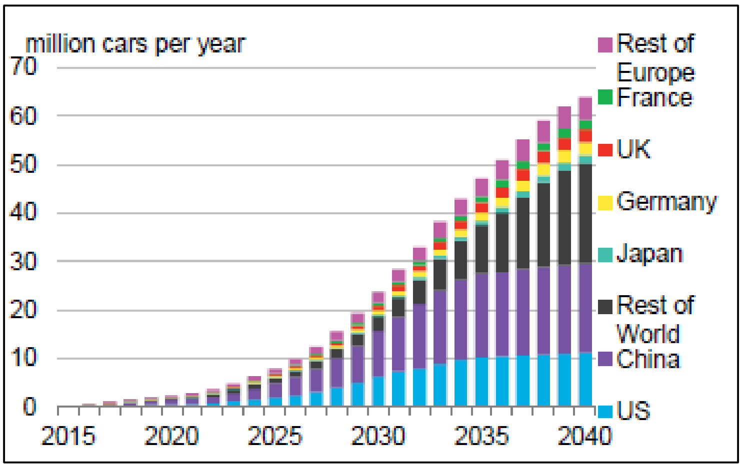


**Figure 10. Annual global EV sales forecast by world region, 2015-2040**[1]

It is expected that China will remain world leader in sales of both EV and PHEV. However, Europe will also considerably increase its shares, especially in Germany, UK and France. According to the figure above, the threshold of 10 million electric cars a year will be reached in 2026, and a threshold of 20 million – in 2029. After that, the increase is forecasted to be approximately 5 million cars a year.

Also, based on the OEM announcements (previously table 4), a total of $150 (approx. €130) billion in investments are expected to achieve the target of 13 million EVs annual sales by 2025, which is to be 10% of car sales. Bloomberg predicts, that by 2040 55% of new cars will be electric.

In Europe, based on different market estimations and studies, the increase in new sales could be from 20% to almost 70%. Figure 11 below provides an overview of recent market forecasts for Europe in literature, and market share projections for EV and PHEV.

According to the figure, there is a big uncertainty for both, new EV car sales and thus the total stock of vehicles in future. Even if it is difficult to estimate the stock of EVs by 2030 – a relatively short term-, there is no doubt that the EV demand will increase rapidly.

[1] BLOOMBERG NEW ENERGY FINANCE. (2017). "Electric Vehicle Outlook 2017 Executive Summary." *Bloomberg Finance L.P.2017* July, 2017. <*https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF_EVO_2017_ExecutiveSummary.pdf*>

The Bloomberg estimation (as also represented in the figure 10) falls in the category below-average projection, with expected sales increase of 30%.[1] The median of other forecasts being approximately 33% - 40%.

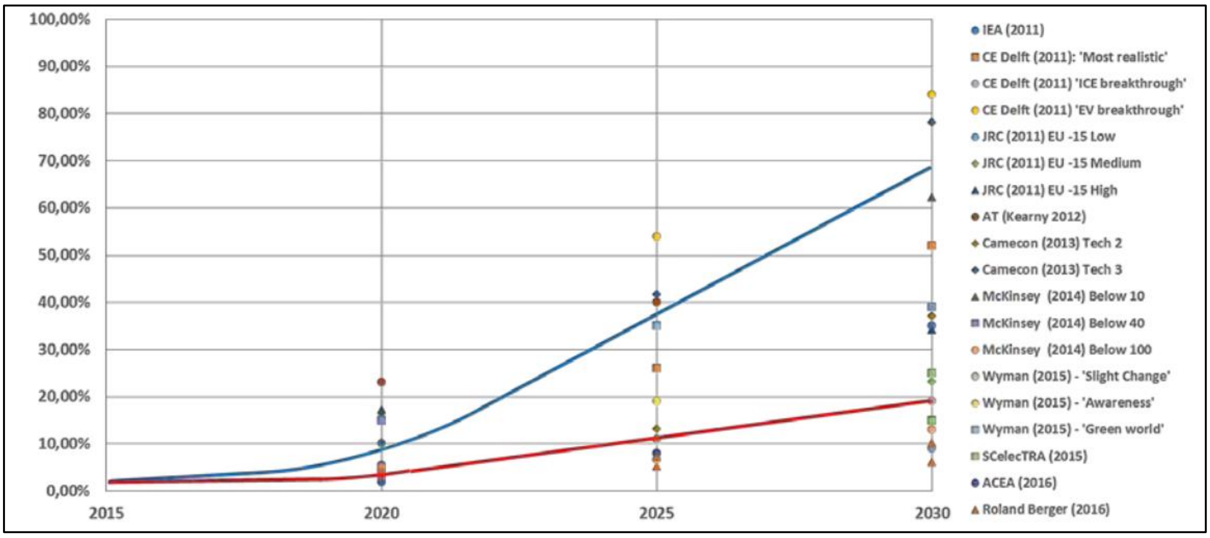


**Figure 11. EV and PHEV sales forecast in Europe, 2020-2030**[2]

Taking into consideration that EU new passenger car registration is about 15 million units yearly[3], the new EV share in Europe could be between 0.75 to 1.5 million units in 2020.

Based on OEM announcements, the **global** electric car stock could range from 9 to 25 million by 2020, and from 40 to 70 million electric cars by 2025 with more than 400 models available on the market.[4,5]

Based on market projections from different reports and OEM strategies, it is commonly believed that the jump of EV sales and mass adoption will incur after 2025. Moreover, as also confirmed by the literature analysis in this section, the EVs will no longer be needing government support and as of 2025 EVs will become price competitive with respect to conventional cars.

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[1] BLOOMBERG NEW ENERGY FINANCE. (2017). "Electric Vehicle Outlook 2017." *Bloomberg Finance L.P.2017*

[2] ERTRAC - EPOSS - ETIP SNET. (2017). "European Roadmap Electrification of Road Transport." *The European Road Transport Research Advisory Council.* June, 2017. <http://www.ertrac.org/uploads/documentsearch/id50/ERTRAC_ElectrificationRoadmap2017.pdf>

[3] ACEA (2018). "Passenger car registrations." *European Automobile Manufacturers Association*. January 17, 2018. <https://www.acea.be/press-releases/article/passenger-car-registrations-3.4-in-2017-4.9-in-december>

[4] INTERNATIONAL ENERGY AGENCY. (2017). "Global EV Outlook 2017." *IEA Publications.* June, 2017. <https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf>

[5] FROST AND SULLIVAN. (2018). "Global Electric Vehicle Market Outlook, 2018 – Summary" *Frost.com* March 27, 2018. <http://www.frost.com/sublib/display-report.do?id=MDAB-01-00-00-00&bdata=bnVsbEB%2BQEJhY2tAfkAxNTI1ODc4MjYzNDE0>

This will be possible mostly because of the rapid cost decrease in Li-ion batteries by more than 70% by 2030 due to new research and developments, mostly in solid-state Li-ion technology, and prospects for mass production.

## 1.3. Battery technologies for energy storage

Batteries are also a driver towards an energy system based on the use of renewable energy both in large scale grid applications and in local energy storage. The renewable energy, such as wind and solar, is intermittent and thus not reliable for guaranteeing the constant supply of electricity. As a consequence, most of the energy in excess is mostly stored using physical energy storage or just wasted.[1]

Batteries could solve this problem by storing electricity when available and releasing it when necessary. They could be used for grid balancing at peak hours, for electricity storage in case of EV off-grid charging, or for customer electricity bill management, etc.

Fitzgerald et al. (2015) identify up to 13 services where batteries could be used for consumers, utilities and regional transmission and system operators (figure 12). Most common services delivered by a battery storage are demand charge reduction, backup power, and increasing solar self-consumption.

When energy storage is used behind the meter (farthest downstream level where energy can be deployed), it can technically provide all 13 services – on residential, commercial, or industrial level. Further upstream to distribution and transmission levels, some services are become not applicable.

The net potential value of using batteries in energy storage differ considerably across studies, most often being between 0-170 €/kW-year. This difference is due to the complexity of integrating a large number of variables involved in estimating the value of energy storage to the electricity grid.

[1] RICHARDSON J. (2018). "No Huge Energy Storage Breakthrough Needed For Renewable Energy To Flourish." *Clean Technica*. March 4, 2018. <https://cleantechnica.com/2018/03/04/no-huge-energy-storage-breakthrough-needed-renewable-energy/>

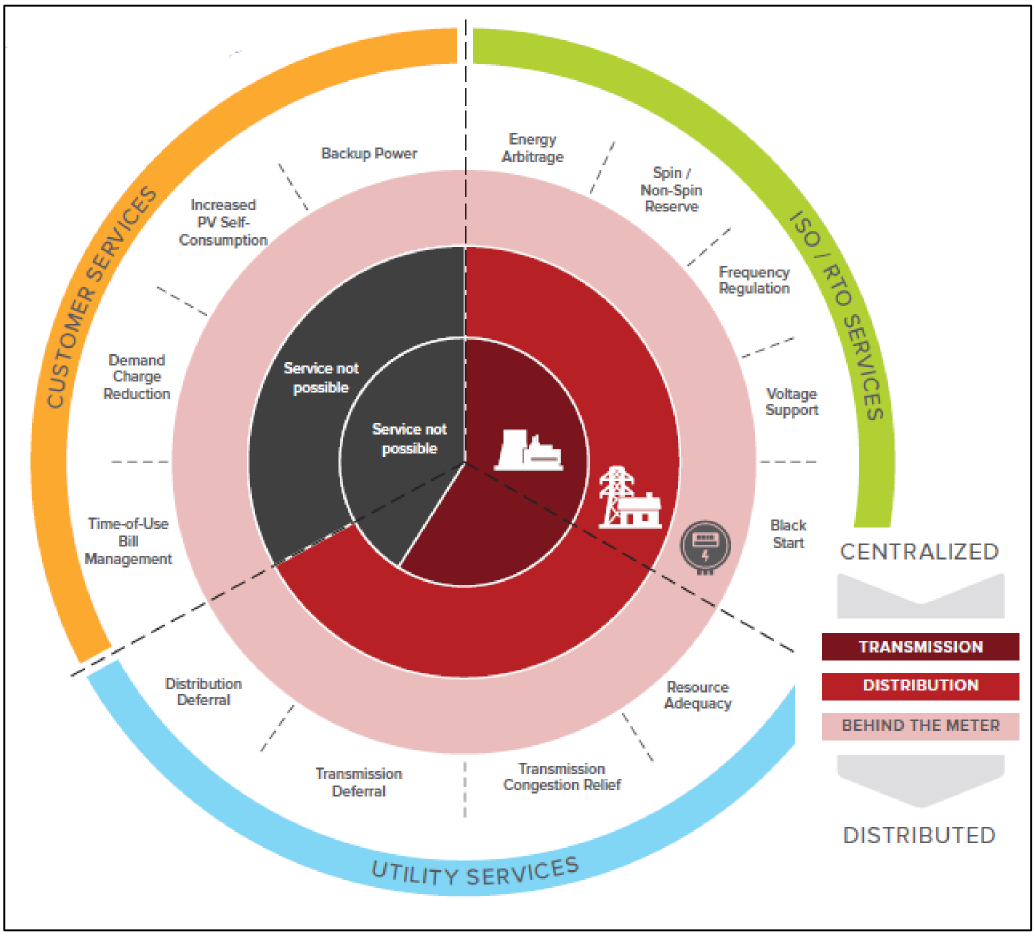


**Figure 12. Services provided by batteries to three different stakeholder groups (Fitzgerald et al., 2015)**

The study has concluded that when batteries are only used for a single service of energy storage, generally they do not bring any net economic benefit (lifetime revenue does not exceed costs) because they are utilised only from 1-50% of their lifetime capacity. Some services though, only under certain conditions and markets, such as consumer bill management could be feasible.

However, the economic benefit changes if a battery is used not only for a primary service (e.g. commercial demand-charge management), but also for secondary services (frequency regulation, energy arbitrage etc). In this case the battery brings more value than costs. Authors admit though, that it is difficult to create these combined-use business models adapted to real life situations, but the development of robust models shall be a priority for industry.

Besides the uncertainty whether batteries would bring value from their use, it is still under discussion what the best technology of storage for energy applications is. The energy storage applications have different limitations - unlike the EVs, the volumetric and gravimetric energy density is not a constraint for energy storage. On the other hand, such aspects as battery lifetime and lower costs are of a crucial importance.

Thus batteries specifically designed for more cycles and calendar lifetime, optimised safety and lower costs are needed in the future for storage applications. Li-ion technologies are currently the front runners for large scale energy storage, but their disadvantages remain limited lifespans, compromised safety and potentially limited supply chains of components.[1]

When looking for the future stationary energy storage research priorities in Europe, the technology of choice seems to be Redox flow and Na-ion batteries in short to medium term, with Mg and Zn systems for the longer term. [2]

It is important to remember that for energy storage systems the CAPEX is the key parameter.[3] Therefore despite the fact that Li-ion is usually the most economical solution across most use cases, including stationary energy storage, flow batteries can potentially offer lower costs for longer duration.[4]

Increasing energy demand is a strong driver for developing electrochemical energy storage. At the same time the promotion of renewable energies and COP21 objectives, force society to move towards the use of renewable energies.

## 1.4. Projections on the battery and related material demand

In this section the battery cell materials will be analysed, followed by an outlook of demand/production for batteries and finally the amount of the required material will be estimated.

The figure below from Umicore shows the share of potential markets for rechargeable batteries. It can be seen that the main driver will be the vehicle electrification, followed by portable electronics and stationary energy storage taking only a small share of the market.

While the figure below shall be perceived with a certain precaution, since batteries for energy storage are developing quickly, it can be true for the use of current technology rechargeable battery market. Since in the previous section it was analysed that the cost is one of the key factors for the stationary energy storage, the current or advanced Li-ion technologies might be still too expensive for the use in stationary energy storage.

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[1] ENERGY STORAGE NEWS. (2017). "Which battery technology will be the future of energy storage?" Energy Storage World Forum. October 6, 2017. <https://energystorageforum.com/blog/which-emerging-battery-technology-will-be-the-future-of-stationary-energy-storage>

[2] MEEUS, M., (2018). "Final report. European Battery Cell R&I Workshop." *European Commission.* February 12, 2018. <http://europa.eu/!ft46wu> p. 30

[3] Idem

[4] LAZARD. (2017). "Lazard's levelized cost of storage analysis – version 3.0." *Lazard and Enovation Partners.* November, 2017. <https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf>

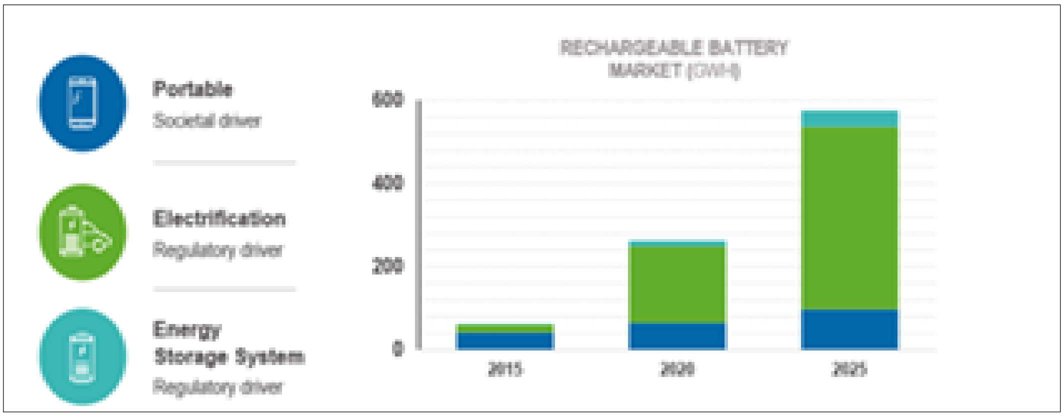


**Figure 13. Market potential for rechargeable batteries**[1]

In the next section the battery cell manufacturing capacities is examined with a focus on their use in electromobility, will be analysed.

### 1.4.1. Battery cell manufacturing in Europe and in the world

The leader for battery production capacity historically has been Japan, until 2016 when China considerably increased its capacities becoming the world leader (see figure 14). This increase is related to China's EV policy which resulted in large amount of domestic EV production and sales. From the total battery production capacity, 84% are batteries for BEVs and 16% for PHEVs.

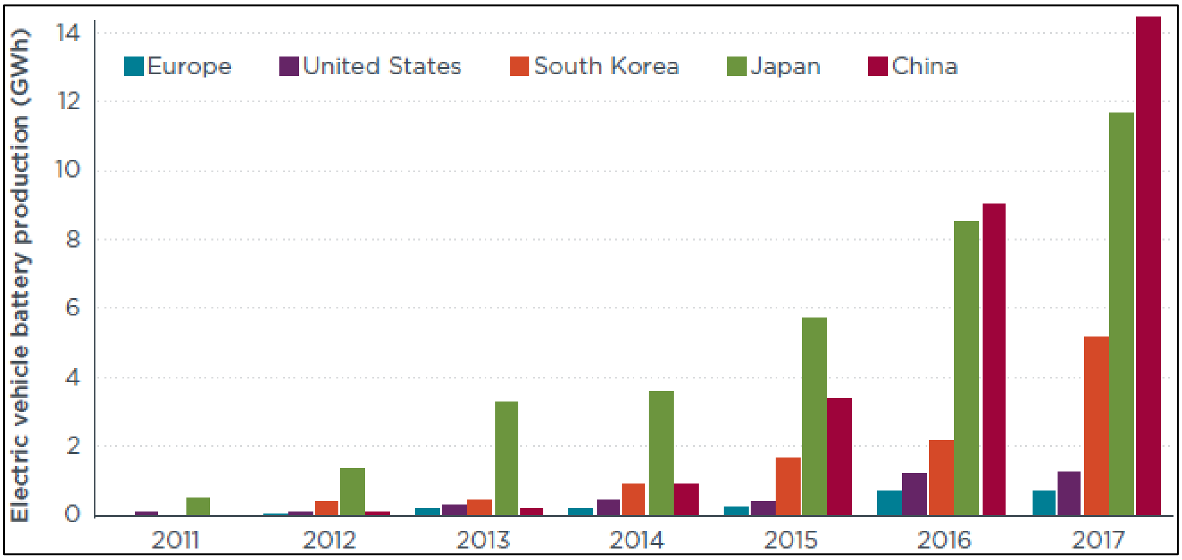


**Figure 14. Electric vehicle battery cell production capacity by region, 2010-2017**[2]

[1] MEEUS, M., (2018). "Final report. European Battery Cell R&I Workshop." *European Commission.* February 12, 2018. <http://europa.eu/!ft46wu> p. 17

[2] LUTSEY N., GRANT M., WAPPELHORST S. & ZHOU H. (2018). "Power play: How governments are spurring the electric vehicle industry." *The International Council on Clean Transportation (ICCT).* May, 2018. <https://www.theicct.org/sites/default/files/publications/EV_Government_WhitePaper_20180514.pdf>

The locations for new battery cell production plants are summarized in the table 5 below. In addition, A123 - recently began operations in new factory in Ostrava, Czech Republic for assembly of advanced 12V Lithium-ion starter battery and next generation 48V battery.[1] BMZ opened the first section of what will be Europe's biggest lithium-ion battery factory in Karlstein, Bavaria, and intends to launch their own, extremely efficient cell manufacturing soon.[2]

**Table 5. Announced and reported new EV battery cell production plants [3]**

| Plant type | Company | Location | Battery production capacity (GWh) | Potential completion timing |
|---|---|---|---|---|
| New | LG | Wroclaw, Poland | 4 | 2018 |
| | SDI | Göd, Hungary | 2.5 | 2018 |
| | Tesla | Nevada, United States | 35 | 2018 |
| | BYD | China | 13 | 2020 |
| | Lishen (multiple) | China | 17 | 2020 |
| | CATL (multiple) | China | 37-42 | 2020 |
| | SKI | Hungary | 7.5 | 2020 |
| | TerraE | Europe | 5 | 2020 |
| | GSR | Sweden | 30 | 2020-2025 |
| | Northvolt | Sweden | 32 | 2020-2025 |
| | Tesla | Europe | 35 | 2020-2025 |
| | Tesla | Shanghai, China | 35 | 2020-2025 |
| | Tesla | To be determined | 35 | 2020-2025 |
| Expansion | LG | Nanjing, China | 6 | 2018 |
| | LG | Michigan, United States | 2 | 2018 |
| | LG | Ochang, South Korea | 10 | 2019 |
| | SKI | Seosan, South Korea | 25 | 2020 |
| | BPP | Liyang, China | 7 | 2020 |
| | SDI | Xian, China | 2 | 2020 |
| | SDI | Ulsan, South Korea | 2 | 2020 |
| | CALB | Luoyang, China | 2 | 2020 |
| | LG | Wroclaw, Poland | 9 | 2020-2025 |
| | TerraE | Europe | 29 | 2028 |

It comes out of the table that there are several so-called battery "gigafactories" that are going to emerge in the next following years. While Chinese manufacturers plan to expand their factories both in China and in Europe, the European-based companies are only

[1] LIVONIA M. (2017). " A123 Systems Celebrates Opening of Czech Plant." *Globe Newswire*. March 2, 2017. <https://globenewswire.com/news-release/2017/03/02/930442/0/en/A123-Systems-Celebrates-Opening-of-Czech-Plant.html>

[2] PROPHET G. (2016). "Gigafactory Battery Factory in Europe Opens." *EE Times*. May 18, 2016. <https://www.eetimes.com/document.asp?doc_id=1329703>

[3] LUTSEY N., GRANT M., WAPPELHORST S. & ZHOU H. (2018). "Power play: How governments are spurring the electric vehicle industry." *The International Council on Clean Transportation (ICCT)*. May, 2018. <https://www.theicct.org/sites/default/files/publications/EV_Government_WhitePaper_20180514.pdf>

targeting the local market. In Europe, by 2020 there will be new manufacturing capabilities accounting 125 GWh, of which only 40 GWh would be produced by European companies. For the moment, the US is only represented by gigafactory for Tesla cars, which is producing battery cells both for cars and for energy storage applications.

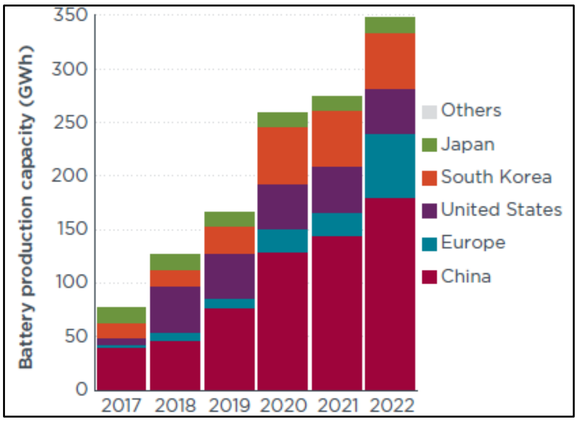


**Figure 15. Announced electric vehicle battery pack production capacity by region, 2017-2022[1]**

According to figures above, the future estimations on battery production predict the constant increase in production volumes. Most of the production will be done in Asia, and almost all supply will be guaranteed by Asian manufacturers. This confirming that most of Asian manufacturers will be establishing European plants for local production. Also Joint Research Center (JRC) study predicts that even in the negative case scenario when EV uptake is low, the European battery cell manufacturing cannot catch up with local battery cell production needs (Steen et al., 2017).

According to different sources, the global battery cell production for EVs in 2016 was around 23 GWh (45 GWh including batteries for busses).[2,3] In 2018 world capacity already reached 131 GWh.[4] In the coming years the capacity of 400 GWh could be reached by 2025 (Lebedeva, Di Persio & Boon-Brett, 2016) or already by 2021[5]; and over 1300 GWh by 2030[6,7]. China is expected to catch 73% of local manufacturing of battery cells. At the same time the European Commission has estimated the potential battery value chain

[1] LUTSEY N., GRANT M., WAPPELHORST S. & ZHOU H. (2018). "Power play: How governments are spurring the electric vehicle industry." *The International Council on Clean Transportation (ICCT).* May, 2018. <https://www.theicct.org/sites/default/files/publications/EV_Government_WhitePaper_20180514.pdf>

[2] BLOOMBERG NEW ENERGY FINANCE. (2017). "Electric Vehicle Outlook 2017." *Bloomberg Finance L.P.2017*

[3] PILLOT, C. (2017). "Lithium-ion battery raw material supply and demand 2016-2025." *Avicenne Energy.* June 19, 2017. <http://www.avicenne.com/articles_energy.php>

[4] BLOOMBERG. (2018.) "Electric Vehicle Outlook 2018." *Bloomberg New Energy Finance.* <https://bnef.turtl.co/story/evo2018?src=LI>

[5] Idem

[6] Idem

[7] BLOOMBERG NEW ENERGY FINANCE. (2017). "Electric Vehicle Outlook 2017." *Bloomberg Finance L.P.2017*

market as being worth 250 billion euros annually, which corresponds to several 10 to 20 GWh production capacities and requires up to €20 billion investments.[1]

### 1.4.2. Material use in batteries and future material demand estimations

Main raw materials used in battery production are copper, aluminium, graphite, nickel, lithium and manganese. Critical raw materials for Europe (those having economic importance and those not available in sufficient amount in Europe) are cobalt, natural graphite, silicon metal, and to a certain extent - refined lithium (Steen et al., 2017).

Currently the supply is only ensured by a few countries (figure 16), which creates European dependence from the raw material imports.

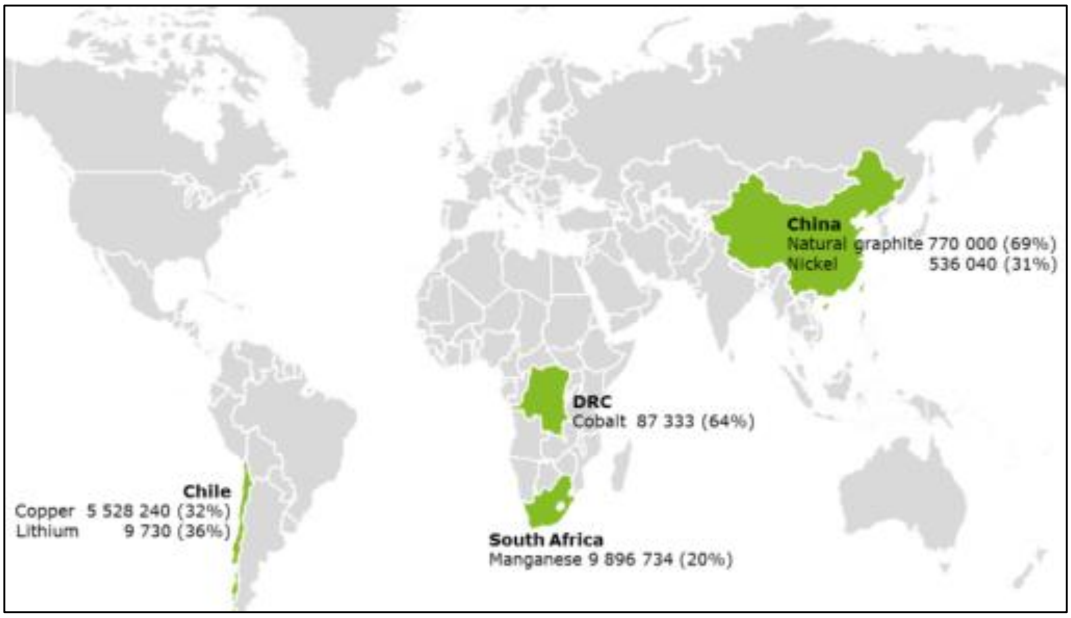


**Figure 16. Countries accounting for the largest share of global production of battery raw materials (tonnes, % global supply)[2]**

China is place for natural graphite (69%) and nickel (31%), Congo possesses 64% of cobalt, South Africa 20% of manganese, and Chile – 32% of copper and 36% lithium. However, the materials are processed in different countries, which change the picture for the availability of processed and refined materials for battery production. For example, China possesses the world's largest share of lithium and cobalt refining facilities. The supply of raw materials shall be secured through international collaboration agreements and R&I in order to decrease the use of these materials whilst keeping same battery performances.

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[1] EUROPEAN COMMISSION. (2018.) " Speech by Vice-President for Energy Union Maroš Šefčovič at the Industry Days Forum on the Industry-led initiative on batteries / the EU Battery Alliance." *ec.europa.eu.* February 23, 2018. < http://europa.eu/rapid/press-release_SPEECH-18-1168_en.htm>

[2] EUROPEAN COMMISSON. (2018.) "Report on Raw Materials for Battery Applications. SWD(2018) 245 final." *ec.europa.eu* May 17, 2018. <https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf>

Europe has potential local reserves of nickel, cobalt and lithium. However, the deposits of European raw materials will not be sufficient to meet the demand (Steen et al., 2017).

With the time, the EV battery capacity increases because of the more effective technologies, especially when it comes to NMC optimisation (as described in section 1.1). The figure below shows the average battery capacity of vehicles sold in different parts of the world.

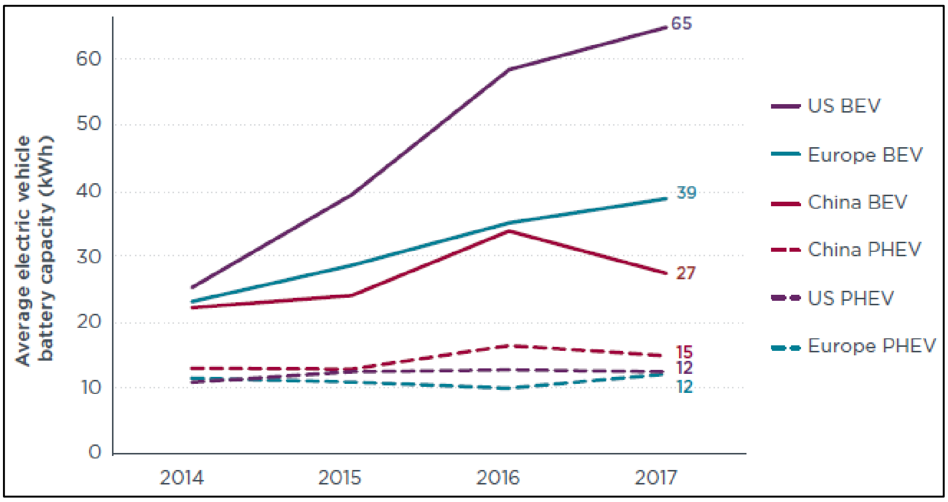


**Figure 17. Average battery capacity of EV by region, 2014 – 2017**[1]

The average capacities are constantly increasing over time. European BEVs have an average capacity of 39 kWh, while in the US it amounts for 65 kWh, due to the high capacity of Tesla batteries.

Larger capacities mean the more extensive use of raw materials. Recent demand estimation for global metal and material demand for passenger EVs is presented below.

The figure 18 below shows that in the next 10 years, the **global** raw material demand will increase exponentially and surpass 7 million metric tons in 2030. Therefore the demand for components (electrolyte, electrodes) will also increase over 10 million metric tons in 2030, currently being only 0.7 million.

[1] LUTSEY N., GRANT M., WAPPELHORST S. & ZHOU H. (2018). "Power play: How governments are spurring the electric vehicle industry." *The International Council on Clean Transportation (ICCT).* May, 2018. <https://www.theicct.org/sites/default/files/publications/EV_Government_WhitePaper_20180514.pdf>

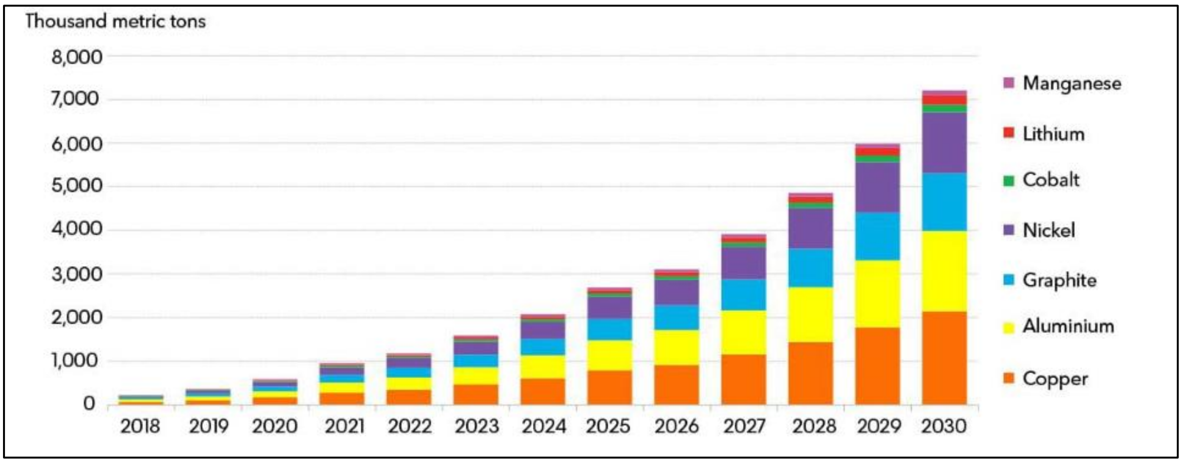


**Figure 18. Metal and materials demand for li-ion battery packs in passenger EVs**[1]

**In Europe**, the critical raw material demand for EV batteries will increase up to 25 times by 2030 compared to 2015.

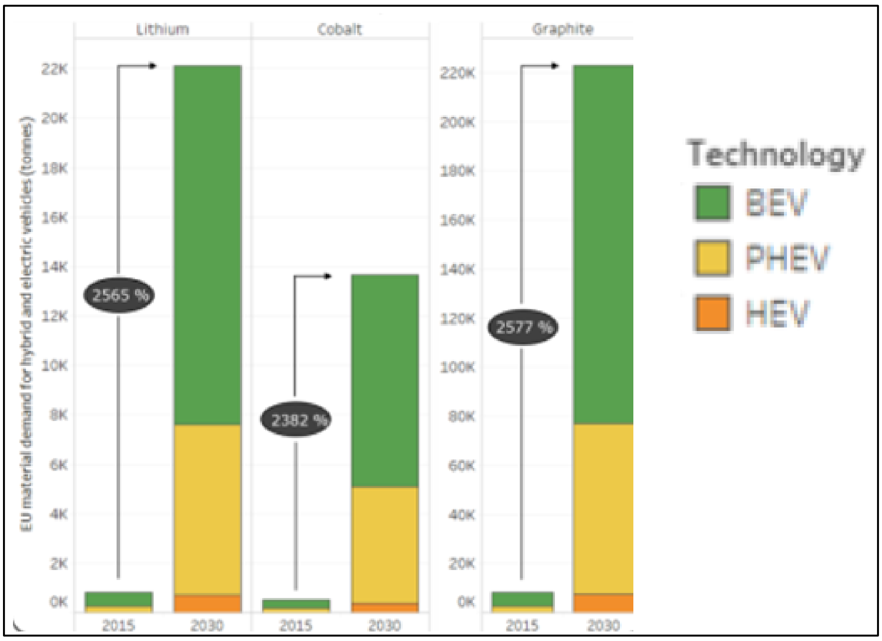


**Figure 19. Demand forecast in Europe for lithium, cobalt and graphite in 2030 by vehicle type**

The total amount of lithium for EVs could reach 22 thousand tons, cobalt would reach 14 thousand tons and graphite 220 thousand tons by 2030. Around 70% of raw materials would be needed for fully electric vehicles. However, the source does not specify the vehicle type (passenger, bus or trucks).

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[1] BLOOMBERG. (2018.) "Electric Vehicle Outlook 2018." *Bloomberg New Energy Finance.* <https://bnef.turtl.co/story/evo2018?src=LI>

### 1.4.3. Battery cell and related material price

Battery accounts for about 50% of EV value, and battery cells represent more than 50% of the value of the battery, from which materials account for about 70% (depending on technology and manufacturer) and therefore materials impact drastically on cell producer's profit.

There is a fundamental difference between the price and cost structures of the battery cell.

When examining **cell component cost**, the most costly parts are the negative (24%) and positive (28%) electrodes, because they require noble materials (Berckmans et al., 2017). Berckmans at al. (2017) have performed cost estimations for both, low production and high production quantities, amounting 432 $/kWh and 300 $/kWh respectively.

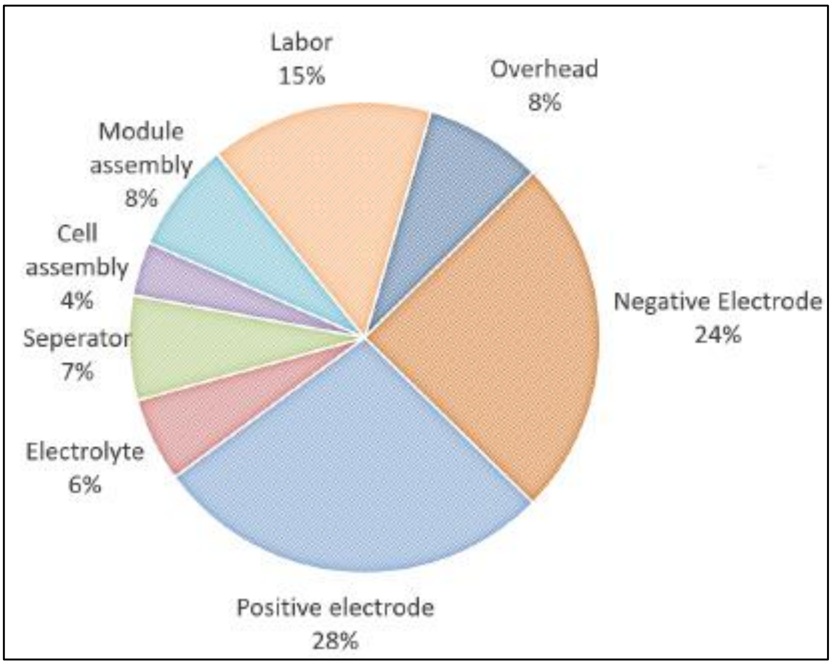


**Figure 20. Cost breakdown of NMC622 battery, 2017**

When looking at at the battery **cell price** on average, as shown in the figure 21, the 22% of the price is the cathode, 6% is the anode and the electrolyte, 7% the separator and 11% are other materials. Among other major expenses the depreciation (14%) and profit margin (about 7%) are the most costly. Berckmans at al. (2017) estimate in their study that the price in low production quantities could increase by 55% if compared to the costs, because of the added profit margins and miscellaneous costs.

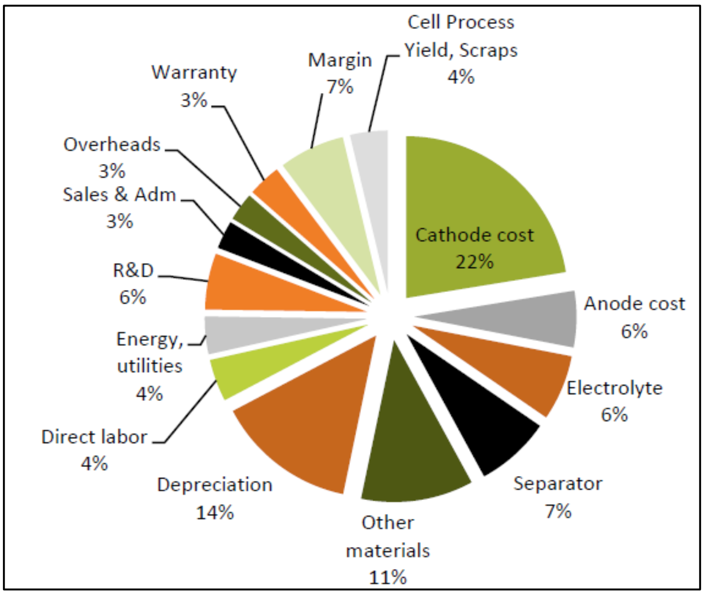


**Figure 21. Average price structure of Li-ion cell, 2016**[1]

On average currently the total price of a cell is approximately 190 €/kWh, thus meaning that the cathode is costing about 42 €/kWh, and the anode about 11.5 €/kWh.

However, the Li-ion battery cell price is expected to decrease, as shown in the figure below. According to recent market analysis, in 2020 the cell cost will be below 160 €/kWh (190 $/kWh) and 125 €/kWh (150 $/kWh) in 2025. This is challenging for the industry, since battery raw materials increase in price, but at the same time the costs of cells have to decrease.

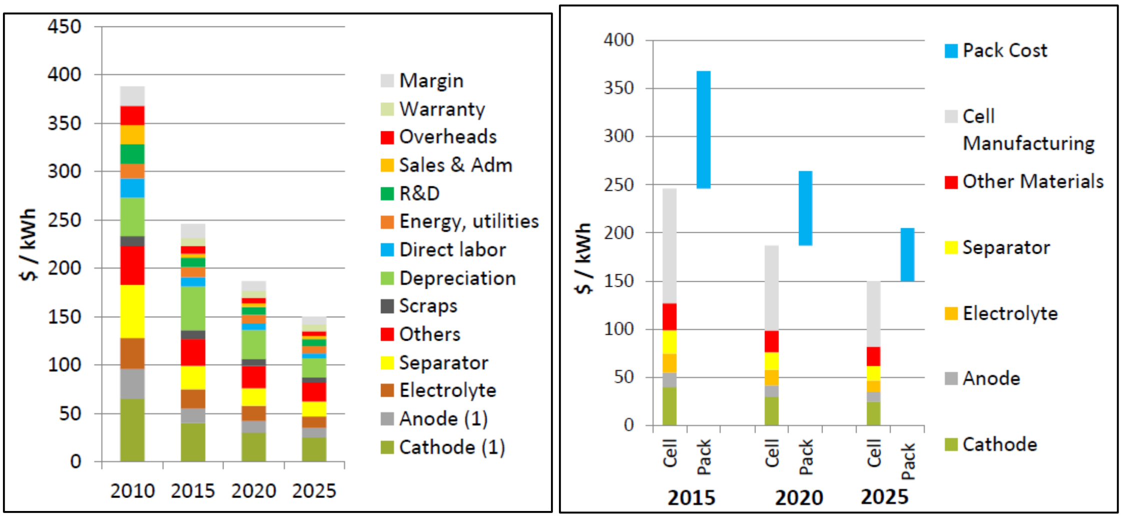


**Figure 22. Li-ion cell (left) & pack (right) average price (NMC pouch for EV)**[2]

[1] PILLOT, C. (2017). " Lithium-ion battery raw material supply and demand 2016-2025." *Avicenne Energy*. June 19, 2017. <http://www.avicenne.com/articles_energy.php>

[2] Idem

Other estimations are more ambitious. BNEF forecasts battery pack prices to fall to approximately 85 €/kWh by 2025, and 63 €/kWh by 2030.[1] The Integrated SET-Plan, which sets the European targets on battery performance, predict that it is feasible to reach 90 €/kWh by 2022 and 75 €/kWh by 2030 for battery packs.[2].

It is important to mention that battery component manufacturing is an energy-intensive process with a total Global Warming Potential (GWP) of 112 kg $CO_2$ eq/kWh. To produce 1 kWh of battery capacity, the necessary energy input is 490 kWh (Steen at al., 2017). Therefore the use of renewable energies in battery manufacturing is crucial.

While demand is increasing rapidly, the raw material production capacities remain quite limited. Large investments have to be made for new mining facilities. Metal and material supply shortages can bring up batteries market price.

Figure 23 represents the price forecasts for the selected metals, according to the data availability.

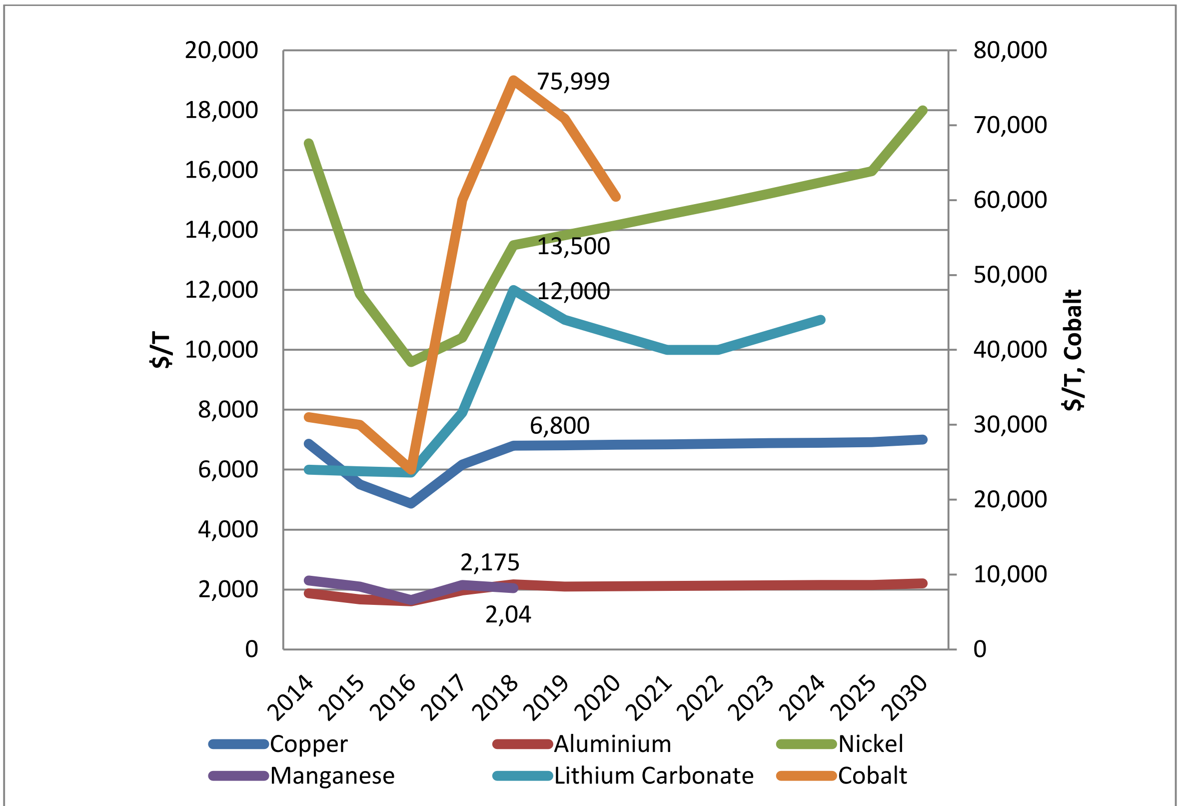


**Figure 23. Price estimates for metals used in batteries, $/T[3]**

[1] CURRY C. (2017). "Lithium-ion Battery Costs: Squeezed Margins and New Business Models." *Bloomberg New Energy Finance.* July 5, 2017. <https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf>

[2] EUROPEAN COMISSION. (2016). " SET-Plan ACTION n°7 –Declaration of Intent." *setis.ec.europa.eu* July 12, 2016. <https://setis.ec.europa.eu/system/files/integrated_set-plan/action7_declaration_of_intent_0.pdf>

[3] Author's work. Sources of data: THE WORLD BANK. (2018). "World bank commodities price forecast." *The World Bank.* April 24, 2018. <http://pubdocs.worldbank.org/en/458391524495555669/CMO-April-

It can be concluded that aluminium and most probably manganese and copper prices will not vary considerably in future. Conversely, cobalt and nickel prices are rapidly changing, and most probably increasing in future. Cobalt price increased by 220% just in two years from 2016 to 2018, but its price is expected to decrease with the development of new technologies using less cobalt. For the same period nickel price increased by 40%, and the price is expected to gradually increase up to 2030. Lithium price fluctuations are expected to remain between $10 and $12 thousand per T, since lithium is relatively highly abundant in the earth crust (Lebedeva, Di Persio & Boon-Brett, 2016).

## 1.5. Conclusions from the Li-ion battery demand

It can be concluded that the demand for the Li-ion batteries will be mostly driven by the rapid uptake of electric vehicles. However, the increasing demand for renewable energy will also raise the use of electrochemical energy in stationary storage.

The EV price is expected to decrease together with the battery price. However, the increasing amount of EVs creates a demand for raw materials, which bring the raw material price up. Since 50% of battery cell cost is derived from material costs, the challenge for the battery industry is to deliver cheaper batteries despite the price of metals tends to increase. Costs cutting are thus expected to be achieved in margins, labour, R&I and other major cost items as presented in the figure 14. Improvements in manufacturing technologies are also sensitive.

Supply increase through new mining facilities could lead to material price decrease. Moreover, raw material price also depends on improved production technologies and costs (for example rock or brine used for lithium production).[1]

Bloomberg estimated that by 2025 a total of 95 GWh of second life batteries could become available, of which 30% would be used in second life applications.[2] If this estimation was valid it would represent a huge market potential for both – second life and recycling which should cope with the remaining 70% of used Li-ion batteries very soon.

In the next chapter a detailed analysis on batteries second life will be performed.

2018-Forecasts.pdf>; INVESTMENT MINE (2018). "Metal price charts" *Investment Mine – Mining markets & Investment.* <http://www.infomine.com/investment/metal-prices/>; TRADING ECONOMICS (2018). "Cobalt – Forecast." *Tradingeconomics.com* <https://tradingeconomics.com/commodity/cobalt/forecast>

[1] EUROPEAN COMMISSON. (2018.) "Report on Raw Materials for Battery Applications. SWD(2018) 245 final." *ec.europa.eu* May 17, 2018. <https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf>

[2] CURRY C. (2017). "Lithium-ion Battery Costs: Squeezed Margins and New Business Models." *Bloomberg New Energy Finance.* July 5, 2017. <https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf>

# 2. BATTERIES SECOND LIFE: MOTIVATIONS AND RISKS

## 2.1. Literature review and PESTEL analysis

In order to analyse impacts of batteries second life from various perspectives, the literature review will be structured according to the PESTEL (Political, Economic, Social, Technological, Environmental, Legal) analysis.

### 2.1.1. Political/Legal

For the time being, there is no specific regulation developed for batteries second life. However there are several emerging policies supporting second life in Europe. An overview of political and legal initiatives and priorities related to batteries on European level is provided below and clustered by the main policy areas – environmental, transport, energy and research.

**Environmental policy**

In the scope of the European Circular Economy Package there are several regulatory and non-regulatory initiatives related to batteries.

- The ***Directive 2006/66/EC*** on batteries and accumulators and waste batteries and accumulators ("the **Batteries Directive**") covers all types of batteries and accumulators, establishes objectives for key stages in their life cycle, such as their placing on the market and recycling aspects and defines obligations for actors involved (authorities, manufacturers, sellers, importers, etc.).[1] The directive on **Waste Electrical & Electronic Equipment 2012/19/EU** also covers appliances containing batteries. These legislative acts and their revisions would include EVs and their components, notably the batteries definition which contain materials such as rare-earths, lithium etc, and comprise EV batteries in the reuse/recovery and reuse/recycling targets.
- Re-use is only defined for the use of the same purpose/original applications in the **Waste Framework Directive 2008/98/EC**. The **Directive 2000/53/EC on end of life vehicles** (ELV) is also currently being revised, and includes the notice, that re-use means that components of end of life vehicles are used for the same purpose. Both notices could hinder the use of second life batteries in stationary storage, since it is not the same purpose use as in the first life. In the present state of the Directive,

[1] EUROPEAN COMMISSION. (2016). "Evaluation of Directive 2006/66/EC of 6 September 2006, on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC" *ec.europa.eu.*August 16, 2016. <http://ec.europa.eu/smart-regulation/roadmaps/docs/2017_env_016_batteries_evaluation.pdf>

batteries meant to be used as vehicle starter batteries and are currently mainly lead-acid batteries.[1]

- Innovation Deal was launched to help removing regulatory barriers for the take up of innovative solutions in general, and in the field of environmental sustainability in particular. The **Innovation Deal "*From E-Mobility to recycling: the virtuous loop of the electric Vehicle*"** was recently signed by the European Commission, French and Dutch governments and industrial partners – Renault, Lomboxnet and Bouygues.[2]

**Transport policy**

- Current regulatory arena in Europe sends clear signals to automakers about the need to deploy clean and energy-efficient technologies in transport. The European Commission recently published "**Europe on the Move**" package, which includes a series of legislative and non-legislative measures to help transport sector to stay competitive and also to drive the transition towards clean energy.[3] It includes such legislations, as $CO_2$ emission standards for cars, vans and heavy duty transport, and promoting procurement for alternative energy public transport.
- Within **GEAR 2030** initiative, established in 2016 to address the challenges faced by the European automotive industry, a working group dealing with the "adaptation of the value chain to new global challenges" proposed recommendations dedicated to zero emission vehicles, in particular for electric vehicles and electric batteries.[4]

**Energy policy**

- The Communication **Accelerating Clean Energy Innovation** provides a forward-looking enabling framework to develop and deploy innovative solutions in support to the transition to a low-carbon energy system. The Commission committed to invest more than €2 billion over the period 2018-2020 into four priority areas among which feature storage and e-mobility.[5]

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[1] EUROPEAN COMMISSION. (2018). "Batteries & Accumulators." *ec.europa.eu.* January 15, 2018. <http://ec.europa.eu/environment/waste/batteries/index.htm>

[2] EUROPEAN COMMISSION. (2018). "European Commission tackles barriers to innovation: the second Innovation Deal focuses on batteries for electric vehicles." *ec.europa.eu.* March 12, 2018. <https://ec.europa.eu/info/news/european-commission-tackles-barriers-innovation-second-innovation-deal-focuses-batteries-electric-vehicles-2018-mar-12_en/>

[3] EUROPEAN COMMISSION. (2017.) " Europe on the Move: Commission takes action for clean, competitive and connected mobility." *ec.europa.eu.* May 31, 2017. <https://ec.europa.eu/transport/modes/road/news/2017-05-31-europe-on-the-move_en>

[4] GEAR 2030. (2017.) " High Level Group report on the Competitiveness and Sustainable Growth of the Automotive Industry in the European Union." *ec.europa.eu.* October 2017. <https://ec.europa.eu/docsroom/documents/26081/attachments/1/translations/en/renditions/native>

[5] EUROPEAN COMMISSION. (2016). " COM(2016) 763 final. Accelerating Clean Energy Innovation." *ec.europa.eu.* November 30, 2016. <https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v6_0.pdf>

- **The Integrated Strategic Energy Technology (SET) Plan**[1] identifies 10 key Actions where research and innovation is needed to accelerate Europe's energy system transformation in a cost-effective way, and which can create jobs and growth, ensuring the European Union's leadership in the development and deployment of low-carbon energy technologies. Of these key actions, Action 7 "Become competitive in the global battery sector to drive e-mobility and stationary storage forward" recognises batteries as a low-carbon energy storage technology and that there is a need to scale-up a competitive manufacturing base in Europe.[2]
- **The EU Battery Alliance** was created in 2017 as a joint industry-led initiative at European level focused, initially, on battery cell manufacturing. The Alliance was established in order to prevent major technological dependences and to ensure that European companies capture the emerging market share. For this, the EU Industry, the innovation community and Member States have to work together to create a competitive and innovative battery cell manufacturing base in Europe.[3]

**Research policy**

European Research funding programmes support collaborative pre-competitive research projects thus driving innovation and securing Europe's global competitiveness.

- **European Union Research funding programmes** have already invested more than EUR 250 million in battery projects (since 2008)[4] and about EUR 200 million have been allocated for future projects for the years 2018 – 2020.[5]

EU funds research on battery constituent materials and chemistries, manufacturing processes of battery components, final pack assembly, battery management systems, ageing assessment, integration of the battery pack, as well as research on recharging systems. Battery reuse and recycling is also included in research priorities.

- **A Project for Policy report on Batteries**[6] summarizes main advancements and impacts from EU funded research projects on batteries. It also addresses the three

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[1] EUROPEAN COMMISSION. (2015). "C(2015)6317 Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation." *ec.europa.eu.* September 15, 2015. <https://setis.ec.europa.eu/system/files/Communication_SET-Plan_15_Sept_2015.pdf>

[2] EUROPEAN COMMISSION. (2016.) " Batteries for e-Mobility and Stationary Storage." *ec.europa.eu.* August 28, 2016. < https://setis.ec.europa.eu/implementing-integrated-set-plan/batteries-e-mobility-and-stationary-storage-ongoing-work>

[3] EUROPEAN COMMISSION. (2018.) " Speech by Vice-President for Energy Union Maroš Šefčovič at the Industry Days Forum on the Industry-led initiative on batteries / the EU Battery Alliance." *ec.europa.eu.* February 23, 2018. < http://europa.eu/rapid/press-release_SPEECH-18-1168_en.htm>

[4] EUROPEAN COMMISSION. (2017). "Batteries - a major opportunity for a sustainable society" *Publications Office of the European Union, Luxembourg* <https://publications.europa.eu/en/publication-detail/-/publication/d9f3bd80-cb49-11e7-a5d5-01aa75ed71a1/language-en/format-PDF/source-69927140>

[5] EUROPEAN COMMISSION. (2018). "Smart, Green and Integrated Transport Work Programme 2018 – 2020."C(2017)7124 of 27 October 2017.http://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-transport_en.pdf>

[6] EUROPEAN COMMISSION. (2017). "Batteries - a major opportunity for a sustainable society" *Publications Office of the European Union, Luxembourg* <https://publications.europa.eu/en/publication-

main policy challenges in the field of battery research: (a) the transformation towards low-emission transport, (b) the production and storage of electricity from renewable energy sources, and (c) the establishment of a sustainable and efficient value chain for batteries. It gives recommendations for future policy orientations, including facilitating the reuse of batteries for new purposes and stimulating recycling of automotive and industrial batteries.

- Within the previously mentioned "Europe on the Move" action, the Commission Staff Working Document on **Transport Research and Innovation contribution towards clean, competitive and connected mobility** was developed. It comprises a roadmap which summarizes the main trends, developments and research needs in the area of transport electrification, including batteries.[1]
- The European Commission together with the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) have launched a common initiative to increase collaboration between the scientific, industry and standardisation stakeholders entitled **"Putting Science into Standards".** A workshop was held on EV performance and safety assessment of batteries, as well as recycling and second-use applications where current activities and future needs for standardization of batteries were discussed (Ruiz et al., 2016).

All in all, European policies potentially support batteries and possibly second life mostly due to the potential environmental benefits it could bring. Also triggering global competitiveness is the second motivation for developing second life batteries. However, apart from political orientations no information was found on existing fiscal or economic incentives directly related to battery second use in energy storage.

### 2.1.2. Economic

As discussed before, the main bottleneck of the EV is its cost, namely, the cost of the battery. One of the solutions is to continue R&I on electrochemistry and manufacturing processes to lower initial costs. However, the second life can also be seen as a strategy to reduce the cost of the battery – by increasing battery lifetime and thus extracting additional services and revenue from it in post vehicle applications, so that the total valuable lifetime of the battery is increased and shared between "first" and "second" life users (Neubauer, Wood & Pesaran, 2015).

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detail/-/publication/d9f3bd80-cb49-11e7-a5d5-01aa75ed71a1/language-en/format-PDF/source-69927140>

[1] EUROPEAN COMMISSION (2018). "SWD (2017)223 final. Towards clean, competitive and connected mobility: the contribution of Transport Research and Innovation to the Mobility package." *ec.europa.eu.* May 31, 2017. <https://ec.europa.eu/transport/sites/transport/files/swd20170223-transportresearchandinnovationtomobilitypackage.pdf>

In this context, **profitability** (discussed in this section) and **liability** (discussed further in section 2.1.6.) are the most challenging aspects to actors across the whole value chain (Reuz et al., 2016).

Some studies suggest that battery replacement before 15 years of operation is not economically justified (Neubauer, Wood & Pesaran, 2015) and that on average the maximum battery lifetime is 20 years (Neugebauer et al., 2012). This implies that batteries will become available for second life applications only after 15 years.

From the perspective of the potential second life battery **seller**, the cost of the second life applications is determined by the initial cost of the used batteries, balance of system cost, refurbishment cost, transportation cost, and operation and maintenance (O&M) costs (Narula et al., 2011). However, main costs remain the replacement are **initial battery costs at the end of the first life** and **repurposing costs** incl. testing and retrofitting (Neubauer & Pesaran, 2012). These costs affect also the value and price (value including incurred costs) of the second life battery and for the battery owner.

From the economic perspective, the dismantling of batteries up to cell level is not economically viable, since it requires additional workforce. Since input streams consisting of various cell chemistries, cell designs are very differentiated, dealing with small individual cells makes the cost of reconditioning prohibitive (Reid & Julve, 2016). But even on pack level a recent study found out from the stakeholder interviews that currently second-use packs are more expensive (in terms of €/kWh/n.cycle) than the first pack use (Bobba et al., 2018).

A study of 2012 estimates that the value of a second life battery would be about 17 – 85€/kWh (20-100$/kWh), and the repurposed battery price would range from 32-110 €/kWh (38-132$/kWh) (Neugebauer et al., 2012). However, in this study as a baseline for the Li-ion battery costs the prediction was taken that costs will fall linearly from $795 in 2012 to $440 per kWh in 2020. This would mean that in 2015 the predicted price would be around $660 per kWh, whereas in the reality the price of was 370 $/kWh (figure 22 previously). This implies that the costs and value of the repurposed battery nowadays could be much lower.

Currently, there are estimations that in order for a second life battery to be viable, the costs for this **battery shall be below $70 (€60) per kWh by 2022** (Reuz et al., 2016). Debnath, Ahmad & Habibi (2016) have demonstrated that if second life battery final price is 10% of the cost of equivalent new battery it can be economically viable.

At the same time there is an evidence that the pilot projects by company NREL have demonstrated the feasibility **to repurpose batteries at a cost of 25-50 €/kWh**, price being dependent on type and state of health of the battery, the amount recycled (economies of scale) and the remanufacturing process (Reid & Julve, 2016).

Assuming that the repurposing costs will not change, it means that the price of the initial battery shall be between 10 - 35 €/kWh by 2022. To evaluate the economic attractiveness of using the second life, in chapter 3 of this thesis the value of materials imbedded will be estimated.

A case study of using 34 €/kWh second life battery to replace a conventional energy storage for dispatching energy when most needed, demonstrates outstanding financial benefits, however, again, under certain set of conditions, such as high conventional energy storage costs, and full utilisation rate (Debnath, Ahmad & Habibi, 2016).

All in all, from the perspective of the car battery owner the second life is definitely a very suitable option in order to generate additional incomes from the extended use of battery. However, the cost of the initial battery at the end of its first life plus repurposing costs, must be lower than the expected revenue.

From the perspective of potential **buyer** or service user of the second life battery, it might be true that the second life battery would sell for the same price as a new battery. Neubauer at al. (2012), estimate that the value to the battery owner would be quite small, since declining battery costs and other factors strongly affect the initial end of first life battery price. Therefore an investment decision would most probably be oriented towards choosing the new battery because of efficiency, remaining lifetime and safety reasons.

Williams & Lipman (2011) also find positive but very moderate economic benefits, but they admit that it is possible only under certain set of assumptions and pre-conditions, which require further coordination, standardizations, code and safety procedure development.

Similarly, savings from the second life batteries use in residential applications arise for peak shaving case, but without government intervention they are very marginal (Heymans et al., 2014) or non-existent for a single use in building energy management systems (Beer et al., 2011).

Narula et al. (2011) conclude that the business case for second life batteries emerge only when applications with a low utilization factor are combined with applications that increase the utilization factor of the system, as already discussed in the section 1.3. about the general economic viability of battery use in energy storage.

However, second life battery use for multiple purposes in microgrid level (intermittent supply regulation on a local level, peak shaving of a network of buildings) generates incomes, and applications in macrogrid (regulation of energy and spinning reserves) reduces system costs the most (Beer et al., 2011).

#### 2.1.3. Societal

A study made by Jiao & Evans (2016) proposed three deciding factors for second life: battery ownership, inter-industry partnerships and government support. These factors impact both the public and the industrial community stakeholders.

**Battery ownership** is important when applying unified management of batteries and facilities for second life on large scale. Currently there are different battery ownership models possible (either by an OEM, or the car owner).

It may be derived that fleet operators might be first potential stakeholders to put their batteries for second use, especially considering recent tendencies in mobility[1] – increasing shared mobility services, automated driving – which will increase the number and role of fleet operators. However, this is only the case if they are deemed responsible for the battery. Therefore the control of the battery is the pre-condition for any kind of second life operations (also questioned under legal aspects below).

Since battery second life is a cross-sectoral concept, it requires **inter-industrial partnerships** to establish collaboration between actors across the mobility and energy value chains.

As a potential solution in Europe, this could be solved by closer collaboration of European players. The existing structures, such as RECHARGE association[2], European Green Vehicles Association[3] and Renewable Energy Associations[4] (mostly wind and solar, but probably others as well) possess required network for enchasing collaboration between stakeholders. On the individual project level, the BRIDGE initiative[5] unites Smart Grid and Energy Storage Projects to create information exchange and collaboration of cross-cutting issues.

Moreover, the European Commission has recently announced a tender for establishing European Technology and Innovation Platform on batteries, gathering all battery stakeholders to work on battery harmonisation activity in Europe. This platform includes work on second life batteries.[6]

A **governmental support** was discussed previously and it has been deemed strong in Europe.

Several studies predict that the most promising applications for second life could be the residential household applications, especially in combination with photovoltaics (Bobba et al., 2018). However, user awareness of the second life concept is still limited and shall be increased.

In general, a positive trend for the second life, is the rising public acceptance of renewables, especially the wind power among all (Wüstenhagen, Wolsink, & Bürer, 2007).

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[1] CORWIN S. & WILLIGMANN P., (2016.) "Future of mobility trends." *Deloitte.* December 10, 2016. <https://www2.deloitte.com/us/en/pages/consulting/solutions/future-of-mobility-trends-industry-ecosystem.html>

[2] The European Association of Advanced Rechargeable and Lithium Batteries. <https://www.rechargebatteries.org/>

[3] European Green Vehicles Association. <https://www.egvi.eu/>

[4] Renewable Energy Associations <https://ec.europa.eu/energy/en/renewable-energy-associations>

[5] Bridge initiative <https://www.h2020-bridge.eu/>

[6] EUROPEAN COMMISSION. (2018). "Establishment of and support to European Technology and Innovation Platform on Batteries." *etendering.ted.europa.eu* <https://etendering.ted.europa.eu/cft/cft-display.html?cftId=3708>

### 2.1.4. Technological

Some studies suggest that 70% of the original battery performance is reached during the 8 years of operation of the EV (Neubauer, Wood & Pesaran, 2015), after which the battery can be repurposed for the second life applications. Other studies predict that EV second life can last up to 3 years (Faria et al., 2014), Ahmadi et al. (2014a) estimated that the EV battery loses 20% of its capacity during its first use in the vehicle and a further 15% after its second use in the stationary storage applications over 10 years. In this thesis the hypothesis is adopted of first life lasting 10 years and second life 5 years.

Remanufacturing of the first life battery process includes removing battery from the EV, transporting it to repurposing facilities, dismantling the battery pack (if deemed necessary), assessing the quality of different components, and re-assembling the battery according to the desired characteristics.

The **level of intrusion** in the battery can be different – from low repurposing to high repurposing. Levels differ by the efforts spent in analysing battery on cell, module or pack level, amount of testing performed, further actions of combining modules according to their remaining capacity etc. Consequently, the more efforts are put in repurposing - the higher effectiveness of the battery, but as well the higher the costs (Williams & Lipman, 2011). Therefore the preferred option from both economic and technical points of view, is the reuse of the whole battery pack (Ahmadi et al., 2014b).

Many researchers have performed a technological feasibility analysis. According to several extensive analysis (Bobba et al., 2018; Neubauer et al., 2012; Cready et al., 2002) **second life is technically possible**. However, several constraints exist specifically relating to second-use, such as determination of degradation levels and state of health (as regards capacity and safety), difficulties in obtaining modules with similar capacity, non-standardized modules, integration of power electronics, and remanufacturing complexity.

However, the most important issues for second life batteries are the **state of health** and **battery degradation** which determine the remaining number of cycles and calendar lifetime of the battery.

In order to estimate the remaining lifetime of a battery, an analysis of battery degradation is required. After first life use, the level of battery cells and modules degradations can be very different (Williams & Lipman, 2011). The battery state of health depends on the driving style, operating conditions, ambient temperature, use of auxiliaries, etc.

There are different empirical, physics-based, semi-empirical models developed to estimate the state of health. For instance, some models are based on data sets of measured battery capacity and resistance, but need large sets of data. Others, more complex physical models are based on simulations and modelling, however, can be very difficult and limited to fixed conditions (Neubauer, Wood & Pesaran, 2015). There are models combining both – the capacity and resistance effects induced by cycling-based and calendar-based mechanisms (Neubauer, Wood & Pesaran, 2015). Alternatively, the models using the data stored in the battery management software can be used for assessment.

However, the results of capacity loss do not necessarily indicate the remaining battery lifetime – it can happen that the capacity can decrease radically within subsequent cycles. Therefore the remaining performance depends on estimations on residual number of cycles and calendar lifetime.

Batteries can lose their performance with each cycle and of time elapsed. Consequently, if batteries are applied in second use, the capacity fade is more critical. However, if battery capacity loss is influential by calendar lifetime, the main driving factor is the battery temperature (primarily determined by climate and weather conditions).

Therefore, in order to estimate the remaining battery capacity also from in-situ measurements and track average battery temperature over time, on board vehicle hardware and software can be installed and used (Neubauer, Wood & Pesaran, 2015).

All in all, the aspect of **battery design** is important, which shall be initially done taking into consideration the possible second life and also recycling. Sometimes it is difficult to extract a battery from the EV due to case welding, and the placement of battery. Also if a battery used in second life applications was not dismantled to module or cell level, one technological challenge is the use of battery management systems (BMS) which are specifically tailored for EVs (Reid & Julve, 2016) which are not always suitable for stationary use.

In these cases a specific battery design and vehicle integration could potentially reduce repurposing costs of dismantling (and recycling eventually) and the use of **BMS** at the individual cell level could help to more effectively identify state of health of each cell (Reid & Julve, 2016).

### 2.1.5. Environmental

Second life concept is mainly attractive from the view point of potential environmental benefits it could bring. They could be used to store renewable intermittent energy and thus increase the proportion of green energy in the energy mix. In addition, prolonging battery lifetime decreases resource use and reduces waste.

Moreover, since this additional lifetime would generate new revenues, it can potentially reduce the cost of the EV (Jiao & Evans, 2016) and thus indirectly contribute to environmental goals through promoting the use of electric powertrains (given that the energy used is coming from renewable sources).

Ahmadi et al. (2014b) found out that replacing natural gas fuel for peak stabilisation by second life batteries reduces $CO_2$ emissions by 56%. This can be compared to the effects on $CO_2$ reduction from switching from using a conventional vehicle to an electric vehicle. Thus, combing both uses, greenhouse gas benefits of vehicle electrification could be doubled by extending the life of EV batteries.

Environmental benefits were also observed when second life batteries were used to replace existing lead-acid storage applications. Environmental and energy impacts have been shown significantly lower in such aspects as assembly and production, accelerating improvements in manufacturing process and in the chemistries themselves (Ambrose et al., 2014).

Also Narula et al. (2011) conclude that the peak shaving is the most promising application, and Farila et al. (2014) further specify that it is heavily dependent on the electricity generation mix.

However, if compared to a conventional vehicle, the BEV production is 60% more emission intensive (2800 kg $CO_2$-eq) due to the battery. It takes 100 000 km driven by EV to compensate this additional environmental impact. The energy required to manufacture the battery is more than 400 times the energy storage capacity. The source of electricity plays an important role in the global warming potential (GWP) of a BEV. Largest contributor to primary energy use and GWP is the cathode, because of complex processing of raw materials and manufacturing process (Steen at al., 2017). Therefore is it crucial to use renewable energies for battery manufacturing.

However, some life-cycle assessment (LCA) GWP studies have demonstrated that second life applications are not always bringing environmental benefits. A case study performed by JRC (Bobba et al.,2018) demonstrated that in the case of peak shaving application *"the addition of a repurposed battery in a building in which no batteries were previously used does not entail benefits."* However, if it is used to replace the new battery, it may be environmentally beneficial, and environmental benefits are even higher if used in a case of increasing photovoltaic (PV) self-consumption. Authors, however, admit that the results are heavily dependent on the battery and system characteristics and the battery chemistries, as well as analysed use cases. Results are confirmed by Farila et al. (2014) study where the second life battery use could even generate higher emissions when compared to a situation where no battery is used for energy storage.

#### 2.1.6. Legal

Legal aspects include the producer **liability** and **warranty** of the second life battery. Currently the OEMs are deemed responsible for the battery, thus obliged to follow legal requirements spelled out in the directives related to waste and recycling. There is not enough clarity on aspects related to passing the responsibility among the business operators from the first to second use. Currently the extended producer responsibility (EPR) is associated to those putting batteries on the market in a certain Member State, whilst at the same time being responsible for end of life management.[1]

Another aspect is the warranty of the repurposed battery. Currently there is no information available about the availability of specifically targeted insurance schemes for the second life applications. No additional public information is available on websites of market actors

[1] TYTGAT J. (2017). "Li-ion battery recycling." *Presentation at the EMIRI Tech Talk on Batteries for Energy Storage - End-of-life and recycling of Li-ion batteries.* February 23, 2017. <https://www.slideshare.net/FabriceStassin/presentation-8-slides-jan-tytgat-umicore?next_slideshow=1>

selling second life energy storage. This is due to the lack of the historical performance data even for the first life applications.

Regarding the decentralised energy production in general, the revision of the Energy Directive in Europe will allow citizens, among other rights, to produce their own electricity and feed any excess back to the grid.[1]

### 2.1.7. Conclusions on PESTEL analysis

Taking into consideration the analysis carried-out above, the table below summarizes main points discussed under each aspect. Moreover an assessment is made as to whether the state of the art situation of each aspect is satisfying, average or insufficient for second life concept uptake.

When the assessment is satisfying all conditions and developments are in favour of second life and the assessment can be considered as a driving factor for second life. Average assessment means that conditions at the given moment are not certain yet. The second life would heavily depend on the future developments in the area of this factor. An insufficient assessment indicates that currently there are blocking factors for the uptake of second life concept and further work has to be done.

**Table 6. Summary of the PESTEL analysis**

| | Motivators | Bottlenecks | |
|---|---|---|---|
| **Political** | Climate and research oriented policies are driving the uptake of EVs and the use of renewable energy storage.<br><br>Extensive governmental financial support for demonstration projects. | Unclear regulations regarding the definitions of "waste", "second use".<br><br>Diverse regulatory barriers in Europe.<br><br>Inexistent incentives for second use batteries. | **Satisfying** |
| **Economic** | Generation of additional revenue streams for the battery owner. | Uncertain price of second life battery in the future.<br><br>Increased price for new materials could raise the price of second life batteries.<br><br>Future competition with new batteries.<br><br>Uncertainty of the concept viability reduces investments. | **Insufficient** |
| **Social** | Associations as a driver for the uptake of the concept.<br><br>Renewable energy is perceived positively in the society. | Battery ownership is a crucial aspect, and not completely detailed for the moment.<br><br>Low user awareness about the second life concept. | **Satisfying** |

[1] EUROPEAN COMMISSION. (2016). "COM(2016) 860 final. Clean Energy For All Europeans." November 30, 2016. <http://eur-lex.europa.eu/resource.html?uri=cellar:fa6ea15b-b7b0-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF>

**Table 6 continued**

| | | | |
|---|---|---|---|
| **Technological** | Models for state of health already developed. | Absence of standards for first and second life batteries.<br>Absence of historical performance data.<br>Inexistent large scale facilities for repurposing.<br>New technologies emerge specifically for energy storage. | **Average** |
| **Environmental** | Increased lifecycle of the battery brings environmental benefits through increased sustainability.<br>New cell production is very energy intensive process. Thus second life increases the value per energy unit used in manufacturing.<br>Promotes the use of renewable energy. | Uncertainty of environmental benefits of second life use.<br>Possibility to generate negative environmental balance of second-use. | **Average** |
| **Legal** | Legal responsibility to deal with first life batteries motivates stakeholders to develop solutions and business cases. | Unclear liability clauses for the use second life battery<br>Inexistent insurance schemes for the use of second life battery<br>Energy directive revision enforces decentralised energy production. | **Insufficient** |

The conclusions was made that the Political and Social environments are encouraging the use of second life batteries in ESS. Developments in Technological and more studies performed in Environmental aspects are necessary to drive the second life battery use. However, Economic and Legal aspects have been assessed as insufficient and can be considered as blocking factors.

## 2.2. Stakeholder analysis

Stakeholder analysis is important to understand the drivers and enablers of each involved actor in the second life ecosystem. An early assessment of stakeholder orientations is very important in overall strategy analysis (Currie, Seaton & Wesley, 2009).

Importance/influence analysis helps to map all stakeholders involved in second life and to identify their relation and influence with regards to the realisation of the second life concept.

Stakeholders with high importance have strong interest in satisfying their needs and interests. On the other hand, stakeholders with high influence have the power to facilitate the way towards second life and have the ability to persuade others into making decisions or to follow a certain path.[1] The stakeholder analysis below is made based on the previously performed literature review.

[1] WAGENINGEN UNIVERSITY AND RESEARCH. (2017). "Stakeholder Analysis: Importance/Influence Matrix." *Mspguide.org*. January 12, 2017. <http://www.mspguide.org/tool/stakeholder-analysis-importanceinfluence-matrix>

**Table 7. Stakeholder analysis for battery second life**

| **High importance/Low influence** | | **High importance/High influence** | |
|---|---|---|---|
| *Actors* | *Instruments* | *Actors* | *Instruments* |
| Research organisations<br>First life battery users (if battery owned by users)<br>Second life battery users | Research results<br>Choice to change the battery<br>Decision to install the second life energy storage | Government<br>OEMs<br>Battery cell recyclers<br>Electricity utility companies | Environmental Policy – regulations on EU/national/regional level<br>Choice of strategy for electric battery end-of-life<br>Better technologies for efficient battery cell recycling<br>Storage of renewable energy – energy price |
| **Low importance/Low influence** | | **Low importance/High influence** | |
| *Actors* | *Instruments* | *Actors* | *Instruments* |
| Component producers<br>First life battery users (if battery owned by OEM) | Choice for chain for raw materials<br>Choice to change the battery | Raw material miners<br>Battery/Cell producers | Raw material supply chain<br>New battery/cell price |

*Low importance/Low influence* actors are involved in the battery ecosystem, but have low engagement rate. Component producers could influence second life by choosing recycled raw materials, and if batteries are owned by an OEM, the battery users do not have the influence or interest to deal with batteries second life.

*High importance/Low influence* actors are those who are directly affected by developments in the second life concept, but cannot directly influence the future of the concept. Those are research organisations who are developing concepts and studies and second life battery end users, who may decide to use the second life batteries.

*Low importance/High influence* actors are those whose decisions will impact second life concept viability, but who are not directly involved in second life development. Those are, for example, raw material miners who can de-risk access to critical raw materials (CRMs), and cell producers who can influence second life through benchmarking the new battery prices.

*High importance/High influence* actors are those whose actions are driving or hindering second life. Governmental policies are impacting private stakeholder strategies. Before the battery can be used in second life applications, the replacement decision has to be made – if the battery is leased or ensured by an OEM, the decision can be straightforward. Therefore OEMs have the strongest motivation to generate additional value in order to decrease the Total Cost of Ownership of the battery. If battery recycling proves to be more efficient than second life, it compromises the second life. Finally, electricity utility companies' strategy towards the utilisation of renewable energy storage directly impacts the uptake of second life batteries.

All in all, direct and indirect actors across the whole batteries value chain are concerned, but their motivations and strategies differ. It is important to consider each of those actors when taking decisions regarding second life.

## 2.3. Second life battery value proposition

As discussed previously the main motivation for the second life use is the additional value it brings. It was found that it could bring economic value to the user of the second life battery and moreover it could decrease the price of EVs.

However, as it was also seen in the literature review, several critical cost and price estimations have been done. In this section an economic competitiveness analysis will be performed according to recent emerging business cases and on Levelized Cost of Energy (LCOS) basis.

**Economic competitiveness analysis**

If taking into account the example of the project "Phénix" (discussed in section 3.1.), the company has announced that the price of repurposed batteries would be the one of a lead acid battery. The project first stage will run from 2018 until 2024. Therefore it can be assumed that repurposed batteries were manufactured in the period of 2008-2014, taking into assumption 10 years of first use. Figure below shows the comparison between Li-ion and Lead acid battery price evolution and estimations.

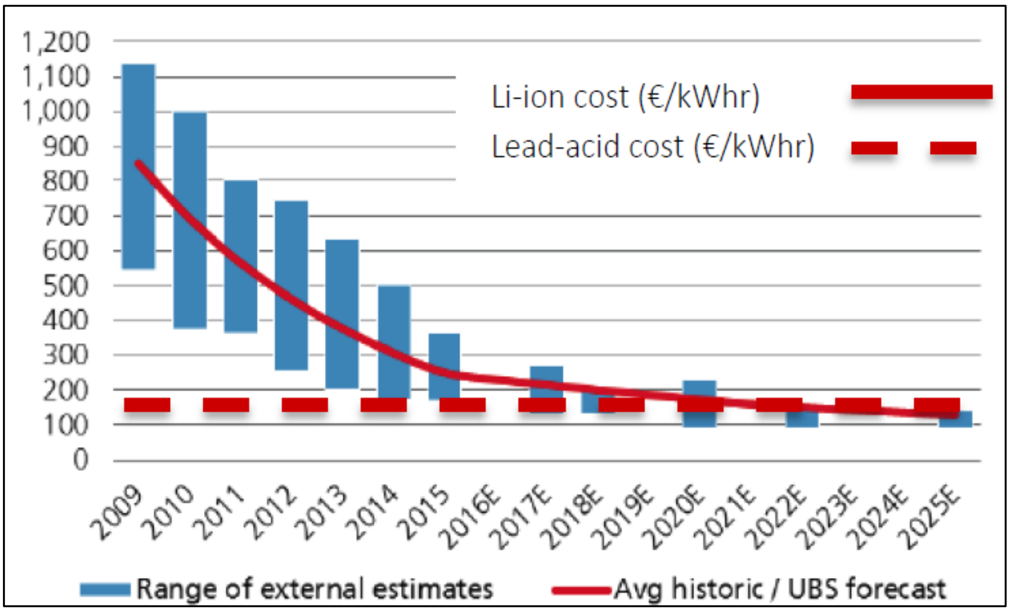


**Figure 24. Li-ion and Lead-acid battery cost forecasts to 2025, €/kWh**[1]

[1] ITRI. (2017). "Lead-Acid Batteries. Impact on future tin use." *Industrial Technology Research Institute.* <https://www.internationaltin.org/wp-content/uploads/2018/03/ITRI-Report-Tin-in-Lead-Acid-Batteries-260318.pdf>

The Li-ion battery produced in 2009 costed on average around 900 €/kWh, and in 2014 the price was approximately 300 €/kWh. At the same time lead acid battery costs remained below 200 €/kWh, it can therefore be assumed that repurposed batteries price will be below 200 €/kWh.

From this the following conclusions can be made –to create additional economic value from batteries manufactured in the time from 2009 to 2014, the second life is a good option. However, according to the announcement of the company, already in 2022 new Li-ion batteries will be cheaper than the repurposed ones. On the other hand, with rapidly decreasing costs of initial batteries, the price of repurposed batteries could drop as well, but this information is not clarified in the announcement of the company.

**Comparative competitiveness analysis**

As analysed in the literature review section, second life does bring environmental benefits if it is replacing the conventional energy storage.

In this section the added-value of the battery will be estimated by comparing the Levelized Cost of Storage (LCOS) of the second life battery to the main alternatives for selected use cases.

LCOS compares cost and performance of different energy storage technologies across several cases of applications. For the analysis performed within this section, the Lazard's LCOS 2017 study was taken as a reference.

In this study the LCOS was compared between major battery technologies – flow battery (V), flow battery (Zn), Lead-Acid, Advanced Lead and Li-ion battery. Five use cases were analysed – in front of meter peak replacement, distribution, microgrid and at the back of the meter applications in commercial and residential scale. Some technologies are applicable only on large scale (flow batteries) and others on smaller scale (lead based batteries). Li-ion has the specify to probably be suitable for both types of applications.

To assess the second life battery positioning within this chart the detailed methodology of calculations is needed. While it can be a topic for further research, in scope of this thesis the simplified approach has been adopted. The second life battery position will be assessed on a basis of a new Li-ion battery.

The figure below demonstrates the low cost scenario of LCOE cost components, which includes capital, operation & maintenance (O&M), charging, taxes and other costs.

It can be seen that behind the meter system costs are substantially higher than those of in front of the meter due to higher unit costs. Also in these applications Li-ion LCOS is lower than the alternative battery technologies.

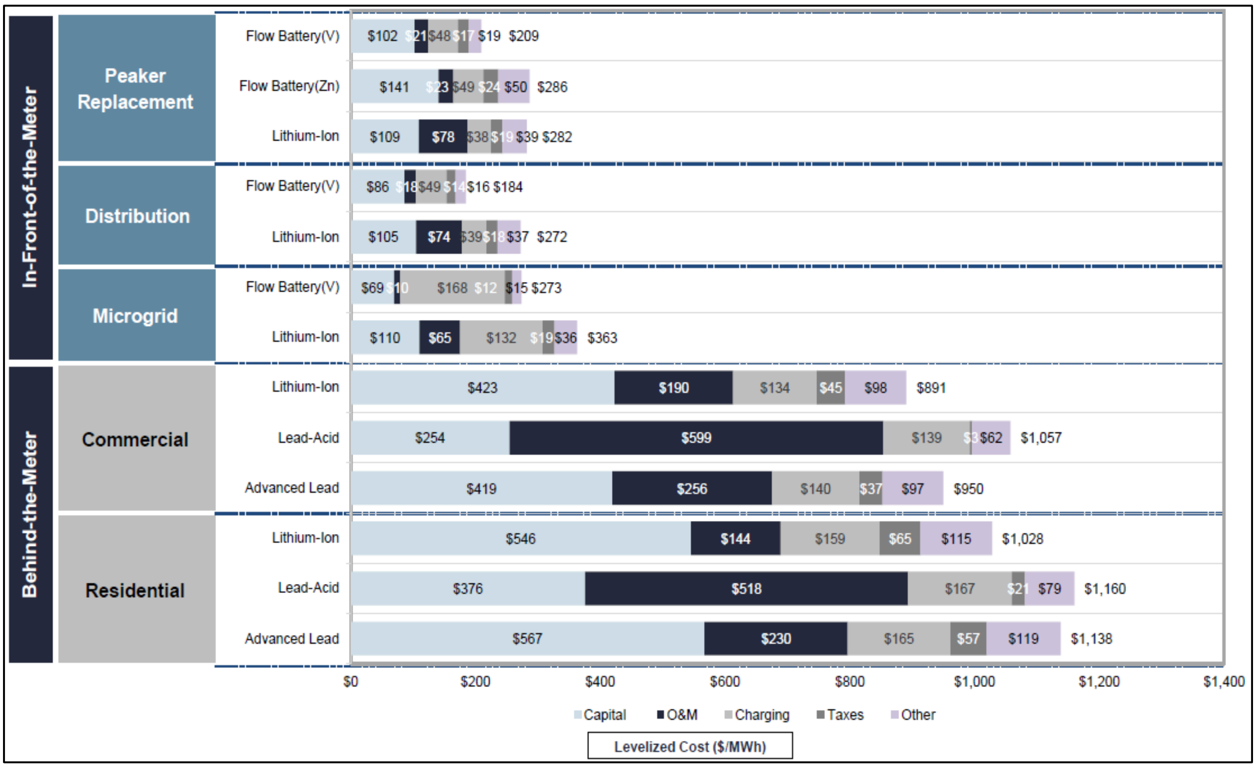


**Figure 25. Lazard's LCOS cost component comparison $/MWh**[1]

Probably O&M costs for second life battery would be higher, since the degradation rates can be accelerated with second life. Literature review demonstrated that second life battery shall be 10% of a new battery value or as low as 10 - 35 €/kWh by 2022. This meaning that the second life battery would significantly decrease the capital costs of the battery, thus making it even more attractive for commercial and residential applications. However, the impact on the competitiveness of in front of the meter technologies has to be further assessed.

The mechanisms for internalisation of negative externalities (e.g. tax) shall be compared with conventional technologies as well, in order to make LCOS of Li-ion batteries more attractive than the conventional storage. Moreover, this shall only be done only if battery storage has been proven to be more environmentally friendly than conventional technologies.

## 2.4. Recycling impact on second life

Recycling is an inevitable process in the battery lifecycle. Battery recycling has the potential to minimize the environmental impacts waste flows by recovering materials for reuse (Hendrickson et al., 2015). Secondary raw materials if compared to primary raw

[1] LAZARD. (2017). "Lazard's levelized cost of storage analysis – version 3.0." *Lazard and Enovation Partners.* November, 2017. <https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf>

materials have less energy consumption, lower costs, less $CO_2$ and SOx emissions (Dunn et al., 2015) and recovering of imported critical raw materials.

Cobalt is already recycled in Europe, and moreover it is the the most interesting material for Li-ion battery recyclers. The end-of-life recycled cobalt input rate is currently 35% of the total cobalt used in Europe, nickel 34%, natural graphite 3% but for lithium - non-existent. Graphite and lithium recovery is technically feasible but not yet economically viable.[1]

There are four types of recycling technologies – mechanical, pyrometallurgical, hydrometallurgical and thermal pre-treatment followed by hydrometallurgical method, - and mainly used to recycle portable li-ion batteries (Lebedeva, Di Persio & Boon-Brett, 2016).

The potential recycling rates using the abovementioned technologies are shown in the table 8.

**Table 8. Efficiency of recycling for various elements in selected processes for NMC and LFP chemistries (Lebedeva, Di Persio & Boon-Brett, 2016)**

| Material | Combination of pyrometallurgical & hydrometallurgical processes - NMC and LFP [%] | Purely hydrometallurgical process - NMC only [%] | Purely hydrometallurgical process - LFP only [%] |
|---|---|---|---|
| Lithium | 57 | 94 | 81 |
| Nickel | 95 | 97 | NA |
| Manganese | 0 | ~ 100 | NA |
| Cobalt | 94 | ~ 100 | NA |
| Iron | 0 | NA | 0 |
| Phosphate | 0 | NA | 0 |
| Natural graphite | 0 | 0 | 0 |

The table above shows positive potential for the recycling using selected technologies. Combination of technologies for NMC and LFP could bring lithium recycling efficiency rate to 57%, and nickel and cobalt to 95%. These rates are higher if customised methodologies are used for each type of chemistries.

[1] EUROPEAN COMMISSON. (2018.) "Report on Raw Materials for Battery Applications. SWD(2018) 245 final." *ec.europa.eu* May 17, 2018. <https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf>

The EU position in recycling in the global Li-ion battery value chain is rated as strong, as well as in battery integration and in systems, at the same time being weak in materials, cells and modules development (Steen et al., 2017).

There are currently many companies in recycling business, and many of them are in Europe. Biggest recycling capacity is owned by Umicore (BE) which can recycle 7000 tons of Li-ion and NiMH batteries yearly; Glencore (CH) – 7000 tons of Li-ion batteries, Accurec (DE) – NiCd, NiMH and Lo-ion batteries with capacity of 6000 tons a year (current volumes up to 2000 though), and many others. Moreover, Umicore and Recupyl (FR) have developed their proper recycling technologies (Lebedeva, Di Persio & Boon-Brett, 2016).

**Advantages and challenges for recycling**

Recycling of batteries is a complex and for the moment costly process because of technological and operational reasons.

Firstly, the final availability of recycled material heavily depends of the **collection rates and the recycling efficiency** which has to be improved at the first step. The infrastructure for recycling is not well established if compared to lead acid batteries (Bobba et al., 2016). Incoming vehicle battery waste streams are very weak and very diverse, and the transportation costs are high. However, the situation will change in the short to medium term, when recycling technologies will develop to match increasing abundance of second life batteries. Recycling can substitute a part of mining which often in energy intensive and environmentally unfriendly process. It is important to highlight, that recycling will eventually happen regardless if second life will be widely deployed or not.

Secondly, the **infrastructure and recycling processes are yet to be developed**. Current dismantling process is done manually thus labour intensive and expensive. The battery packs are not standardized for effective dismantling, incoming waste streams have different chemistries, designs and history of use. Moreover, unknown state of charge might compromise **safety** – reaction with inflammable solvents creates the risk of fire. Therefore there is also a need to ensure optimum conditions for pyrometallurgy technology which offers the highest potential benefits, as it can cope with a variety of input materials, thus allowing flexibility in accepting different battery characteristics.[1] However, it can bring big environmental damages and increase human health risks if implemented unsupervised. On the other hand hydrometallurgy has the highest rates of recovery of metals and lithium, however, the state of the art technology and its efficiency has still to be improved (Hendrikson et al., 2015). The most efficiency is achieved in terms of overall energy use and emissions is achieved when facilities operate at high capacity (Dunn et al., 2015).

Finally, **prices and supply of primary raw materials** are still relatively attractive therefore the need for secondary raw materials has not yet emerged. For example, for the

[1] TYTGAT J. (2017). "Li-ion battery recycling." *Presentation at the EMIRI Tech Talk on Batteries for Energy Storage - End-of-life and recycling of Li-ion batteries.* February 23, 2017. <https://www.slideshare.net/FabriceStassin/presentation-8-slides-jan-tytgat-umicore?next_slideshow=1>

moment the value for the recycling business is currently high for valuable metals, such as nickel and cobalt, but on the contrary, almost all recycled lithium containing slag is used in a construction sector, due to the low level of processing (Reid & Julve, 2016). The situation will, however, change when supply of raw materials will be scarce. As shown in the figure 23 price of raw materials is expected to increase slightly or for some valuable metals considerably. After the recycling will be well established the challenge will be to ensure that the quality of recycled products meets industry standards,[1] since it impacts the overall performance of the cell. Therefore several major battery cell producers develop cathode materials internally (Lebedeva, Di Persio & Boon-Brett, 2016).

## 2.5. Conclusions on motivations and risks of the second life concept

According to Steen et al. (2017) drivers along the battery value chain differ. Thus meaning that material, component and cell manufacturing is driven by **costs and global** markets, whereas pack manufacturing, battery integration and recycling are driven by **value** and by dominated application therefore is not a subject for global competition. This approach does not take into consideration the cross-sectoral competition (such as second life versus recycling; new batteries; other types of energy storage).

It can be anticipated that the main driver for the environmental impacts would be public actors, and the process will be overtaken by private entities if it generates revenue streams. However, currently economic and environmental benefits are not straightforward and heavily depend on a case by case basis.

Recycling and technologies designed specifically for energy storage can be considered as the main threats for second life concept. Moreover, waste streams coming directly from first use could be easier to ensure and manage rather than those from second use applications.

[1] TYTGAT J. (2017). "Li-ion battery recycling." *Presentation at the EMIRI Tech Talk on Batteries for Energy Storage - End-of-life and recycling of Li-ion batteries.* February 23, 2017. <https://www.slideshare.net/FabriceStassin/presentation-8-slides-jan-tytgat-umicore?next_slideshow=1>

# 3. BATTERIES SECOND LIFE: PRACTICAL APPLICATION ANALYSIS

## 3.1. Demonstration projects and start-ups

There are currently many demonstration projects ongoing on integrating battery energy storage in the grid for renewable energy storage, especially in the remote or isolated areas. Also, research activities are done to evaluate EV battery use in grid peak stabilisation. However, in this section an overview of the ongoing pilot projects is given, where the second life battery was used for stationary applications.

**Europe**

- EU-funded project READY has demonstrated 130 kWh battery energy storage system integrated in the building in Ringgaarden, Denmark.[1]
- EU-funded project ELSA works on applying innovative local ICT-based energy management system on second life batteries in order to develop low-cost, scalable and easy-to-deploy battery energy storage system. Project is running from 2015 to 2019. Six demonstration sites in four countries have been installed deploying vehicle second life batteries:[2]
    - Paris, France - two Kangoo batteries with a total capacity of 32kWh;
    - Sunderland, United Kingdom - three 2nd life Nissan Leaf batteries with a total capacity of 48 kWh;
    - Paris, France (Nissan Office) - 12 second life Nissan LEAF batteries with a total capacity of 192 kWh;
    - Aachen, Germany - six second life Renault Kangoo batteries with a total capacity of 96 kWh;
    - Kempten, Germany - six second life Renault Kangoo batteries with a total capacity of 96 kWh;
    - Terni, Italy - six second life Renault Kangoo batteries with a total capacity up to 96 kWh.
- Daimler together with The Mobility House created a JV Enbase Power 13 MWh second life battery storage unit Lünen, Germany in 2015. It is the largest demonstration site with about 1000 used e-vehicle batteries.[3]
- 280 Nissan Leaf batteries (85 new and 63 second life) will provide back-up power of a capacity 4MWh to Amsterdam Arena, the Netherlands. Batteries are installed

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[1] READY project (2018). "Resource efficient cities implementing advanced smart city solutions." <http://www.smartcity-ready.eu/>

[2] ELSA project. (2018). "Energy Local Storage Advanced system." <https://www.elsa-h2020.eu/Home.html>

[3] DAIMLER. (2016). "World's largest 2nd-use battery storage is starting up." *Daimler.com* September 13, 2016. <http://media.daimler.com/marsMediaSite/en/instance/ko/Worlds-largest-2nd-use-battery-storage-is-starting-up.xhtml?oid=13634457>

by the company Eaton. The aim is to ensure sustainability and the use of renewable energies.[1]

- Pampus[2] trial project included installing second life batteries to ensure autonomy of the Pampus Island, the Netherlands.
- Collaboration between Vattenfall, BMW and Bosch in 2013 resulted in creation of a second life storage facility in Hamburg, Germany. 2600 BMWi battery modules from more than 100 vehicles were used for a storage capacity of 2800 kWh, and 2MW power.[3]
- Mitsubushi and PSA Group together with EDF and Forsee Power will use Peugeot Ion, Citroen C-Zero, i-MiEV, and Outlander PHEV batteries to demonstrate high voltage (330 volts) energy storage systems.[4]
- It is reported that Renault-Nissan is drawing up plans to build 100 MWh power storage plant in Europe from second life batteries.[5]
- Memorandum of Understanding was signed between VHH and MAN Truck and Bus (VW Group) to work on reusing the batteries from electric busses to store energy at the depot to charge busses in Hamburg, Germany. Main benefit is the peak stabilisation.[6]

**Businesses and Start-ups worldwide**

A start-up FreeWire has developed mobile "on wheel" battery systems, which can be used also to charge EVs. The battery system deployed also a second life battery. An article from 2015 reveals that the company payed €85 ($100) per kWh for used Nissan battery packs. At the time the price of new pack would be six time higher. The estimated remaining calendar lifetime according to FreeWire would be 5 years, charged twice a day.[7]

A concept brought to market was made real by Renault and Powervault in the UK. Powervault used 50 trial batteries provided by Renault for consumers who have solar

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[1] JOHAN CRUYFF ARENA. (2016). "Amsterdam arena more energy efficient with battery storage." *johancruijffarena.nl* November 20, 2016. http://www.johancruijffarena.nl/default-showon-page/amsterdam-arena-more-energy-efficient-with-battery-storage-.htm

[2] VAN DE VEGTE H. (2015). "The Pampus Project.". *DNV-GL* November 25, 2015 <http://www.gridplusstorage.eu/system/resources/W1siZiIsIjIwMTUvMTEvMzAvMTVfNThfNDJfMTgzXzQuX1BBTVBVUy5wZGYiXV0/4.%20PAMPUS.pdf>

[3] JAHN B. (2016). "A second life for used batteries." *Bosch.* September 22, 2016. <https://www.bosch-presse.de/pressportal/de/en/a-second life-for-used-batteries-64192.html>

[4] FORESEE POWER. (2015). " Battery Second Life Project." Foresee power. July 10, 2015. <http://www.forseepower.com/sites/default/files/pdf/2017-07/10072015_2nd_life_project_eng.pdf>

[5] STEITZ C. & TAYLOR E. (2017). " Renault plans foray into energy market with mega battery." *Reuters.* June 8, 2017. < https://uk.reuters.com/article/uk-renault-batteries-utilities-idUKKBN18Z0PN>

[6] VW (2018). " Second life energy storage: VHH and MAN testing use of second life of batteries for eBus charging station." *Volkswagen.* March 16, 2018. <https://www.volkswagenag.com/en/news/2018/03/MAN_VHH.html>

[7] WESOFF E. (2015). "How Much Would the Storage Market Change if Batteries Were One-Sixth the Current Price?" *Green Tech Media.* April 29, 2015. <https://www.greentechmedia.com/articles/read/How-Much-Would-the-Storage-Market-Change-if-Batteries-Were-One-Sixth-The-Cu#gs.NF3ZNc0>

panels at home.[1] Main motivation for this cooperation is battery lifecycle optimisation, and cost saving for consumers.

Company Eaton, through a partnership with Nissan, provides energy storage for buildings for residential homes and buildings, as well as on a grid scale with both second life and new batteries. Depending on the configuration and purpose, the capacity of battery proposed range from 3.5 -10 kWh for residential applications, 20 - 8000 kWh for buildings, 5-15 MWh for industrial use and more than 15MWh for grid scale.

The standard battery pack second life battery capacity is 4.2 kWh, 70% of the same LMO chemistry new battery pack of 6 kWh. The new battery pack is also proposed in NMC chemistry with nominal of 7.5kWh. For the new battery back company provides warranty during 10 years, and for the second life one - 5 years.

Connected Energy has launched project E-STOR, which is offering energy storage solutions to businesses, using second life Renault batteries[2] from Renault Zoe, Kangoo Z.E., Twizy, Fluence Z.E., and SM3 Z.E.

Most of these projects join forces with automotive OEMs for battery pack supply, however, one French recycling company – SNAM – is planning to act as an intermediary between automotive battery pack suppliers and the second life battery application markets. A work within the project named "Phénix " will include splitting batteries to module level, evaluating them using a specific state of health model developed together with CEA, and reassembling them for the second use. In six year time up to 2024 they plan to produce a capacity of 4 GWh repurposed batteries. Company claims that the price of repurposed batteries will be the same as the one of lead battery. Phénix will firstly address the housing market and the of-grid applications, gradually expanding to renewable energy production parks and to industry and large electricity consumers. The total investment is €25 million.[3]

## 3.2. Projections on the second life battery availability by 2030

### 3.2.1. Methodology

In this section the analysis on battery second life battery availability in future is made.

The analysis was made in the following steps:

**Step 1:** Statistics of EV sales in Europe was aggregated for the period 2011-2017, based on European Alternative Fuels Observatory data.[4] Data are presented for top 10 BEV and top

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[1] FARISSIER C. (2017). " Renault and Powervault Give EV Batteries a “second life” in Smart Energy Deal." *Renault.com* June 5, 2017. <https://media.group.renault.com/global/en-gb/media/pressreleases/92203/renault-et-powervault-donnent-une-seconde-vie-aux-batteries-des-vehicules-electriques1>

[2] E-STOR. (2018). Connected Energy website <https://www.c-e-int.com/technology/e-stor-benefits/>

[3] MEDIA 12. (2017). "SNAM veut fabriquer des batteries recycles." *Media12.fr* December 12, 2017. <http://www.media12.fr/snam-veut-fabriquer-des-batteries-recyclees-650-emplois/>

[4] EAFO (2018). "Vehicle statistics." *European Alternative Fuels Observatory.* <http://www.eafo.eu/vehicle-statistics/m1>

10 PHEV models sold in Europe, as well in category "Others" representing the remaining sales.

**Step 2:** Predictions were made for EV sales in 2018-2019-2020. The assumption was made that EV sales growth by 2020 would be 50% increase per year, as based on recent dynamics in 1Q 2018, when the electric vehicle growth rate was +47%.[1] As a result, estimated amount of BEV and PHEV new sales in 2020 is almost one million vehicles. This corresponds to the estimations made in section 2.3. on EV deployment scenarios, which predicted from 0.75 to 1.5 million new EVs sold yearly.

The aggregated and estimated amount of sales is reflected in the figure below.

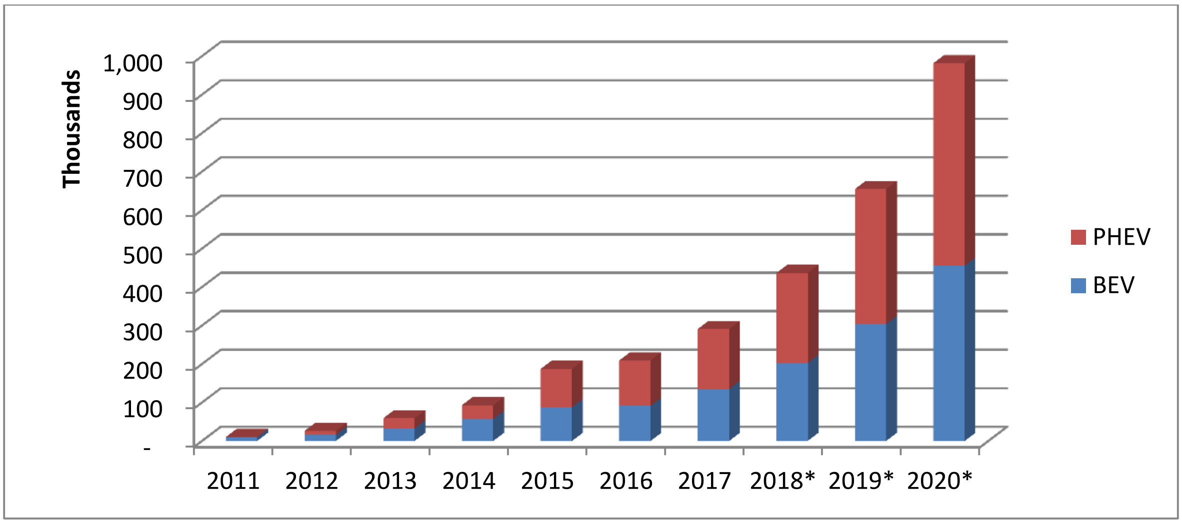



**Figure 26. Calculated and estimated (*) EV sales in Europe from 2011-2020**

Figure above shows that the equal division between BEV and PHEV will remain. This corresponds to the figure 8 which shows that in all European countries this share differs, but on average the division shown in the figure above of around 55% PHEV and 45 BEV is confirmed.

**Step 3:** The data on battery pack capacity were retrieved for each model sold.[2] For the category "Others" the average pack capacity was taken, or based on the reports analysed in this thesis.

→ ***output 1:*** The total amount of battery MWh was estimated to be embedded in EV stock in Europe by 2020.

$$Total\ EV\ battery\ capacity\ [kWh] = vehicles\ sold\ unit\ x\ battery\ pack\ capacity\ [kWh]$$

[1] ACEA (2018). "Fuel types of new cars." *European Automobile Manufacturers Association.* May 3, 2018. <https://www.acea.be/press-releases/article/fuel-types-of-new-cars-diesel-17-petrol-14.6-electric-47-in-first-quarter-o>

[2] Based on the public information available. In case the information was not available, the most probable assumption was made.

**Step 4:** The data on battery cell chemistries used in each model were aggregated. For the category "Others" the most common chemistry was taken.

**Step 5:** The material use per chemistry was aggregated – for nickel, cobalt and manganese.

➔ ***output 2:*** The total amount of battery material [kg] was estimated to be embedded in EV stock in Europe. Material use per cell technology was estimated using the modelling tool BatPac. Detailed analysis is available in annex.

$$Total\ metal\ use\ [T] = vehicles\ battery\ capacity\ [MWh]\ x\ material\ use\ per\ cell\ technology\ [T/MWh]$$

**Step 6:** Assumption was made based on the literature review that the electric vehicle battery is fit for usage in the EV for 10 years, after that becoming suitable for second use.

> ➔ ***output 3:*** the amount of available second life battery capacity estimated on a timescale.
>
> ➔ ***output 4:*** the amount of material amount in electric vehicle batteries estimated on a timescale.

### 3.2.2. Results

➔ ***Output 1:*** *The total amount of battery MWh estimated to be embedded in EV stock in Europe by 2020.*

Annex shows the results of analysis made on different model pack capacity. For those models where the data was not available, the assumption of most probable technology was made.

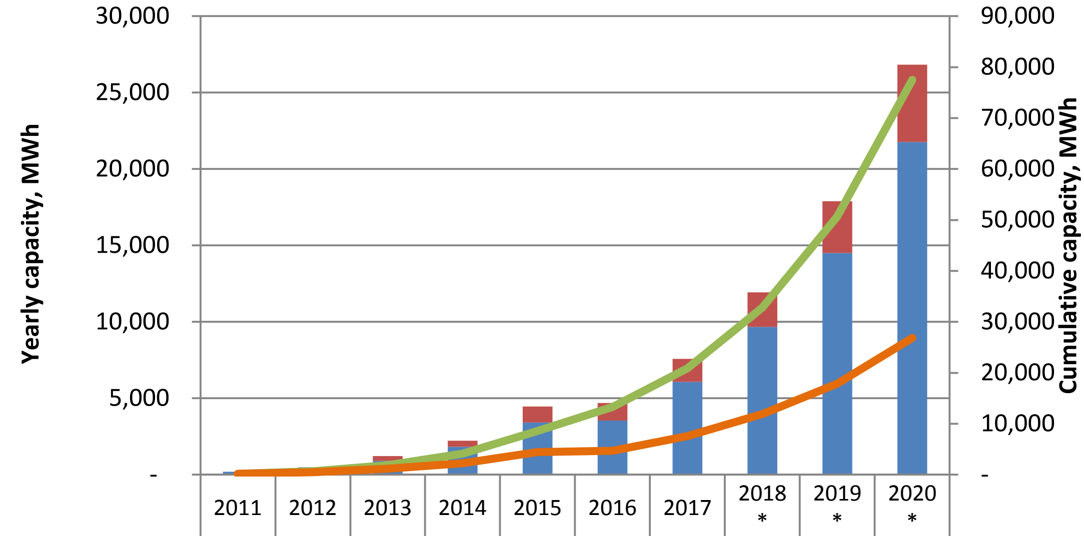
In scope of this thesis, the estimations for pack capacities for the period 2018-2020 were fixed at 2018 level. Despite of several OEM announcements to dramatically increase pack capacity, the estimated date of mass production of these technologies is after 2020.

In case where with introduction of a new generation vehicle model to the market, and at a given year both generations are available for sale, the highest capacity was considered for multiplication. For example, in 2017 both Renault Zoe 22 and 41 kWh versions were available. However, for calculations of battery capacities sold that year, the highest capacity has been considered.

Even though the relation between BEV and PHEV remains quite considerable, the share of the total capacity of BEV batteries is much higher as shown in the figure 25 below. This is due to the fact, that BEV battery pack is much larger (45 kWh on average in 2017 for BEV, and about 10 kWh for PHEV).

As a result, the estimated capacity of batteries sold with EVs in Europe in 2017 is 7,6 GWh, and the capacity of all vehicles sold from 2011 – 2017 is about 21 GWh. Regarding estimations for the following years, the battery capacities sold would be 11.9 GWh in 2018, 17.9 GWh in 2019 and 26.8 GWh in 2020. This results in total of 77.5 GWh battery capacity accumulated by 2020.

In terms of vehicle sales (figure 24), those are 430 thousand BEV and 445 thousand PHEV sold from 2011 – 2017. Adopted assumption of 50% sales increase yearly, leads to 1.4 million BEV and 1.55 PHEV sold by 2020 in Europe.




| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 * | 2019 * | 2020 * |
|---|---|---|---|---|---|---|---|---|---|---|
| Total MWh PHEV | - | - | 316 | 401 | 1,043 | 1,144 | 1,501 | 2,252 | 3,378 | 5,067 |
| Total MWh BEV | 196 | 484 | 898 | 1,830 | 3,427 | 3,542 | 6,081 | 9,674 | 14,51 | 21,76 |
| Cumulative capacity | 196 | 680 | 1,894 | 4,125 | 8,595 | 13,28 | 20,86 | 32,78 | 50,67 | 77,51 |
| Total yearly capacity | 196 | 484 | 1,214 | 2,232 | 4,470 | 4,685 | 7,582 | 11,92 | 17,88 | 26,83 |

**Figure 27. Calculated and estimated (*) battery capacity of EVs sold in Europe from 2011 – 2020, MWh**

In order to validate the outcomes, the results were compared to data included in the study of Kauranen (2017). In his report, he estimated the (global) battery capacity in 2016 (table 9) for 472 thousand BEV to be 21.2 GWh, which is close to 22 GWh estimated in this study for 445 thousand vehicles in 2020 (in Europe).

The comparison on PHEV shows that the average battery size in this thesis is 9.5 kWh compared to 13 kWh in the study of Kauranen. This is due to the fact that for years 2018-2020 the pack capacity was assumed to be frozen at 2017 level. However, indeed, it is probable that the average pack capacity in Europe for PHEV could increase in the upcoming years, as it has not considerably improved for most models since they were massively introduced to the market around 2014.

**Table 9. An estimate of the BEV and PHEV use of lithium batteries globally in 2016[1] and forecast for 2020 in Europe**

| Vehicle type | Global sales 2016, thousand | Average battery size, kWh | Total battery capacity, GWh | EU sales 2020*, thousand | Battery capacity*, GWh |
|---|---|---|---|---|---|
| **BEV** | 472 | 45 | 21.2 | 445 | 22 |
| **PHEV** | 302 | 13 | 3.9 | 525 | 5 |
| **Total** | 774 | 33 | 25.1 | 970 | 27 |

→ ***Output 2:*** *The total amount of battery material estimated to be embedded in EV stock in Europe.*

Different vehicle models use different cell chemistries and different pack sizes.

In order to estimate material use in all those different variations, firstly, the total capacity of each chemistries on the market from 2011-2020 was calculated. The detailed data set is available in Annex.

Since many OEMs using NMC333 chemistries have switched to NMC622, an assumption was made that until 2015 the technology of choice was NMC333 and after 2015 it was the NMC622. It is predicted that as from 2020 the NMC811 will be used, but this is out of scope of this analysis. Moreover, it was assumed that all PHEV batteries are NMC622.

As a result, the battery capacities of vehicle sold in 2011-2020 per chemistry are reflected in the table below.

**Table 10. Total battery capacities of EVs in Europe (2011-2020*) by chemistry type**

| Chemistry | BEV | PHEV | Total |
|---|---|---|---|
| LMO | 1,153 | 2,842 | **3,996** |
| NCA | 25,599 | - | **25,599** |
| LMO-NMC | 1,317 | - | **1,317** |
| NMC333 | 1,278 | - | **1,278** |
| NMC622 | 33,061 | 12,259 | **45,321** |
| **Total capacity** | **62,408** | **15,102** | **77,510** |

Secondly, the material use per kg/kWh was estimated for each of the chemistries, based on the simulations with BatPac tool. Constrained by available information, only cathode metals were taken into account in this estimation. Simulations showed that no matter the pack configuration, the relation kg/kWh remains the same. Table below shows the results, and detailed calculations are included in the Annex.

[1] Kauranen P. (2017). "Raw material needs by the Li-ion battery industry." Closeloop. May 17, 2017. <http://closeloop.fi/wp-content/uploads/2017/05/Li-raw-materials-20170517.pdf>

**Table 11. Selected metal content in cells of different chemistries, kg/kWh**

| Total EV | kg/kWh | | | | |
|---|---|---|---|---|---|
| | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** |
| Nickel | - | 0.072 | 0.672 | 0.606 | 0.397 |
| Cobalt | - | 0.072 | 0.127 | 0.189 | 0.399 |
| Manganese | 1.576 | 0.672 | - | 0.203 | 0.372 |
| Total | **1.576** | **0.816** | **0.799** | **0.998** | **1.168** |

It can be seen that the material use per chemistry differs substantially according to the technology used. The most "metal-consuming" in absolute terms is the LMO (1.6 kg/kWh), the most efficient in terms of metal consumption is the NCA (0.8 kg/kWh).

Thirdly, by multiplying the battery capacity by technology and the metal content per kWh, the total use of metals was calculated.

**Table 12. Selected metal content in EVs sold in Europe 2011-2020**

| BEV | kg of metals per chemistry | | | | | |
|---|---|---|---|---|---|---|
| | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **Total kg** |
| Nickel | - | 94,494 | 17,207,422 | 20,032,712 | 507,553 | 37,842,182 |
| Cobalt | - | 94,795 | 3,240,039 | 6,251,237 | 509,715 | 10,095,786 |
| Manganese | 1,817,815 | 884,757 | - | 6,707,315 | 475,037 | 9,884,923 |
| | | | | | | ***57,822,891*** |
| **PHEV** | kg of metals per chemistry | | | | | |
| | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **Total kg** |
| Nickel | - | | | 7,428,216 | | 7,428,216 |
| Cobalt | - | | | 2,317,986 | | 2,317,986 |
| Manganese | 4,480,362 | | | 2,487,101 | | 6,967,463 |
| | | | | | | ***16,713,664*** |
| **Total EV** | kg of metals per chemistry | | | | | |
| | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **Total kg** |
| Nickel | - | 94,494 | 17,207,422 | 27,460,927 | 507,553 | 45,270,397 |
| Cobalt | - | 94,795 | 3,240,039 | 8,569,223 | 509,715 | 12,413,772 |
| Manganese | 6,298,177 | 884,757 | - | 9,194,416 | 475,037 | 16,852,386 |
| | | | | | | ***74,536,555*** |

In total by 2020, the total amount of metals embedded in EVs by 2020 is as follows: nickel 45.3 MT, cobalt 12.4 MT, manganese 16.8 MT. Most of these raw materials (78%) will be used for BEV batteries.

➔ ***output 3:*** the amount of available second life battery capacity estimated on a timescale.

➔ ***output 4:*** the amount of material amount in electric vehicle batteries estimated on a timescale.

As a next step, the sold battery capacities and relevant material use were put on a timescale y+10 assuming that the EV battery will be used for 10 years, regardless the technology and type of vehicle, although this could be further detailed and analysed.

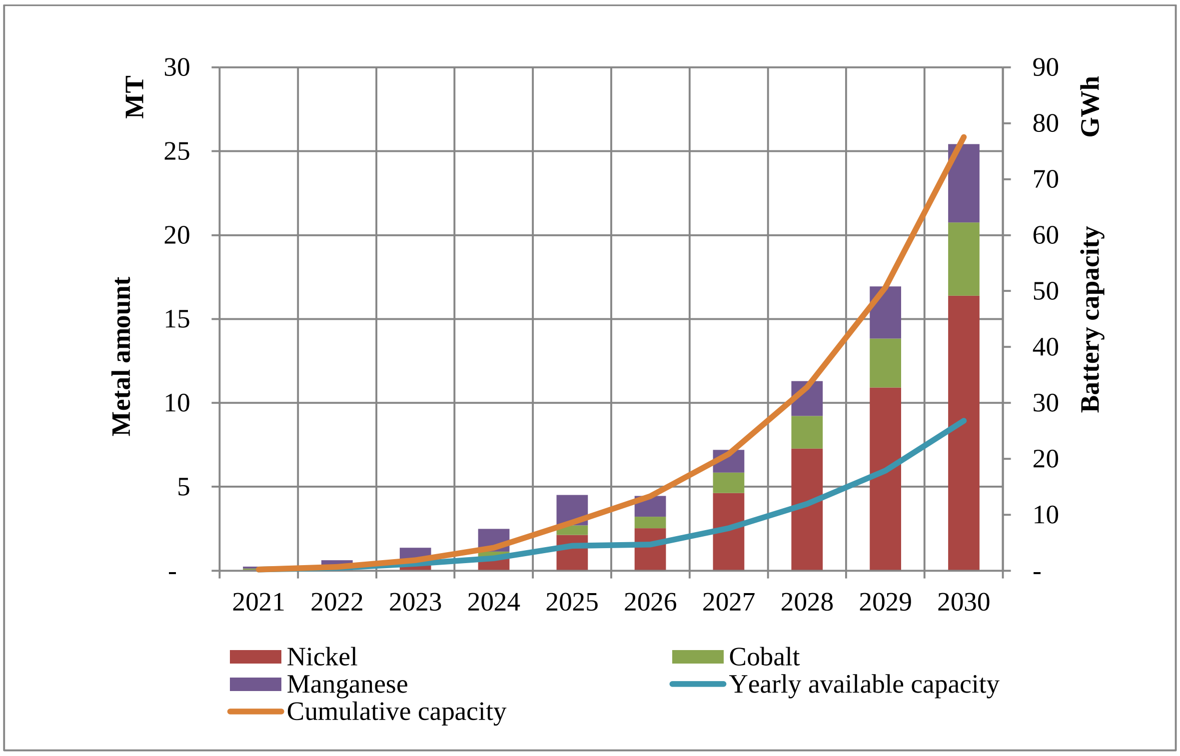



**Figure 28. Second life battery capacity availability and metal amount embedded in those batteries from 2021-2030 in Europe**

This projection shows that the considerable amount of second life batteries will be available as from 2027, when the cumulative capacity will exceed 20 GWh, and it will reach 77.5 GWh in 2030.

If estimated that 5 million EVs will be sold in Europe in 2030 (according to figure 10 previously), the necessary amount of raw materials for these battery production is 82 MT of nickel, 22 MT of cobalt and 23 MT of manganese, in total 130 MT (considering the current technology and recycling rate 100%). At the same time accumulated raw material amount in batteries after their first use in 2030 account for 74.5 MT, which results in 58.7% of raw material needs for new car batteries in 2030. Batteries, reaching their end of life in 2030 alone, might supply 20% of necessary raw materials for new battery production in 2030.

## 3.3. Raw material value embedded in batteries at the end of their first life

The reason for an end user to choose a second life battery is mainly the cheap price of it. However, it is not clear if it will be the case taking into consideration the increasing costs for the primary raw materials.

In order to estimate the economic value of metals embedded in the cell, the **price** forecasts for raw materials were multiplied by the **use** of metals in NMC622 technologies in 2015, 2018 and 2025.

Thus, the baseline information for one concrete example is as follows:

- Chemistry assumed: NMC622
- Metal contents as calculated in table 11
- Metal price forecasts in 2015, 2018 and 2025 as shown in figure 23

Results are shown in the table 13 below.

**Table 13. Raw material price estimations used in NMC622 battery cathode in 2015, 2018, 2025***

| 2015 | | | | | |
|---|---|---|---|---|---|
| **NMC622** | **kg/kWh** | **Price $/kg** | **Converted Price to €/kg** | **Cost of raw materials €/kWh** | **Total €/kWh** |
| Nickel | 0.606 | 11.9 | 10.1 | 6.12 | 11.31 |
| Cobalt | 0.189 | 30 | 25.5 | 4.82 | |
| Manganese | 0.203 | 2.1 | 1.8 | 0.37 | |
| **2018** | | | | | |
| **NMC622** | **kg/kWh** | **Price $/kg** | **Converted Price to €/kg** | **Cost of raw materials €/kWh** | **Total €/kWh** |
| Nickel | 0.606 | 13.5 | 11.5 | 6.97 | 19.54 |
| Cobalt | 0.189 | 76 | 64.7 | 12.22 | |
| Manganese | 0.203 | 2 | 1.7 | 0.35 | |
| **2025** | | | | | |
| **NMC622** | **kg/kWh** | **Price $/kg** | **Converted Price to €/kg** | **Cost of raw materials €/kWh** | **Total €/kWh** |
| Nickel | 0.606 | 15.9 | 13.5 | 8.18 | 18.24 |
| Cobalt* | 0.189 | 60.4 | 51.39 | 9.71 | |
| Manganese * | 0.203 | 2 | 1.7 | 0.35 | |

** Estimations on these material prices are not available for 2025, latest available forecast taken into account*

The total metal (nickel, cobalt and manganese) value in 2018 in the cathode is 19.54 €/kWh. As a result of this calculation, the crude metal price is about 10% of the total battery price, if considered the battery cell price being €190 €/kWh. According to the analysis performed before, currently the whole cathode cost is 22% of the battery cell price.

In 2015 the metal price was 11.31 €/kWh, whilst in 2025 it will be 18.24 €/kWh. With cell price assuming to be 90 €/kWh, the metal amount will be composing more than 20% of the battery price.

In summary, the value of metals will raise by more than 60% from 11.31 €/kWh in 2015 to 18.24 €/kWh in 2025. At the same time the price of the cell is expected to decrease.

### 3.4. Conclusions on practical application analysis

It can be concluded that there are some pilot demonstration projects coming up, however, in most of the times are on an individual basis. New business models emerging from second life applications are oriented towards local scale or application-based energy storage. Main motivations for these projects are sustainability and reducing system costs.

The calculations show that a large amount of critical raw materials will be embedded in batteries at the end of their first life. The amount of metals varies by technologies used, and the future technology of choice could have a considerable impact on the material needs if applied on a large scale.

The decision will have to be made – to recycle them or to use in second life applications. However, even in the case where all batteries are recycled, only a small part of demand for critical raw materials could be satisfied by recycled materials.

Because of rising price of primary raw materials, the strategic value of second life battery could increase because of the material amount embedded in them. As analysed before, for the second life to be viable the initial battery price shall be 10 - 35 €/kWh by 2022. However, from the calculations above, just the raw material value for cathode can exceed the initial required battery price at the end of its first life. In this case the decision of recycling can be deemed more profitable for battery owner.

# 4. CONCLUSIONS AND RECOMMENDATIONS

The development and production of clean technologies drive Europe’s transition to clean **mobility** and clean **energy** systems.

Besides, main bottleneck for **electric vehicle** rapid uptake is overcoming consumer anxiety with respect to EVs price, range, recharging time and infrastructure availability. Since these performance characteristics heavily depend on the battery performances, massive efforts in their improvement are being put in place across the globe. The current technology of choice is the improved Li-ion with diverse chemistries.

In 2017 global electric vehicle sales reached 1.2 million units a year, a 58% increase with respect to 2016. Along with the rapid uptake of the EVs and in order to guarantee the supply of these vehicles, batteries, which are the most important component of the EV and which represent up to 50% of the price of the EV, will have to be developed and manufactured in large quantities.

China is the world leader in the electric vehicle market, mostly due to heavy governmental subsidies. Also a large share of new sales of EVs in Norway (29%) is a result of extensive financial and non-financial incentives. However, it is expected that by 2025 governmental support will not be needed since EVs will become price competitive.

Regarding the use of **batteries in stationary applications, they would bring economic advantage if their use is not limited to single use, but rather if multiple uses are combined to increase the utilisation rate.** At the same time other types of technologies, specifically designed for satisfying energy storage characteristics (such as redox flow) are emerging and could provide more benefits than Li-ion technology. This is because Li-ion delivers needed characteristics for automotive applications (high power, possibility of fast charge, optimal gravimetric and volumetric energy density, etc.) whereas the requirements for energy storage applications are less stringent and other technologies can deliver more appropriate solutions.

Taking into consideration the projected market growth, **second life batteries** would become available in massive amounts as from 2030, when batteries from 10 – 25 million cars would not be suitable for their operations anymore.

If market projections are met, battery production will rise exponentially, together with the need for raw materials. Global battery cell production capacity could increase up to 10 times from 2018 reaching **1300 GWh by 2030**, meaning that 7 million metric tons of raw materials would be needed to support this demand.

**Cobalt and nickel are among the raw materials, whose price is rapidly increasing, whilst the price of other raw materials is expected to stay relatively stable due to easy access to new mines.** Thus the challenge for industry is to deliver cheaper batteries with increasing price of most scarce metals.

The PESTEL analysis for batteries and second use was performed. It can be concluded that the overall the **political environment in Europe is supporting and promoting battery**

**use in the second life applications mainly due to potential environmental benefits it could bring**, **but also for increasing global competitiveness.** There are some policies supporting second-use, but they are not supported by legislation which in present time is vague regarding second use case. Financial or non-financial incentives were not identified. **Currently there are no warranty or liability schemes for second life batteries**. Before second life batteries can be commercially available, these aspects have to be developed.

*Regulation shall more specifically elaborate such notions as battery second use versus waste, extended producer responsibility in case of second life and develop new safety standards for transporting and processing second life batteries, as well as develop new requirements for quality insurance, warranty and liability.*

Regarding the economic benefits of second life use in energy storage, the situation is more complex. On the one hand, second life brings economic benefits to the battery owner due to extended lifetime. However, on the other hand, for a second life battery to be competitive with new batteries and other energy storage alternatives, it has to be very cheap, being max 10% of a new battery price according to some studies, or €60/kWh to others. Considering the additional costs for repurposing (estimated to be 25-50 €/kWh) the remaining initial value to the "first" life owner is very low. All in all, **costs for initial battery at the end of its first life plus repurposing costs must be lower than the expected generated revenue during its second life.**

In this regard, several researchers have demonstrated **marginal or moderate economic benefits from second life battery use**, provided that certain conditions and assumptions, such as governmental support or combination of several use cases for one battery. **Most promising applications for second life batteries would be in residential households for peak shaving and for PV self-consumption.** Second life battery competitiveness is equally questioned if compared to other technologies in the scope of LCOS.

Potential second life battery supply streams could be fleet managers and operators, but the value chain **requires inter-industrial partnerships to establish collaboration between these mobility actors and energy storage actors. However, second life could potentially even harm recycling since waste streams would be more diversified** (instead of one source of batteries, vehicles, to numerous small locations and different stationary storage applications). *European e-mobility, battery and renewable energy associations shall consider closer collaboration to promote second use applications. A potential cross-sectoral working groups, stakeholder forums or workshops can be organised collectively. Currently, the collaboration between cross-industrial partners happens only on an individual demonstration project or initiative basis.*

From the **technical point of view, it is deemed that second life is possible**, however, several constraints still exist, such as estimating state of health and combining packs with different remaining lifetimes. *Further research is needed to develop more effective and reliable processes for estimating the remaining lifetime and capacity of the battery.*

The absence of standardized battery cell chemistries, formats and battery pack characteristics hinders both – second life use and recycling. Currently, battery casing does not take into account future dismantling needs. Moreover, most car battery models are not designed to be electric from the beginning, which results in inconvenient integration and thus problematic dismantling of battery in the vehicle. *Standards shall be developed to facilitate battery recycling and second use. Eco-design shall be promoted across the whole value chain, especially to OEMs, to make battery replacement/dismantling easier.*

Battery production is very energy consuming process – to produce 1 kWh of battery, the required energy input is more than 400 times higher. **Second life would increase battery lifetime and thus amortize environmental costs over time and total energy stored.** However, even taking this fact into consideration, second life batteries bring considerable environmental benefits only if they replace conventional fuels or lead-acid batteries. However, some studies have demonstrated that second use battery could not bring any benefits or bring negative benefits under certain conditions*Batteries second life use shall be promoted in such a way that it brings the maximum environmental and economic benefits without compromising safety and consumer rights for warranty.*

PESTEL analysis concluded that political and social environments are encouraging the use of second life batteries in ESS. However, more technological developments and more studies on the environmental impact are necessary to drive second life battery use. Furthermore, economic and legal aspects have been assessed as insufficient and can be considered as blocking factors.

When analysing different stakeholders across the second life value chain, it was concluded that the **highest importance and highest influential stakeholders are governments, OEMs, battery recyclers and electricity utility companies.**

**There are numerous research demonstration projects** funded by public actors and private companies, but are mostly individual collaborations projects between OEMs and second life battery sellers. Regarding **start-ups** and innovative companies, several businesses offer second life batteries for residential storage, for EV charging or for proving back-up energy. French company SNAM is the first one to announce repurposing batteries on a commercial scale.

In this thesis a projection was made on second life battery and embedded raw material availability in the future.

It was forecasted that from the period of 2018-2020 yearly EV sales will increase by 50% both for BEVs and PHEV. As a result it was estimated that **1.4 million BEV and 1.55 PHEV will be sold in Europe by 2020. This corresponds to an accumulated battery capacity of 77.5 GWh.** Second life batteries will become available approximately after 10 year use in EV. Projections show that this market could emerge after 2025 when second life battery availability will exceed 10 GWh, by then this market will increase exponentially and reach 77.5 GWh by 2030.

Electric car models show the high diversity in the battery technology and capacity. The largest share of batteries in electric cars will have battery with NMC622 and NCA chemistries, and by 2020 the accumulated capacity of these battery technologies will be 45.3 GWh and 25.6 GWh respectively.

Cathode metal use also differs considerably by the technology used. Most metals are needed for LMO technology (1.6 kg/kWh) and most efficient in terms of raw material use is NCA (0.8 kg/kWh). **It was calculated that by 2030 a total of 45.3 MT of nickel, 16.8 MT of manganese and 12.4 MT of cobalt will be embedded in EV batteries. If recycled it could represent up to 60% of selected metal needs for new cars in 2030.**

Regarding the choice between recycling and second life, on the one hand, the increased battery lifetime and postponed recycling allows raw material extractors to increase their markets by producing new batteries. On the other hand, the increased price of raw materials might make the second life battery too expensive due to the amount of metals it contains for the purpose it would be used. Moreover, new battery cell production is increasingly robotised whereas repurposing is much labour intensive and thus costly.

In this line battery recyclers are acting as indirect competitors for second life batteries, moreover because **recycling is an inevitable step in the battery lifecycle.** Recycling can partly substitute mining and guarantee supply secondary raw materials (up to 60% in 2030 for passenger cars). However, **technologies and infrastructure for effective and efficient recycling still have to be improved.** *Recycling shall be better supervised by public authorities, studies identifying optimised locations for recycling facilities shall be conducted and collection of waste streams harmonised.*

A case study for the price comparison of metals used in cells in 2015, 2018 and 2025 shows that the metal price will increase for nickel and cobalt. **If the necessary metals for the same cell in 2015 costed 11.31 €/kWh, then in 2025 this price could rise by 60% to 18.24 €/kWh.**

When evaluating both, recycling and second life, alternatives, possibly both are feasible if taking into account European position in the global battery value chain. With battery cell manufacturing value chain moving closer to end user market in Europe, the recycling phase will be easier to integrate within the lifecycle of batteries. Thus meaning, **the recycled materials would easily find their way into local European cell production line.**

Moreover, since the raw materials are not sufficiently available in Europe, in order to meet the internal demand, additional imports will have to be secured from third countries. This increases risk of dependence of external supply and enforces vulnerability of internal industry. **By incorporating raw materials into second life applications, the strategic importance of second life battery might actually increase over time.**

All in all, answering the research question of this master thesis – *What is the viability and added value of battery second life concept, in particular in terms of generating environmental and economic benefits* – is difficult. Value proposition and profitability were considered as the main deciding factors for the second life concept feasibility. Driven by the public actor, the value added of the second life battery could be measured in terms of generating environmental benefits which are however demonstrated only under certain conditions and assumptions. Nevertheless, **the concept of second life batteries will most probably not be viable in a long term and not further brought to large scale markets due to marginal potential economic benefits and the complex business environment**. Therefore even though a large amount of batteries will be available for second life, the choice of second life or recycling will not be based on the value added side, but driven by cross sectoral cost competition (cost of recycling, price of new batteries etc.).

Thus the hypothesis - *EV battery second life applications will trigger new sustainable business models by 2030* –is assumed to be wrong within the conceptual framework of this thesis.

Main reflection to be made in the future is whether is it worth using less performant battery if more performant new cheap batteries are available. It is also possible that future batteries will be able to serve EV for their whole lifetime and thus second life will not be deemed necessary.

**Future research**

The analysis performed was for passenger cars in Europe. It could be extended to the global level and to other vehicle types (busses, trucks, two-wheelers).

Taking into consideration the international picture, some externalities could be encountered – such as old battery exports to developing countries, or establishing repurposing facilities in countries with cheap labour which would induce high transportation costs and thus incur substantial environmental impacts. A study on the second life international dimension could be performed.

Taking into consideration that the major EV uptake is predicted for 2025-2030, the drastic increase of second life batteries will start as from 2035-2040. Moreover, since the technology will evolve – NMC811 and introduction of solid state batteries – these new battery generations will change the landscape of metals needed, and thus technologies available for second life. A study on impacts of emerging technologies on second life concept could be performed.

In addition, on the one hand such aspects as connected and automated driving, shared mobility services, fast charging and driver behaviour changes might increase the individual utilisation rates of batteries in future. This meaning that the battery calendar lifetime could be reduced. On the other hand, improvements in battery cyclability would increase the battery calendar lifetime. The study could be made on emerging trends in transport which will impact battery lifetime and consequently second life.

It was concluded that from the economic and technical points of view the preferred option is to repurpose the battery on the pack level, however, in compared to LCOE analysis the most probable use case for second life to be economically viable is the use in small consumer applications, which most probably would mean dismantling the battery further to cell level. Further research could be done to estimate LCOS for second life, taking into consideration varying repurposing costs.

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# ANNEXES

# Annex 1 – Vehicle battery data statistics for BEV and PHEV (up to 2017 and estimations up to 2020)

## Vehicle sales statistics (including division by battery chemistry type indicated in different colours), units sold

Vehicle sales

| Rankin | OEM | Model | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018* | 2019* | 2020* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Nissan | Leaf | 1,737 | 5,383 | 10,894 | 14,691 | 15,346 | 18,601 | 17,460 | 26,190 | 39,285 | 58,928 |
| 2 | Renault | Zoe | - | 68 | 8,833 | 11,029 | 18,566 | 21,350 | 30,683 | 46,025 | 69,037 | 103,555 |
| 3 | Volkswagen | e-Golf | - | 48 | - | 2,931 | 11,170 | 6,678 | 12,902 | 19,353 | 29,030 | 43,544 |
| 4 | BMW | i3 | - | - | 998 | 5,458 | 6,217 | 9,470 | 14,562 | 21,843 | 32,765 | 49,147 |
| 5 | Tesla | Model S | - | - | 3,975 | 9,550 | 16,651 | 12,525 | 15,561 | 23,342 | 35,012 | 52,518 |
| 6 | Smart | Fortwo ED | 907 | 1,029 | 3,351 | 2,945 | 2,037 | 323 | 5,191 | 7,787 | 11,680 | 17,520 |
| 7 | Hyundai | Ioniq Electric | - | - | - | - | - | 1,143 | 6,126 | 9,189 | 13,784 | 20,675 |
| 8 | Tesla | Model X | - | - | - | - | - | 3,756 | 12,637 | 18,956 | 28,433 | 42,650 |
| 9 | Kia | Soul EV | - | - | - | 598 | 5,812 | 4,484 | 5,556 | 8,334 | 12,501 | 18,752 |
| 10 | Smart | Forfour ED | - | - | - | - | - | - | 1,480 | 2,220 | 3,330 | 4,995 |
| Others | / | Others | 6,859 | 9,547 | 4,275 | 9,910 | 11,899 | 13,045 | 12,895 | 19,343 | 29,014 | 43,521 |
| | | **Total** | **9,503** | **16,075** | **32,326** | **57,112** | **87,698** | **91,375** | **135,053** | **202,580** | **303,869** | **455,804** |
| | | LMO | 1,737 | 5,383 | 10,894 | 14,691 | 15,346 | | | | | |
| | | NCA | | | 3,975 | 9,550 | 16,651 | 16,281 | 28,198 | 42,297 | 63,446 | 95,168 |
| | | LMO-NMC | | 68 | 8,833 | 11,029 | 18,566 | 21,350 | | | | |
| | | NMC333 | 7,766 | 10,624 | 8,624 | 21,842 | | | | | | |
| | | NMC622 | | | | | 37,135 | 53,744 | 106,855 | 160,283 | 240,424 | 360,636 |

| Rankin | OEM | Model PHEV | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018* | 2019* | 2020* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Mitsubishi | Outlander PHEV | - | - | 8,193 | 20,035 | 31,275 | 21,343 | 19,202 | 28,803 | 43,205 | 64,807 |
| 2 | Volkswagen | Passat GTE | - | - | - | - | 4,819 | 13,332 | 13,621 | 20,432 | 30,647 | 45,971 |
| 3 | Volvo | XC60 PHEV | - | - | - | - | - | - | 3,852 | 5,778 | 8,667 | 13,001 |
| 4 | Mercedes | GLC350e | - | - | - | - | - | 1,704 | 11,285 | 16,928 | 25,391 | 38,087 |
| 5 | BMW | 530e | - | - | - | - | - | 14 | 6,166 | 9,249 | 13,874 | 20,810 |
| 6 | Volkswagen | Golf GTE | - | - | - | 768 | 17,258 | 11,106 | 9,316 | 13,974 | 20,961 | 31,442 |
| 7 | BMW | 330e | - | - | - | - | 89 | 8,695 | 10,155 | 15,233 | 22,849 | 34,273 |
| 8 | Kia | Niro PHEV | - | - | - | - | - | - | 1,854 | 2,781 | 4,172 | 6,257 |
| 9 | BMW | 225xe Active Tourer | - | - | - | - | 266 | 5,937 | 10,872 | 16,308 | 24,462 | 36,693 |
| 10 | Porsche | Panamera PHEV | - | - | 481 | 944 | 703 | 445 | 4,055 | 6,083 | 9,124 | 13,686 |
| Others | / | Others | 354 | 9,758 | 17,759 | 13,983 | 44,879 | 55,237 | 65,384 | 98,076 | 147,114 | 220,671 |
| http://www.eafo.eu/vehicle-statistic | | Total | **354** | **9,758** | **26,433** | **35,730** | **99,289** | **117,813** | **155,762** | **233,643** | **350,465** | **525,697** |

# Battery pack capacities, kWh

Battery pack kWh

| Ranking | Make | Model | 2011 Total | 2012 Total | 2013 Total | 2014 Total | 2015 Total | 2016 Total | 2017 Total | 2018* | 2019* | 2020* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Nissan | Leaf | 24 | 24 | 24 | 24 | 24 | 30 | 30 | 40 | 40 | 40 |
| 2 | Renault | Zoe | 0 | 22 | 22 | 22 | 22 | 22 | 41 | 41 | 41 | 41 |
| 3 | Volkswagen | e-Golf | 0 | 26.5 | 26.5 | 26.5 | 36 | 36 | 36 | 36 | 36 | 36 |
| 4 | BMW | i3 | 0 | 0 | 22 | 22 | 22 | 22 | 34 | 34 | 34 | 34 |
| 5 | Tesla | Model S | 0 | 85 | 60 | 70 | 90 | 90 | 90 | 100 | 100 | 100 |
| 6 | Smart | Fortwo ED | 16.5 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 |
| 7 | Hyundai | Ioniq Electric | 0 | 0 | 0 | 0 | 0 | 28 | 28 | 28 | 28 | 28 |
| 8 | Tesla | Model X | 0 | 0 | 0 | 0 | 0 | 90 | 90 | 90 | 90 | 90 |
| 9 | Kia | Soul EV | 0 | 0 | 0 | 27 | 27 | 27 | 27 | 30 | 30 | 30 |
| 10 | Smart | Forfour ED | 0 | 0 | 0 | 0 | 0 | 0 | 17.6 | 17.6 | 17.6 | 17.6 |
| Others | / | average Total | 20.3 | 35.0 | 28.7 | 30.4 | 35.3 | 36.3 | 41.4 | 43.1 | 43.1 | 43.1 |

| Ranking | Make | Model PHEV | 2011 Total | 2012 Total | 2013 Total | 2014 Total | 2015 Total | 2016 Total | 2017 Total | 2018* | 2019* | 2020* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Mitsubishi | Outlander PHEV | 0 | 0 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 2 | Volkswagen | Passat GTE | 0 | 0 | 0 | 0 | 9.9 | 9.9 | 9.9 | 9.9 | 9.9 | 9.9 |
| 3 | Volvo | XC60 PHEV | 0 | 0 | 0 | 0 | 0 | 0 | 10.4 | 10.4 | 10.4 | 10.4 |
| 4 | Mercedes | GLC350e | 0 | 0 | 0 | 0 | 0 | 8.7 | 8.7 | 8.7 | 8.7 | 8.7 |
| 5 | BMW | 530e | 0 | 0 | 0 | 0 | 0 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 |
| 6 | Volkswagen | Golf GTE | 0 | 0 | 0 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 |
| 7 | BMW | 330e | 0 | 0 | 0 | 0 | 7.6 | 7.6 | 7.6 | 7.6 | 7.6 | 7.6 |
| 8 | Kia | Niro PHEV | 0 | 0 | 0 | 0 | 0 | 0 | 8.9 | 8.9 | 8.9 | 8.9 |
| 9 | BMW | 225xe Active Tourer | 0 | 0 | 0 | 0 | 6 | 6 | 6 | 6 | 6 | 6 |
| 10 | Porsche | Panamera PHEV | 0 | 0 | 9.4 | 9.4 | 9.4 | 9.4 | 14.1 | 14.1 | 14.1 | 14.1 |
| Others | / | Average | 16 | 12 | 12.0 | 10.4 | 10.2 | 9.7 | 9.8 | 9.8 | 9.8 | 9.8 |

## Battery total capacities per chemistry, MWh

Battery MWh per chemistry

| Ranking | OEM | Model | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018* | 2019* | 2020* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Nissan | Leaf | 41.69 | 129.19 | 261.46 | 352.58 | 368.30 | 558.03 | 523.80 | 1047.60 | 1571.40 | 2357.10 |
| 2 | Renault | Zoe | 0.00 | 1.50 | 194.33 | 242.64 | 408.45 | 469.70 | 1258.00 | 1887.00 | 2830.51 | 4245.76 |
| 3 | Volkswagen | e-Golf | 0.00 | 1.27 | 0.00 | 77.67 | 402.12 | 240.41 | 464.47 | 696.71 | 1045.06 | 1567.59 |
| 4 | BMW | i3 | 0.00 | 0.00 | 21.96 | 120.08 | 136.77 | 208.34 | 495.11 | 742.66 | 1113.99 | 1670.99 |
| 5 | Tesla | Model S | 0.00 | 0.00 | 238.50 | 668.50 | 1498.59 | 1127.25 | 1400.49 | 2334.15 | 3501.23 | 5251.84 |
| 6 | Smart | Fortwo ED | 14.97 | 18.11 | 58.98 | 51.83 | 35.85 | 5.68 | 91.36 | 137.04 | 205.56 | 308.35 |
| 7 | Hyundai | Ioniq Electric | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 32.00 | 171.53 | 257.29 | 385.94 | 578.91 |
| 8 | Tesla | Model X | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 338.04 | 1137.33 | 1706.00 | 2558.99 | 3838.49 |
| 9 | Kia | Soul EV | 0.00 | 0.00 | 0.00 | 16.15 | 156.92 | 121.07 | 150.01 | 250.02 | 375.03 | 562.55 |
| 10 | Smart | Forfour ED | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 26.05 | 39.07 | 58.61 | 87.91 |
| Others | / | / | 138.89 | 334.34 | 122.62 | 300.77 | 419.64 | 473.10 | 534.28 | 833.66 | 1250.49 | 1875.74 |
| | | **Total MWh BEV** | **196** | **484** | **898** | **1,830** | **3,427** | **3,542** | **6,081** | **9,674** | **14,511** | **21,766** |
| LMO | 1,153.2 | | 41.7 | 129.2 | 261.5 | 352.6 | 368.3 | | | | | |
| NCA | 25,599.4 | | | - | 238.5 | 668.5 | 1,498.6 | 1,465.3 | 2,537.8 | 4,040.1 | 6,060.2 | 9,090.3 |
| LMO-NMC | 1,316.6 | | | 1.5 | 194.3 | 242.6 | 408.5 | 469.7 | | | | |
| NMC333 | 1,277.6 | | 154 | 354 | 204 | 566 | | | | | | |
| NMC622 | 33,061.4 | | | | | | 1,151 | 1,607 | 3,543 | 5,634 | 8,451 | 12,676 |

| Ranking | Make | Model PHEV | 2011 Total | 2012 Total | 2013 Total | 2014 Total | 2015 Total | 2016 Total | 2017 Total | 2018* | 2019* | 2020* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Mitsubishi | Outlander PHEV | | | 98 | 240 | 375 | 256 | 230 | 346 | 518 | 778 |
| 2 | Volkswagen | Passat GTE | | | - | - | 48 | 132 | 135 | 202 | 303 | 455 |
| 3 | Volvo | XC60 PHEV | | | - | - | - | - | 40 | 60 | 90 | 135 |
| 4 | Mercedes | GLC350e | | | - | - | - | 15 | 98 | 147 | 221 | 331 |
| 5 | BMW | 530e | | | - | - | - | 0 | 57 | 85 | 128 | 191 |
| 6 | Volkswagen | Golf GTE | | | - | 7 | 152 | 98 | 82 | 123 | 184 | 277 |
| 7 | BMW | 330e | | | - | - | 1 | 66 | 77 | 116 | 174 | 260 |
| 8 | Kia | Niro PHEV | | | - | - | - | - | 17 | 25 | 37 | 56 |
| 9 | BMW | 225xe Active Tourer | | | - | - | 2 | 36 | 65 | 98 | 147 | 220 |
| 10 | Porsche | Panamera PHEV | | | 5 | 9 | 7 | 4 | 57 | 86 | 129 | 193 |
| Others | / | / | | | 213 | 145 | 459 | 537 | 643 | 964 | 1,447 | 2,170 |
| | | **Total MWh PHEV** | **-** | **-** | **316** | **401** | **1,043** | **1,144** | **1,501** | **2,252** | **3,378** | **5,067** |
| LMO | 2,842 | | | | 98 | 240 | 375 | 256 | 230 | 346 | 518 | 778 |
| NCA | | | | | | | | | | | | |
| LMO-NMC | | | | | | | | | | | | |
| NMC333 | | | | | | | | | | | | |
| NMC622 | 12,259 | | | | 218 | 161 | 668 | 887 | 1,271 | 1,906 | 2,859 | 4,289 |

# Annex 2 – Metal contents in batteries

## Metal contents by cell chemistry, kg/kWh - based of BatPac tool

| cell chemistry | NMC333 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Battery 1 | Battery 2 | Battery 3 | Battery 4 | Battery 5 | Battery 6 | Battery 7 |
| **Lithium Content** | | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh |
| Positive electrode, g Li/g active material | 0.08 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 |
| Negative electrode, g Li/g active material | - | - | - | - | - | - | - | - |
| Electrolyte (1.2M LiPF6), g Li/L electrolyte | 8.33 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| ***Total Lithium content*** | | - | - | - | - | - | - | - |
| **Transition Metal Content** | | 0.15 | | | | | | |
| Nickel, g/g active material | 0.22 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Cobalt, g/g active material | 0.22 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Manganese, g/g active material | 0.21 | 0.37 | 0.37 | 0.37 | 0.38 | 0.37 | 0.37 | 0.37 |

| cell chemistry | NMC622 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Battery 1 | Battery 2 | Battery 3 | Battery 4 | Battery 5 | Battery 6 | Battery 7 |
| **Lithium Content** | | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh |
| Positive electrode, g Li/g active material | 0.08 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Negative electrode, g Li/g active material | - | - | - | - | - | - | - | - |
| Electrolyte (1.2M LiPF6), g Li/L electrolyte | 8.33 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| ***Total Lithium content*** | | - | - | - | - | - | - | - |
| **Transition Metal Content** | | 0.13 | | | | | | |
| Nickel, g/g active material | 0.40 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 |
| Cobalt, g/g active material | 0.13 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Manganese, g/g active material | 0.14 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |

| cell chemistry | NCA | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Battery 1 | Battery 2 | Battery 3 | Battery 4 | Battery 5 | Battery 6 | Battery 7 |
| **Lithium Content** | | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh |
| Positive electrode, g Li/g active material | 0.072 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Negative electrode, g Li/g active material | - | - | - | - | - | - | - | - |
| Electrolyte (1.2M LiPF6), g Li/L electrolyte | 8.33 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| ***Total Lithium content*** | | 0.10 | | | | | | |
| **Transition Metal Content** | | | | | | | | |
| Nickel, g/g active material | 0.49 | 0.67 | 0.68 | 0.67 | 0.68 | 0.68 | 0.68 | 0.68 |
| Cobalt, g/g active material | 0.09 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Manganese, g/g active material | - | - | - | - | - | - | - | - |

| cell chemistry | LMO | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Battery 1 | Battery 2 | Battery 3 | Battery 4 | Battery 5 | Battery 6 | Battery 7 |
| **Lithium Content** | | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh |
| Positive electrode, g Li/g active material | 0.04 | 0.10 | 0.11 | 0.10 | 0.11 | 0.10 | 0.10 | 0.11 |
| Negative electrode, g Li/g active material | - | - | - | - | - | - | - | - |
| Electrolyte (1.2M LiPF6), g Li/L electrolyte | 8.33 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| ***Total Lithium content*** | | - | - | - | - | - | - | - |
| **Transition Metal Content** | - | 0.11 | | | | | | |
| Nickel, g/g active material | - | - | - | - | - | - | - | - |
| Cobalt, g/g active material | - | - | - | - | - | - | - | - |
| Manganese, g/g active material | 0.62 | 1.58 | 1.59 | 1.58 | 1.59 | 1.58 | 1.58 | 1.59 |

| cell chemistry | LMO-NMC | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Battery 1 | Battery 2 | Battery 3 | Battery 4 | Battery 5 | Battery 6 | Battery 7 |
| **Lithium Content** | | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh | kg/kWh |
| Positive electrode, g Li/g active material | 0.05 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Negative electrode, g Li/g active material | - | - | - | - | - | - | - | - |
| Electrolyte (1.2M LiPF6), g Li/L electrolyte | 8.33 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| ***Total Lithium content*** | | - | - | - | - | - | - | - |
| **Transition Metal Content** | | 0.12 | | | | | | |
| Nickel, g/g active material | 0.03 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Cobalt, g/g active material | 0.03 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Manganese, g/g active material | 0.29 | 0.67 | 0.68 | 0.67 | 0.68 | 0.68 | 0.68 | 0.68 |

# Metal contents in EVs by chemistry type, kg

| BEV | kg/kWh | | | | | kg of metals per chemistry | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **Total kg** |
| Nickel | - | 0.072 | 0.672 | 0.606 | 0.397 | - | 94,494 | 17,207,422 | 20,032,712 | 507,553 | **37,842,182** |
| Cobalt | - | 0.072 | 0.127 | 0.189 | 0.399 | - | 94,795 | 3,240,039 | 6,251,237 | 509,715 | **10,095,786** |
| Manganese | 1.576 | 0.672 | - | 0.203 | 0.372 | 1,817,815 | 884,757 | - | 6,707,315 | 475,037 | **9,884,923** |
| | | | | | | | | | | | **57,822,891** |

| Total accumulated capacity, BEV | | |
|---|---|---|
| | LMO | 1,153,224 |
| | NCA | 25,599,389 |
| | LMO-NMC | 1,316,612 |
| | NMC622 | 33,061,435 |
| | NMC333 | 1,277,627 |
| | kWh | **62,408,287** |

| PHEV | kg/kWh | | | | | kg of metals per chemistry | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **Total kg** |
| Nickel | - | 0.072 | 0.672 | 0.606 | 0.397 | - | | | 7,428,216 | | **7,428,216** |
| Cobalt | - | 0.072 | 0.127 | 0.189 | 0.399 | - | | | 2,317,986 | | **2,317,986** |
| Manganese | 1.576 | 0.672 | - | 0.203 | 0.372 | 4,480,362 | | | 2,487,101 | | **6,967,463** |
| | | | | | | | | | | | **16,713,664** |

| Total accumulated capacity, PHEV | | |
|---|---|---|
| | LMO | 2,842,347 |
| | NCA | |
| | LMO-NMC | |
| | NMC622 | 12,259,322 |
| | NMC333 | - |
| | kWh | **15,101,669** |

| Total EV | kg/kWh | | | | | kg of metals per chemistry | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **LMO** | **LMO-NMC** | **NCA** | **NMC622** | **NMC333** | **Total kg** |
| Nickel | - | 0.072 | 0.672 | 0.606 | 0.397 | - | 94,494.467 | 17,207,422 | 27,460,927 | 507,553 | **45,270,397** |
| Cobalt | - | 0.072 | 0.127 | 0.189 | 0.399 | - | 94,795.404 | 3,240,039 | 8,569,223 | 509,715 | **12,413,772** |
| Manganese | 1.576 | 0.672 | - | 0.203 | 0.372 | 6,298,177 | 884,757.107 | - | 9,194,416 | 475,037 | **16,852,386** |
| | | | | | | | | | | | ***74,536,555*** |

| Total accumulated capacity, EV | | |
|---|---|---|
| | LMO | 3,995,571 |
| | NCA | 25,599,389 |
| | LMO-NMC | 1,316,612 |
| | NMC622 | 45,320,757 |
| | NMC333 | 1,277,627 |
| | **kWh** | **77,509,956** |

## Second life battery availability in terms by 2030, MWh

| | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Yearly available capacity of second life batteries | **196** | **484** | **1,214** | **2,232** | **4,470** | **4,685** | **7,582** | **11,926** | **17,889** | **26,833** | |
| Cummulative available capacity of second life batteries | **196** | **680** | **1,894** | **4,126** | **8,596** | **13,281** | **20,863** | **32,789** | **50,678** | **77,511** | |
| LMO | 42 | 129 | 360 | 593 | 744 | 256 | 230 | 346 | 518 | 778 | **3,996** |
| NCA | - | - | 239 | 669 | 1,499 | 1,465 | 2,538 | 4,040 | 6,060 | 9,090 | **25,599** |
| LMO-NMC | - | 1 | 194 | 243 | 408 | 470 | - | - | - | - | 1,317 |
| NMC333 | 154 | 354 | 204 | 566 | - | - | - | - | - | - | 1,278 |
| NMC622 | - | - | 218 | 161 | 1,819 | 2,494 | 4,814 | 7,540 | 11,310 | 16,965 | **45,321** |

| | |
|---|---|
| LMO | 3,995,571 |
| NCA | 25,599,389 |
| LMO-NMC | 1,316,612 |
| NMC622 | 45,320,757 |
| NMC333 | 1,277,627 |
| **kWh** | **77,509,956** |

## Metal amount embedded in second life batteries by 2030, kg

| | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nickel | 61,123 | 140,626 | 386,994 | 789,401 | 2,138,831 | 2,529,881 | 4,622,739 | 7,284,379 | 10,926,569 | 16,389,854 | **45,270,397** |
| Cobalt | 61,383 | 141,225 | 166,536 | 358,537 | 563,021 | 690,857 | 1,231,416 | 1,937,010 | 2,905,514 | 4,358,272 | **12,413,772** |
| Manganese | 122,919 | 336,166 | 817,526 | 1,341,101 | 1,815,647 | 1,225,337 | 1,339,834 | 2,074,496 | 3,111,744 | 4,667,616 | **16,852,386** |
| Total | **247,446** | **620,039** | **1,373,079** | **2,491,063** | **4,519,524** | **4,448,101** | **7,196,016** | **11,297,913** | **16,945,857** | **25,417,771** | **74,536,555** |

**Recycled raw material share in potential raw material demand for EVs in Europe in 2030**

| | Raw material availbaility in batteries after their first life in 2030 | Accumulated raw material availbaility in batteries after their first life by 2030 | 2030 est. raw material needs (for 5 million vehicles, current technology) | % of potential raw material supply of accumulated raw materials |
|---|---|---|---|---|
| Nickel | 16,389,854 | 45,270,397 | 81,949,268 | 55.24% |
| Cobalt | 4,358,272 | 12,413,772 | 21,791,358 | 56.97% |
| Manganese | 4,667,616 | 16,852,386 | 23,338,081 | 72.21% |
| Total | **25,417,771** | **74,536,555** | **127,078,707** | 58.65% |

## Annex 3 – Metal price statistics and forecast, $/T

| Years | Coppe | Aluminiun | Nickel | Manganese | Lithium Carbonate | Cobalt |
|---|---|---|---|---|---|---|
| **2014** | 6,863 | 1,867 | 16,893 | 2,300 | 6,000 | 31,000 |
| **2015** | 5,510 | 1,665 | 11,863 | 2,100 | 5,950 | 30,000 |
| **2016** | 4,868 | 1,604 | 9,595 | 1,650 | 5,900 | 24,000 |
| **2017** | 6,170 | 1,968 | 10,410 | 2,150 | 7,900 | 60,000 |
| **2018** | 6,800 | 2,175 | 13,500 | 2,040 | 12,000 | 75,999 |
| **2019** | 6,816 | 2,100 | 13,828 | | 11,000 | 70,877 |
| **2020** | 6,833 | 2,109 | 14,163 | | 10,500 | 60,427 |
| **2021** | 6,849 | 2,118 | 14,507 | | 10,000 | |
| **2022** | 6,866 | 2,127 | 14,859 | | 10,000 | |
| **2023** | 6,883 | 2,136 | 15,219 | | 10,500 | |
| **2024** | 6,899 | 2,145 | 15,588 | | 11,000 | |
| **2025** | 6,916 | 2,154 | 15,967 | | | |
| **2030** | 7,000 | 2,200 | 18,000 | | | |

*Sources of data:*

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