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Contents

1 INTRODUCTION

Batteries are considered as a key technology for the mobility and energy system transformation, to meet the ambitious CO_2 goals of the United Nations COP 21 conference in Paris. That being said, “Sustainability” is much more than CO_2 footprint only. Sustainability is about reduction of air pollution (Green House Gases, methane, NOx, CO_2, fine particles, and others), reduction of water and soil pollution, landscape and biodiversity protection, waste management, efficient use of clean renewable low-carbon energy sources, protection of workers from exposure to hazardous substances, and protection of workers in their working conditions (decent social rights and salary). Sustainability is also about economical sustainability and geopolitical independence. In fact, in this paper, we want to have a holistic view on what is sustainability about and how Europe could become an attractive location for “sustainable” batteries production and businesses. Three main area have been identified for sustainability: economic sustainability, social sustainability, and environmental sustainability.

Present Lithium-Ion Batteries (LIBs), despite their success, have manifold challenges from a sustainability perspective, including:

- Relying on critical materials, such as Co, Li and P, and potentially critical materials in the future, such as Ni and Cu;
- High environmental and social impacts of production (including toxicity of materials);
- High production cost (even if the costs declined significantly in recent years);
- Carbon neutrality in terms of energy mix and water used for the production and complex synthesis processes generating emissions of CO_2;
- Life cycle costs (including use phase) are, for many applications, too high;
- Technical performance needs improvement to lower costs and environmental impacts regarding the use phase (beside energy and power density also cycle lifetime, calendric lifetime, internal resistance, and others);
- Present recycling is too complex and requires a lot of effort (relatively high costs and environmental impacts);
- Safety issues during production, use phase, second use and recycling (influence societal acceptance); and
- Poor traceability along the value chain.

Future post-lithium battery systems (Post-LIBs) have to overcome present challenges and outperform present LIBs from both a battery performance and a sustainability perspective. This is certainly not an easy mission and can only be achieved by a multi- and interdisciplinary research. The early design phase is very important for the future performance (technical, economic, ecological) of a developed battery cell system. The high degree of freedom in the early development stage can be used to guide the development towards increased sustainability (“Design for Sustainability”). Depending on the considered TRL level, different methods can be used to support the development process. During low TRLs, qualitative methods should be used, such as the criticality of used raw materials (also for the precursor) or potential costs or toxicity. Such information can be used in screening tools, to support the selection of the group of most promising (e.g. cathode) materials. During higher TRLs, quantitative methods like Life Cycle Assessment (LCA) can be used to analyse the potential environmental impacts of developed materials or test cells[1].

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[1] Marcel Weil et al. Life cycle sustainability analysis of present and future battery systems. Web-Conference: European perspectives on batteries of the future. Battery 2030+. May 25th and May 26th 2020

MCDA methodology

Multi Criteria Decision Analysis (MCDA) can address the different dimensions of sustainability to analyse and evaluate in a holistic manner the technology in the R&D phase or products. With the consideration of economic, ecological and social assessment results of an analysed technological artefact (like batteries), MCDA helps to understand the sustainability implications. The assessments of the sustainability of a technology or option requires the consideration of a wide variety of information types, parameters and related uncertainties, which is a challenging task. Multi Criteria Decision Analysis (MCDA) is a suitable methodology to combine and condense the different outcomes of the sustainability dimensions (which can be conflicting) towards a certain decision or selection. In addition, MCDA can be used to analyse and determine the preferences of the society or specific stakeholder group regarding the weighting (of the importance) of the different sustainability dimensions.

2 ECONOMIC SUSTAINABILITY

2.1 Lack of raw materials & geopolitical considerations

New green technologies in general, and the value chain for batteries in particular, are sensitive to geopolitics, as a large share of the necessary raw materials are sourced from outside the EU. The current production of critical battery raw materials is currently mainly outside the EU. Today, only small shares of the total production are EU-based, including Lithium (<1%), Cobalt (<2%) and graphite (<1%). Lithium, nickel and manganese mainly come from South America and Asia, and the largest share of cobalt production originates from the Democratic Republic of Congo.[2]

The dependency on individual countries outside the EU for battery raw materials makes the European battery industry and its supply chains vulnerable to geopolitical sensitivities. Furthermore, the growth of the battery demand and the need to secure the supply of raw materials for batteries is leading to international competition that may well affect the geopolitical balance and cause political tensions in exporting countries. The EU therefore needs to act swiftly to ensure that it has access on the global market and can develop additional sources (primary and secondary) for important raw materials. Non-European countries have commerce agreements to ensure their supply of the raw materials needed for battery production. Europe needs to ensure its supply of these important raw materials and develop alternative technologies not relaying on these scarce raw materials or technologies reducing the energy and environmental impact of raw materials in the total impact of the batteries that utilise these materials. For example, 1kg of NMC111 powder presents an energy and environmental impact[3] (GHG, SOx, NOx emissions, water consumption, and others) coming from the calcination and co-precipitation steps to produce the active material as well as from the productions of the precursors being carbonates, sulphates, hydroxide salts coming from the ores (Figure 1).

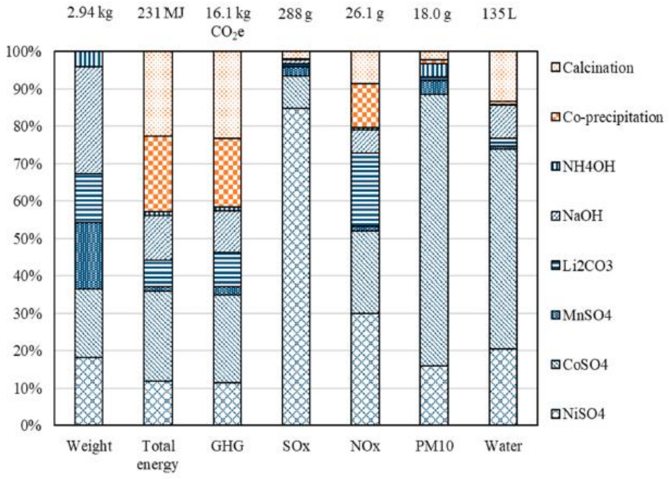

Figure 3. Energy and environmental impact breakdowns of 1 kg NMC111 powder. Blue denotes material inputs; orange denotes energy inputs and non-combustion emissions for NMC111 powder production.

FIGURE 1: ENERGY AND ENVIRONMENTAL IMPACT BREAKDOWN OF 1KG NMC111[4]

The same problems occur in the value chains for equipment, such as components and machinery for battery production, where the innovation in Europe is high but technical readiness remains low in

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[2] Stathis Peteves et al., JRC, Materials' supply chain bottlenecks in the course of the EU energy transition, WRF 2017.

[3] Qiang Dai et al. 2019 'Life cycle analysis of Lithium-ion batteries for Automotive Applications'

[4] Ibid

combination with a lower competitiveness from an economic standpoint. As a result, currently the Asian suppliers‘ offer remains larger and more attractive economically. In addition, a large share of the battery applications placed on the European market today are depending on third party import of battery cells.

EU research and innovation activities can be used to find new sources of primary (including mining and refining capacities) and secondary raw materials. This enables the examination of different battery chemistries and alternative materials to decrease the high dependency on importing raw materials and components outside the EU as well as the strengthening of the European suppliers and producers to develop mature technologies and skills required to support the battery value chain abilities on the European market.

In the short term (before 2025), the EU needs to put in place mechanisms to secure recurrent access to enough critical raw or refined materials, components and equipment for battery production in Europe at competitive market conditions. The key criteria for the selection of these materials, components and equipment should be traceability (including social aspects), carbon footprint, and sustainable sourcing via short and reliable supply chains (through preferred economical accords). Supporting new business initiatives (production, recycling and others) on current battery technologies (including Li-ion) in the EU is critical to ensure the growth of an economy and trained workforce around batteries.

In the longer term (from 2025 on), the EU should aim at supporting the development at higher TRLs of **current** and **new** economically viable technologies with low environmental and social impact. There is a need for new businesses in the following fields: new processes, machinery, factory to synthesize, assemble and manufacture current and next generation materials, components, cells and batteries based on fewer scarce elements while targeting high yield, low scrap %, less or combined steps, low energy consumption and/or combination at plant level with renewable energy (solar, geothermal, wind, and others), low/no solvent processing, water and energy management system, low CO_2 footprint.

2.2 Import and sustainability of the production outside EU

The premise on which the development of e-mobility rests is that an increased use of Electric Vehicles (EVs) will lower the carbon footprint of transportation. This will be recognised by citizens as long as ICE powered cars are in the process of being substituted.

Once a sizeable portion of vehicles is electrified, the onus will be on reducing the CO_2 footprint of the battery itself. This has been recognised by the European Commission and it is expected that the EU regulatory framework will soon be pushing towards reporting and reducing the CO_2 footprint of e-mobility batteries.

The manufacture of these high value component requires the coordination of a supply chain which starts in mineral rich countries and leads towards the assembly of battery modules into a final battery at the site of an automobile OEM. The ongoing worldwide effort to decarbonise GDP requires that all manufacturing steps be assessed for their contribution to GWPG emissions.

Creating the scientific and technical foundations for the manufacture of low CO_2 footprint batteries in the EU is therefore a strategic differentiating feature.

New business models enhancing sustainability and competitiveness

Four possible mechanisms would allow established industry to carry out competitive investments with high sustainability standards:

- Development of competitive sustainable technologies.
- Development of a recognised and broader eco-label than exists today for sustainable battery and battery related products, trustworthy due to traceability at environmental and socio-economical levels; this could lead to a higher level of responsibility and willingness to pay (customer demand).
- Implementing the new battery regulation[5].
- Focused funding policies at both EU and member state levels and/or taxes to reach Green batteries standards[6].

The current EU eco-label promotes Europe's transition to a circular economy, but focuses mostly on environmental aspects (less waste, CO_2, energy, raw materials; longer lifetime and easy to repair or recycle). We propose to emphasise and add criteria on socio-economical aspects to reflect the broader definition of sustainability.

Obviously, a delicate balance must be found between increasing regulation and/or taxes and keep the economic viability of the battery materials, processes, products and derivatives produced and/or used in Europe.

R&D and low-TRL development

Development of competitive sustainable technologies is the most time-consuming and investment-heavy route. It also requires fundamental as well as application driven basic research. However, favourable policy, targeted regulation, and communication to customers tend to speed up the development. This means also that the research must have an accelerated pace to enable the targeted regulation to be meaningful. In practice this means a better integration of novel tools provided by the new era of digitalisation to improve experimental understanding and advancement in research fields impacting sustainability: green chemistry routes for sustainable synthesis, substitution of toxic material and solvents in electrodes and electrolytes, life-time improving studies to enable a safe and long-term use of a battery. In this context, technical aspects such as recycling and raw material efficiency present necessary sustainability advantages. Total cost of ownership will be lower if the right R&I actions will be stimulated to increase the battery reliability.[7]

A special attention must be made to support the creation of new businesses and companies developing competitive sustainable technologies today in European R&D centre or universities that have not yet been found attractive by the established European industry because of the low TRL (1-2) of their technology today, which still has a long path to market (the final products including materials, components, battery cell, BMS, tool, device, apps, and others) due to the need to become more competitive first. Ideally, we need to avoid that those competitive sustainable technologies developed

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[5] REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798

[6] Ibid.

[7] Battery 2030+ roadmap: Sensor in the cell. https://battery2030.eu/digitalAssets/861/c_861008-l_1-k_roadmap-27-march.pdf

in Europe would reinforce the non-European industry even further by a lack of an internal funding mechanism to bridge the gap from TRL 2 to 6.

Traceability and influencing customer demand

For manufacturers, responsible raw material sourcing is not only about building consumer trust and protecting brand and reputation, but more fundamentally about securing access to the raw materials required to deliver on their electrification strategies. Moreover, consumers are increasingly aware that their choices have consequences for the environment and other people. These are some of the main drivers creating business opportunities in parallel to sustainability enhancements.

Transparency and traceability standards will help consumers ensure good quality batteries. Increased awareness of responsibility issues in the value chain will raise interest in the customers valuing such battery products. They are possibly willing to pay higher price for higher quality products. This trend has already taken place in the food industry, industry and textile industries. It is only matter of time when this takes place in the automotive and energy storage industries.

A traceability system will increase the value of sustainably and responsibly produced batteries and battery materials in first and second life. This will give room for new business cases and encourage producers to use solutions reducing the societal and environmental footprint of batteries. The information can be used in both B2B and B2C marketing enabling choices based on both quantified and validated environmental and social performance. This requires, amongst others, setting ethical, social and environmental indicators to be measured as well as standards for chain of custody data and active engagement of value chain key players and stakeholders.

2.3 Recycling

Recycling is still relatively limited today: indeed, the availability of batteries to be recycled depends mainly on the available volumes (tonnes) of batteries placed on the market and the moment they reach end-of-life, which is postponed as the battery lifetime increases every year. As such it is important to realise that batteries equipping vehicles today would not become available for recycling before the next 10-15 years.[8]

From a circular economy perspective, when it comes to Lithium-ion batteries, there is a need to enhance the design and manufacture from recycled sources. To overcome the current symbolic low recovery rates of some critical materials, such as lithium and graphite, a comprehensive ex-ante life cycle assessment and the life cycle material modelling envisioning also new applications for the recycled batteries material are essential prior to any product design.

Already in the design phase of new batteries, aspects of recycling (on material, cell and battery level) and sustainability should be included. That means methods like design for recycling or design for sustainability should be used at an early stage and further developed.

The expected result of this approach will enhance the valorisation of “waste” material fractions not only in closed loop applications.

Furthermore, user-centred analysis involving players in the upstream (waste treatment providers) but also in the downstream value chain (consumers) of the products based on recycled materials need to

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[8] The lithium-ion battery life cycle report 2021, Circular Energy Storage Research & Consulting

be anticipated at an early stage. These investigations will ultimately avoid the high economic losses and the prestige burdens due to frequent failures caused by consumer/user rejection upon implementation of "recycled-based" products in the market.

In the case of battery coming at the end of their life (typically when SOC in Battery Electric Vehicle is below 80% of the initial performances), it is important *in the first instance* to consider and assess the possibility of re-using (in the same application) and/or re-purposing of battery cells (for another application) as optional additional steps that may be applied where feasible; whenever batteries become waste (for example, where further reuse or repurposing is not feasible), they should be recycled (see Figure 2)[9]. New business models might emerge from re-furbishing and/or re-using battery cells for second use, while the right balance between competitiveness and sustainability is yet to be found and therefore should be investigated.

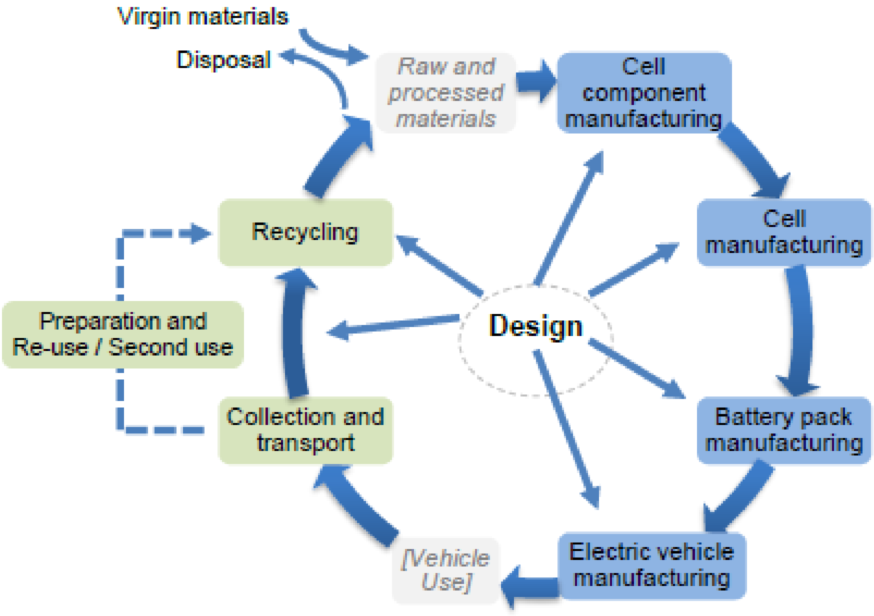

FIGURE 2: CIRCULAR VIEW OF THE EV BATTERY VALUE CHAIN FOR EUROPE

An in-depth cost analysis as well as an updated LCA inclusive of such options have to be developed. Note that the sorting and selection of cells to be re-used or refurbished should be cost-efficient compared to new cell cost (decreasing every year) or recycling costs, and automatisation assisted by in situ cell sensors monitoring accurately the state-of-health (SoH) of battery cell might help to minimise the cost of this sorting step[10]. Also the labeling of cells (and battery components) would allow a more efficient recycling and thus reducing the costs. Last but not least, the safety of such cells should be ensured over its first and second life, to guarantee the traceability of cells.

As demands to increase the vehicle range and habitability continues to expand, higher specific energy batteries will continue to be expected from new generations of batteries. It is therefore expected that designs will continue to change in the way of compaction, and the chemical systems at play will further evolve. In this context, to ensure a solid future of the battery recycling industry, it is highly desirable

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[9] Ricardo report: Circular economy perspective for the management of batteries used in Electric Vehicles. https://ec.europa.eu/jrc/en/publication/circular-economy-perspectives-management-batteries-used-electric-vehicles

[10] Battery 2030+ roadmap: Sensor in the cell. https://battery2030.eu/digitalAssets/861/c_861008-l_1-k_roadmap-27-march.pdf

that their recycled output be able to address a wide range of industries to limit the risks of a loss of downstream markets (which will happen to Pb when it is finally substituted by Li-ion).

The need for recyclers to connect their output to the main streams of base metal supplies is the only successful hedging strategy.

2.4 Improve technical performance and costs decrease

The already mature lithium-ion batteries can still be improved to increase performances when it comes to both specific energy and power. Even the life-time can still be improved to a higher number of cycles that will keep the price low. The expectation is that solid-state batteries with metallic lithium will more than double today's battery capacity when the problem of dendrite formation for lithium and long-term cycling is solved. An overview of expected new battery chemistries is shown in Figure 3, taken from the BATTERY 2030+ roadmap[11]. Some of the new concepts have a very high gravimetric capacity but may be less valuable in applications where volumetric capacity is more important. For the new values, the capacities to be reached are only tentative.

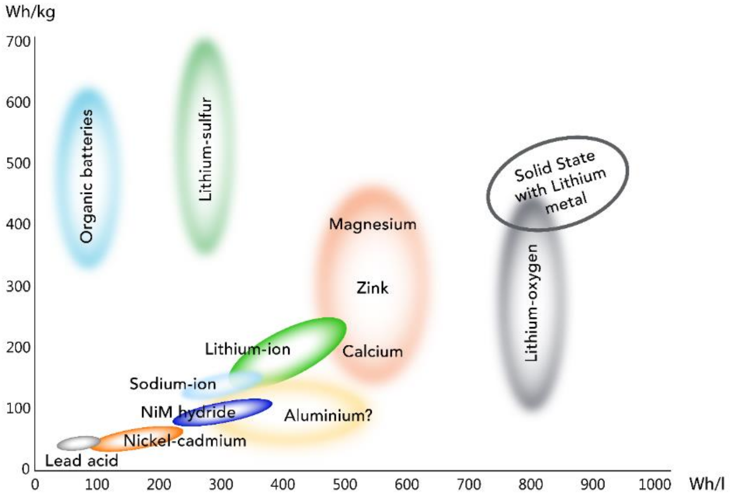

FIGURE 3: OVERVIEW OF EXPECTED NEW BATTERY CHEMISTRIES

Technical performance of the production processes as well as the performance of the products can be enhanced by increasing the information tagged with the products and their intermediates. With the mechanisms beyond state of the art, this target is not opposite to security or confidentiality. Increased transparency within and between organisations increases process efficiency. For example, battery chemical refining, battery assembly, 2nd use, refurbishment and recycling of the batteries would be supported by valuable information on the batteries and material chemistry that could be utilised in, for example, making better decisions/choices and processes more efficient and safer.

2.5 Regulatory aspects related to R&D projects

One key aspect of the regulatory burden linked to R&D&I activities are the burdens and procedures when entering cooperative and EU-funded R&D activities. Criteria such as data sharing, openness of

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[11] Battery 2030+ roadmap: Sensor in the cell. https://battery2030.eu/digitalAssets/861/c_861008-l_1-k_roadmap-27-march.pdf

data and transparency when entering research projects could potentially raise the bar for needed R&D&I. Battery production and applications include many aspects of immaterial property rights, such as the chemical development, cell design, BMS programming and stored data on battery usage. As information is a key factor in battery development, EU criteria for data and information transparency, when entering public funded projects, could potentially hamper battery R&D activities in the EU, lowering battery producers’ willingness to receive public funding for such activities.

3 SOCIAL SUSTAINABILITY

3.1 Social Life cycle assessment (S-LCA)

Social life cycle assessment (S-LCA) is considered a comprehensive methodology that aims to assess the positive and negative social impacts of a product or service. The methodology is described within the technical report of JRC[12], SETAC[13] and others[14].

Problematic are the different available S-LCA databases. There is a lack of information on social impacts of the sourcing, production and recycling of batteries. The methodology for S-LCA is still developing, and the UNEP/SETAC guidelines on S-LCA are currently being reviewed through UN pilot studies.

The interpretation of the results is difficult, because often the uncertainties are higher than the differences of the compared options.

The results of S-LCAs are more interesting for raw material provider, cell producer or policy-makers. For technology process developers the sourcing of raw materials (of a specific country and related social issues) are less interesting. However, S-LCA offers a complementary approach to considering social impacts of a process alongside the assessment of environmental impacts using traditional LCA and whole-life cycle costing[15]. Ultimately, the S-LCA should reach the end customers to trigger his willingness to choose a sustainable product above another: eco-label for battery and battery related products proposed earlier in addition to bring traceability of the materials and processes involved should include (at least one) criterion on social traceability reflecting the results of S-LCA.

3.2 Workers' rights and social aspects in value chain

The current situation for the European actors within the battery industry is uneven. The production outside of Europe is heavily boosted by the local governments. This creates a clear disadvantage for Europe, which will, in the future increase its demand for batteries and their raw materials. The production, especially the raw and advanced material delivery, is expected to not be able to keep up with the demand in the coming years. There is a strong need for levelling the playing field for the European actors.

A clear advantage point for the European actors can be found from the social aspects of battery production. In the current situation, imported material gains advantage compared to European production. Social issues such as child labour and poor occupational safety are often linked with the battery minerals production, especially in Africa. Transparency through the traceability system would at least allow consumers to make choices based on social issues. It will provide tools both for customer selection and regulation. Overall, this is expected to provide advancements in social conditions related to battery value chain, especially in the battery raw materials production.

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[12] Social Life Cycle Assessement, Serenella Sala, Alessandro Vasta, Lucia Mancini, Jo Dewulf, Eckehard Rosenbaum, JRC. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC99101/lbna27624enn.pdf

[13] Life Cycle Initiative, Guidelines for social life cycle assessment of products, UNEP, SETAC. https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2009%20-%20Guidelines%20for%20sLCA%20-%20EN.pdf

[14] Positive impacts in social life cycle assessment: state of the art and the way forward, Silvia Di Cesare, Federica Silveri, Serenella Sala & Luigia Petti , https://link.springer.com/article/10.1007/s11367-016-1169-7

[15] Mancini L, Sala S. Social impact assessment in the mining sector: Review and comparison of indicators frameworks. Resour Policy 2018. https://www.researchgate.net/publication/276267553_Social_Life_Cycle_Assessment_as_a_pillar_of_sustainability_analysis_of_batteries_The_case_of_LiFePO4

Batteries in general and e-mobility batteries in particular have been identified as key enablers for the decarbonisation of the economy. It is widely agreed that this industry will be growing at unprecedented rates over the next two decades.

With success comes responsibility. It would be greatly ironic, if not outright unsustainable, if the growth of this industry was built on below standard, or just average environmental and social practices.

Amongst key elements of the growth are the recognition that the battery industry has to ensure, throughout its supply chain, the implementation of due diligence obligations with regard to labour rights and environmental protection.

In order to ensure these values are upheld, the battery industry has to implement the five steps of a due diligence plan:

- Get to know the supply chain and identify the risks;
- Encourage transparent public reporting;
- Conduct third party evaluation of suppliers, in line with the identified risks;
- Implement risk mitigation programs where deviations have been identified;
- Deploy a claim gathering mechanism to capture violations;
- Implement a follow-up mechanism to assess the deployment of mitigation measures and their effectiveness.

3.3 Jobs, reskilling and training

Jobs, reskilling and training are pre-requisites for a fast transformation to a fossil-free society. The multidimensional concepts constituting sustainability, including knowledge about raw material and production of battery materials for mining, are the basis for the design of new training schemes for education at academia as well as re- and up-skilling the workforce to meet the new demands. The EU expects an increase in battery cell manufacturing capability in Europe from 3% 2018 to 25% to 2028[16]. This expectation needs to be met with an increasing workforce handling production technology, but also in all parts of the battery value-chain: materials, recycling, applications, and others. From a sustainability perspective, this includes understanding how processes at all levels can be made to decrease CO_2 emissions. For some of the actors, it means also knowledge about the legislation or how toxic batteries or production of batteries can be, if not handled correctly.

Europe has a competent class of engineers working in the transportation sector. Most of these are trained for combustion engine drive-lines. Re- and up-skilling this group will be vital to achieve the best benefits of the new battery systems for different applications. Sustainability is related to the life expectancies of batteries, and proper knowledge of how to improve drive-lines built of batteries is a necessary new skill but also how to select the most sustainable product to fit to the application purpose.

To increase the speed for the transition to meet the green deal means also to influence the attitude of prosumers to accept the new technologies. It is then important that the information provided for the general public is based on facts and honesty, reflecting the influence of the technology on the surrounding nature.

In summary, education for sustainability in this sector means development of new curricula for:

- Engineers that are reskilled to handle electrical drive-lines;

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[16] Global supply and demand of Li-ion batteries and the European share in manufacturing. Source: JRC April 2019.

- Materials and battery cell producers understanding the sustainability requirements for batteries to be able to develop better and cheaper methods;
- Legal representatives who understand the basics of batteries and sustainability;
- Environmentalists understanding when a battery is toxic or not and put the battery qualities in the right perspective;
- Economists to build new business models also including the role of sustainability into their perspectives;
- The general public to learn enough to take motivated decision as consumers of the different applications.

A general knowledge and appreciation of life cycle assessment will be important for all above mentioned groups.

4 ENVIRONMENTAL SUSTAINABILITY

4.1 Life cycle assessment and carbon footprint

Life Cycle Assessment (LCA) is a methodology used to evaluate environmental impacts of products and systems. It is standardised by ISO 14040:2006/ 14044:2006 and has widely been applied to batteries, and the EC has developed PEFCR on rechargeable batteries. The environmental impacts of battery manufacturing are driven by energy production when focusing on greenhouse gas (GHG) emissions and carbon footprint[17]. However, other impacts such as toxicity, air pollution, water footprint and resource depletion[18] show that raw material extraction and processing are key stages. There is a need for development of models and data required to assess these additional impact categories.[19]

The sustainability criterion obtained from Life Cycle Assessment (LCA) can be used to compare the environmental performance of different battery products, and to select between alternative process development routes for manufacture of battery components and technologies for recycling of raw materials at end-of-life. Many existing LCAs are based on only a few original primary datasets (like energy and raw material consumption), which increase the uncertainties of the environmental impact results significantly[20]. Thus, there is a need for more and better primary data to support more robust LCA modelling studies. Especially for the whole production process (on industrial scale), the key raw materials used to prepare the battery precursor chemicals for the active cathode materials (for example, metal sulphates, and others) and anode materials (for example, graphite) and the different recycling processes. These primary data are often represented using proxies and outdated or incomplete datasets. For the pre-chain of raw materials, there is also a need for regionalised LCA data for mining, such as water footprint and harmonised energy source declarations from exploration to products. Regarding the use phase in different application fields, all relevant performance indicators (e.g. including internal resistance, cycle lifetime) needs to be taken into consideration, to allow a comprehensive and fair comparison. More reliable LCA data, and disaggregated data on the production and recycling processes, could support more comprehensive evaluations of the primary and secondary materials. This implies also for the recycling process and battery type (for example, NMC111, LFP) the need for specific approaches in the future.[21]

Beyond advancement in the data and models for pure LCA studies, the PEF Category Rules should be extended from the battery product level to also consider primary data for the active electrode materials, and battery components (for example, cathode and others) as well as secondary data from recycling of battery components at the end-of-life.

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[17] - Philippot M, Alvarez G, Ayerbe E, Van Mierlo J, Messagie M. Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs. *Batteries*. 2019; 5(1):23. https://doi.org/10.3390/batteries5010023
  - Marmiroli, B.; Messagie, M.; Dotelli, G.; Van Mierlo, J. Electricity generation in lca of electric vehicles: A review. Appl. Sci. 2018, 8, 1384.

[18] Peters, J.; Buchholz, D.; Passerini, S.; Weil, M. Life cycle assessment of sodium-ion batteries. 2016. Energy and Environmental Science, 9 (5), 1744–1751. doi:10.1039/C6EE00640J

[19] Batteries Europe ETIP WG2. (2020). Raw Materials and Recycling. https://ec.europa.eu/energy/content/batteries-europe-raw-materials-and-recycling-roadmap_en
Roadmap. https://ec.europa.eu/energy/content/batteries-europe-raw-materials-and-recycling-roadmap_en

[20] Peters, Jens F., Baumann, Manuel, Zimmermann, Benedikt, Braun, Jessica and Weil, Marcel, (2017), The environmental impact of Li-Ion batteries and the role of key parameters – A review, *Renewable and Sustainable Energy Reviews*, **67**, issue C, p. 491-506.

[21] Mohr, Marit & Peters, Jens & Baumann, Manuel & Weil, Marcel. (2020). Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. Journal of Industrial Ecology. 10.1111/jiec.13021.

4.2 Use of hazardous materials

Looking at the current batteries, the uses of toxic, explosive and hazardous materials in manufacturing are being managed and well documented, and a series of countermeasures are taken for these materials or systems addressed by risk management measures, while the potential harm caused by the end-product on the environment is typically addressed by risk avoidance measures. At present, toxic and hazardous materials can be found in LIBs, especially in active components like cathode and electrolyte. For the manufacturing of these batteries in the future, efforts need to focus on the: (1) safe management of hazardous materials; (2) substitution of hazardous materials with safer alternatives if feasible; and (3) reduction of hazardous materials where possible. In such cases, the attention points should be to ensure that technical performances of batteries remain high, while the processes are upgraded to more environmentally friendly and still cost-efficient processes. A clear quantification of the gain should be provided.

Most hazardous substances are today regulated in the EU REACH regulation. The regulatory aspects of hazardous substances are many. It is worth noting that the battery industry is currently growing, leading to increased use of regulated substances. Safe management of these materials is key. One critical global sustainability issue is the fact that restricted use in the EU might increase production of the material/substances in other parts of the world, where regulation is less comprehensive. Substitution of hazardous substances is therefore a priority to increase sustainability along the entire value chain.

The next generation batteries might bring new risks for the environment and the workers linked to the use of those potentially toxic, explosive or hazardous new materials. Those risks and impacts on environment (during both the elaboration of the materials or battery or potential harm caused by the end-product on the environment) still need to be mapped, assessed and compared (for each new technology using standard protocols to be defined), while countermeasures are to be developed. Bringing such environmental aspects up at the early stage, during the design and production engineering processes, is crucial to ensure that future battery technologies are sustainable and economically viable compared to the current commercial batteries.

4.3 Resource use across the value chain

Production of batteries and battery applications requires large amounts of resources. Critical inputs across the value chain are raw materials, chemicals, water, electricity and potentially other fuels. The environmental impact of batteries must consider the resource use across the value chain from raw materials and refining through the production process to the use phase and finally the end-of-life.

R&D&I activities can contribute to resource efficient batteries by promoting and developing new products and processes with resource efficiency KPIs. The resource use can also be estimated by using a thorough LCA analysis. Possible activities are sustainable processing of elements for active battery components, production of materials and electrode components stable in water-based processes, treatment of waste water, circular material and resource flows in manufacturing processes and replacing and development of new solvents.

The battery value chain consumes energy in mining, refining, production, use and recycling of batteries. As the energy need is especially large in the production process of batteries, R&D&I activities should support, promote and stimulate the use of renewable electricity for production, reducing the need for natural gas and fossil fuels in the production process as well as the other steps of the value chain. Sourcing of electricity, to validate emissions related from energy consumptions, will be a critical tool to assess the environment impacts from resource use.

In the same time, battery application often stimulates a more efficient resource and energy use, compared to the alternative technologies they replace. R&D&I activities increase the use of batteries and promote electrification in more sectors, and will hence be important tools to increase resource efficiency by, for example, electrifying machinery, powered tools and transport applications.

4.4 Environmental aspects of recycling

Recycling is a relatively labour-intensive activity, as workers are still needed for separating materials from each other before they can be mechanically or chemically treated. A traceability system, including the information of material chemistries and battery life, would help in extending the battery first life to second life and, in the recycling stage, feeding information to the recycler on what kind of processes should be used to maximise the recovery and value of the material. It would also give information on the unrecovered materials and help in finding new innovative solutions for using or recovering those materials.

The early design phase of batteries determines the future recycling options and possibilities. Therefore, the potential recycling should be considered on material, cell and battery level as early as possible. Methods like “Design for Recycling” can be adjusted and applied. A major challenge of the future recycling will be the potential very low material value in battery cells. Thus, present recycling technologies are not sufficient, because they require too much energy or chemicals. Here, physical recycling technologies could be an option to allow potentially a (rather simple) direct recycling of active materials. In any case, the future recycling options depend on the design decisions in low TRLs. Therefore, it is necessary that Post-LIB developers interact with recycling experts as early as possible to ensure a low effort recycling technology in the future, which is important to be competitive with other technologies like H_2, power2X, or flow batteries.

Overall, battery recycling could potentially reduce energy consumption and GHG emissions, and result in considerable natural resource saving. Preformed studies show, however, that the benefits of battery recycling are not unequivocal, and the environmental benefits is an area in great need of further analysis. At present, it seems that Li-Ion battery recycling has some disadvantages regarding environmental impacts against the recycling of, for example, redox flow batteries[22]. Some studies show that the largest contributors to the environmental impacts are electricity generation, incineration of plastics and landfilling of residue. In terms of environmental effects, it is suggested that the most beneficial processes are those that utilise low temperatures and are capable of recovering plastic. Comparative and ex-ante life cycle assessments need to be performed for the different recycling processes in order to accurately define the associated environmental impacts and act in consequence.

However, it is yet to be determined which recycling processes have the least impact on the environment. There is thus a need to investigate the different processes currently used for recycling batteries (such as hydrometallurgy, pyrometallurgy, combinations and direct recycling). The physical

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[22] Peters, J. F.; Weil, M.; Baumann, M. The Importance of Recyclability for the Environmental Performance of Battery Systems. 2019. Cascade Use in Technologies 2018: Ed.: A. Pehlken, 104–110, Springer, Berlin. doi:10.1007/978-3-662-57886-5_13

recycling processes and a direct recycling of battery materials and cathode components also show future potential[23].

Research should be conducted to ensure that all recycled substances extracted from batteries are refined to the level that allows them to access the widest stream possible, or to the level that causes the lowest sustainability impact.

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[23] Mohr, Marit & Peters, Jens & Baumann, Manuel & Weil, Marcel. (2020). Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. Journal of Industrial Ecology. 10.1111/jiec.13021.

5 CONCLUSION

Sustainability requirements are a cross-cutting topic that impacts all the different steps of the battery value-chain, and which has to be considered through the social, economic and, of course, environmental perspective. In order for the battery value chain to fulfil the sustainability requirements needed to set up a strong battery industry in Europe, specific challenges still need to be overcome. R&I is still needed to achieve a future battery system which has a significantly better performance and better environmental footprint than today.

Moreover, competitiveness and sustainability, two aspects that can be hard to articulate, need to be thought of in relation with each other, especially in EU regulations and dissemination action that can address this potential conflict. Dissemination actions towards end-customer via the introduction of a new 'sustainability label' going much further in scope than the current 'eco-label' might help overwin the dilemma sustainability versus competitiveness. Sustainability appears as a key factor that industry must take into account in order to ensure the green energy transition, and which needs to be integrated from an early stage in order for the industry to succeed.

6 APPENDIX

6.1 Table 1 Cross cutting table

	Economic	Social	Environmental
Raw materials	- Geophysical and Geopolitical considerations for supply -Lack of raw materials	-Workers' rights and social aspects in the value chain -Jobs, reskilling and training	-Use of hazardous materials -Resource use across the value chain - GHG (CO_2, NOx, SOx, and others) equivalent released during mining, refining, preparation of precursors and active materials)
Cell design materials	-Geopolitical considerations -Lack of raw materials -Improve technical performance and costs decrease	-Workers' rights and social aspects in the value chain -Jobs, reskilling and training	-Use of hazardous materials (solvents, electrolytes, and others) -Resource use across the value chain
Manufacturing	-Import and sustainability of the production outside EU -Geopolitical considerations -Improve technical performance and costs decrease	-Workers' rights and social aspects in the value chain -Jobs, reskilling and training	-Resource use: chemicals, energy, water and resources in manufacturing - Type of infrastructures needed (solvent recovery and/or recycling; dry/clean room category, machinery energy consumption...)
Applications	-New business models enhancing sustainability and competitiveness	-Workers' rights and social aspects in the value chain -Jobs, reskilling and training	-Resource use across the value chain -Energy transition and electrification
Recycling	-Recycling aspects; economic feasibility, economic degradation and business models	-Workers' rights and social aspects in the value chain -Jobs, reskilling and training	-Resource use across the value chain -Environmental benefits/negative impacts Recycling
Other	-Regulatory aspects related to R&D projects	-Social LCA	-Life cycle assessment and carbon footprint (more generally GHG equivalent footprint)

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