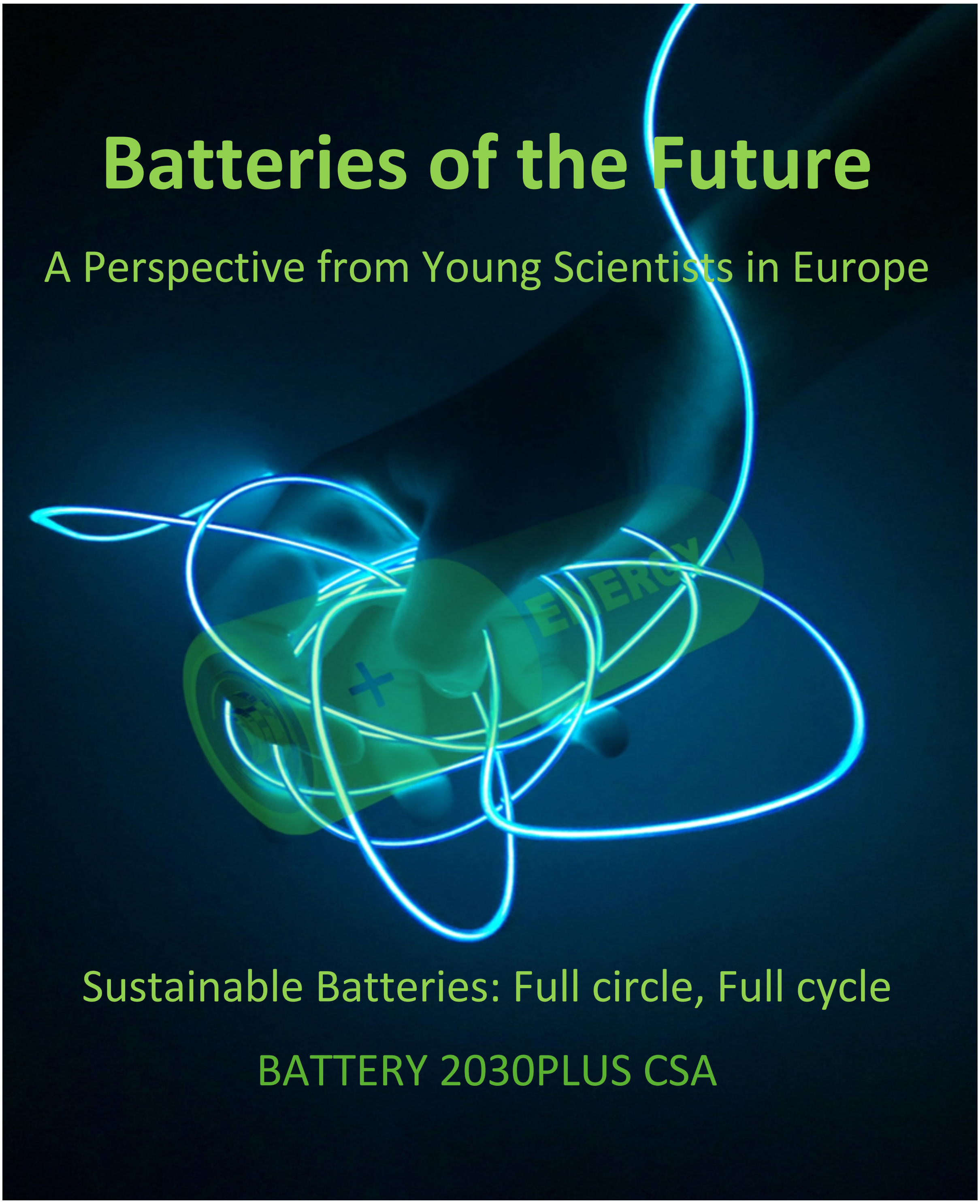
Batteries of the Future

A Perspective from Young Scientists in Europe



Sustainable Batteries: Full circle, Full cycle

BATTERY 2030PLUS CSA

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PREMISE

BATTERY 2030+ is a Coordinated Supporting Action, connecting major research centers and universities in Europe. Its ambitious vision is to **reimagine the way we design batteries of the future**, by fostering an innovative and collaborative community among researchers and industry leaders. One of the work packages is specifically dedicated to education, new curricula, and engagement of young scientists.

In this framework, the first edition of the Young Scientist Event held on the 1st June 2022 was aimed at engaging young scientists (no more than 7 years after obtaining the Ph.D. degree) and challenging them to express their ideas about the future battery research landscape, by providing the BATTERY 2030+ roadmap and curricula as inputs for fruitful discussions. The scientists were selected in order to gather a wide range of experience and competencies, i.e. battery experts, engineers, chemists, physicists, economists, doctors in medicine, people with all humanistic specializations, etc. Gender equality has been well taken into consideration.

The event was held simultaneously at four universities in Europe, defined by their geographic positions (POLITO Politecnico di Torino, UU Uppsala University, VUB Vrije Universiteit Brussel, WUT Warsaw University of Technology). All universities were connected via a live web connection to allow an open discussion.

Young scientists of different expertise were grouped to discuss the outlook of European battery research and expectations, and were stimulated by short presentations given by experts in different fields. The list of speeches and topics were as follows:

Silvia Bodoardo POLITO	Welcome
Johan Blondelle and Aymard De Touzalin EC	European Commission
Kristina Edström UU	Battery2030
Robert Dominko NIC	Batteries of the Future
Guido Saracco POLITO	Societal impacts of electrification
Anna Monticelli Intesa San Paolo Innovation Center	Financial drivers for the electric transition
Philippe Desprez ACC	Battery production in Europe
Sandra König BASF	Materials for E-Mobility - Tackling Sustainability Challenges
Robert Eriksson Volvo	Our Journey Towards Full Electrification

One of the goals for the event was to produce a “Manifesto for batteries of the future” by the new generation of scientists in Europe. Each table was coordinated by a table leader, who also took care of the main draft of this manifesto, which will be presented in Rome at the NanoInnovation conference in September 2022.

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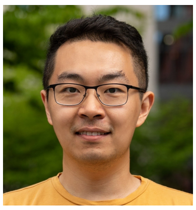
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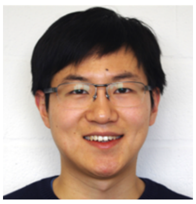
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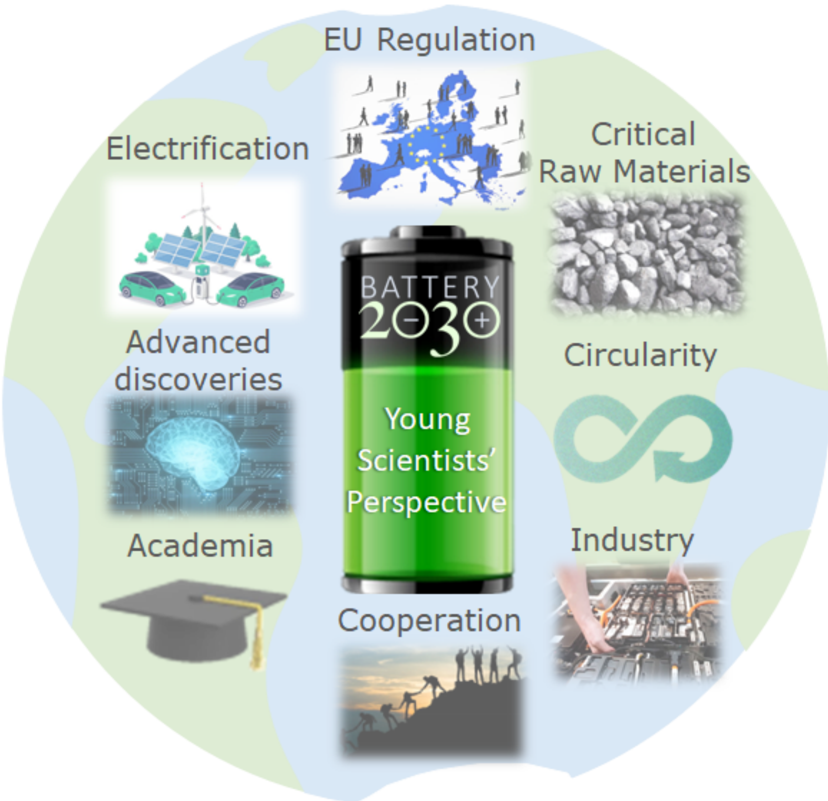
Note: all authors of the Manifesto would like to express their utmost gratitude to local organizing teams, individually led by Prof. Silvia Bodoardo (POLITO), Prof. Daniel Brandell (UU), Dr. Pavlo Ivanchenko (VUB), and Prof. Marcinek Marek (WUT), for making the first edition of the Young Scientist Event possible. The Battery 2030+ coordinating team (Eva Regårdh, Kajsa Saykali, Camilla Dann), led by the project coordinator Prof. Kristina Edström (UU), is also greatly acknowledged for providing the stage for Young Scientists to shape the future of batteries.

GRAPHICAL ABSTRACT



INTRODUCTION

This Manifesto is the result of the thorough discussion of an interdisciplinary selection of European Young Battery Scientists on the future of battery research informed by a wide variety of fields: chemistry, physics, engineering, biology, philosophy, economy, and psychology). Consisting of four key sections (chemistry and critical raw materials, circularity, industry, and society), this Manifesto has been contextualized within the necessity of holistic approaches to accelerate the electrification of transportation and to achieve a geo/socio-politically independent European-based battery supply chain (from metal mining to battery cell production and recycling), eventually meeting the goals set by the Paris agreement on the reduction of CO_2 emission. Through the concerted efforts from the whole society and all the key players across industry, R&D, and higher education, we believe a shift towards the development of a sustainable battery industry is possible.

CHEMISTRY AND CRITICAL RAW MATERIALS

To accelerate the necessary technological breakthroughs, immense multi-disciplinary, cross-sector research efforts and investments are needed. However, most raw materials for current rechargeable batteries are either listed as critical (CRM) or are located in geopolitically compromised areas outside Europe. For example, most of the EU supply for lithium, graphite, and cobalt comes from Chile, China, and Democratic Republic of Congo, respectively. Based on the extensive discussion during the Young Scientist Event, two strategies are envisioned to tackle this drawback (see **Figure 1**). First, efficient recycling strategies should be developed urgently to recover and reuse most battery materials and components, in particular the critical ones. To reach this objective, future design of batteries must consider easier handling and dismantling to allow simple recycling methods. Moreover, as there are currently very few recycling sites in Europe, the most expensive part of recycling regards the transport of batteries to these sites, and therefore many new sites should be created. The second strategy concerns materials research with the aim of discovering cheaper and more widely available materials with similar (or better) electrochemical properties. In order to reduce the dependency on CRM, new battery chemistry alternatives that eliminate cobalt and use more abundant metals (such as sodium, magnesium, etc.) should be developed, which are economically and ecologically justified. Application-oriented battery design, matching individual cell chemistries with specific end-uses, will broaden the range of materials used and thereby reduce the dependency on individual elements.

Similarly, the R&D&I (research, development, and innovation) sector should prioritize sustainability in all processes. For example, development of materials suitable for water-based processing is crucial in the aim of eliminating most toxic organic solvents; meanwhile, water can be easily recovered, purified and reused, thus implementing a closed loop and limiting waste production. Before envisioning battery recycling, another important point regards extending the battery's lifespan. To this end, investigation of self-healing materials to be used in electrodes (as binders) or electrolytes, and sensors monitoring the state of health of battery cells, is of prime importance.

The development of new technologies based on cheaper, locally available, and more abundant raw materials like sodium, magnesium, and aluminum is highly encouraged. However, the technology readiness level (TRL) of these technologies is low and new chemistries are still in the lab development phase. In this regard, it is important to bridge the gap between the lab-level and production *en masse*. Therefore, new materials and chemistries need to be developed, involving scalable processes that can be applied to a large-scale production. Additionally, the new materials' properties should be tested using realistic cell formats and conditions that are similar to those used for practical applications.

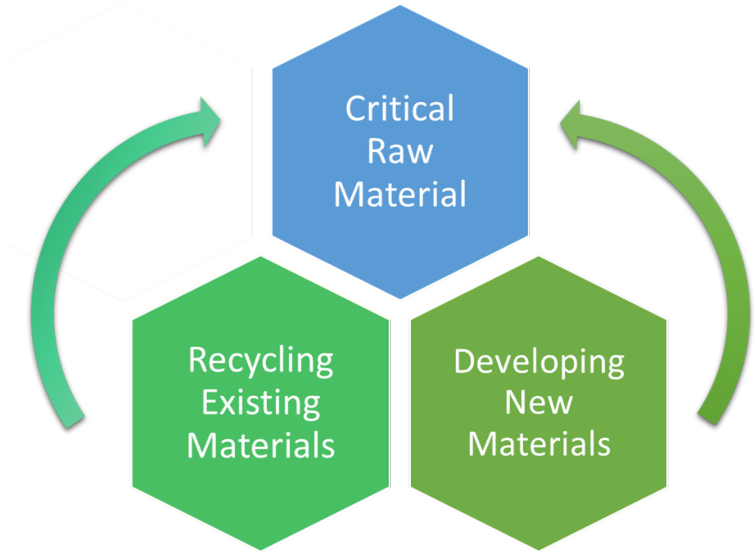


Figure 1. Strategies to reduce dependency on CRMs.

CIRCULARITY

The extraction of non-renewable natural resources has a negative impact on our environment. A sustainable design of the battery, reliable and responsible sourcing of raw materials, and the whole battery production process must consider the environmental and social impact: from the extraction of raw materials and waste treatment, to the battery's disposal and recycling. For battery manufacturers, the short-term profit is insufficient to justify early investment in battery recycling facilities, thus, incentives and legislation are necessary to prevent the large and inevitable accumulation of spent batteries 5–10 years from now.

The introduction of regulations and/or incentives would force manufacturers to either use recycled materials or to facilitate the recycling process (for example, the usage of Radio Frequency Identification (RFID) could help to segregate batteries using artificial intelligence). Also, as we move to reduce our dependence on critical raw materials, we must take into account potential negative externalities associated with new ways of extraction, as well as socio/geo-political aspects.

One significant initiative is the introduction of the "Worldwide battery passport" and standardizations – a set of rules that regulate design identification and second-life applications (in a block chain perspective), ensuring the full cycle life is used before recycling, not only for the EU, but all countries in the world. The EU has presented the *New EU regulatory framework for batteries: Setting* *sustainability requirements*, which provides detailed directions for the manufacturers. However, there is also a need to establish legislation and regulations for the recycling of batteries, setting minimum standards on life cycle, and second use of batteries for other countries too. For example, legislation, policies, and incentives could encourage industries to use a declared recycled quantity of their own materials or to have a declared recycled percentage (even if recycled by other enterprises). A good option could be the introduction of an European Digital Battery Passport: to track the entire value chain of the battery and to allow its evaluation for a second-life use. Transparency in the battery passport is also important. The regulations should be introduced to enforce companies to share information and make it equal in Europe (and eventually worldwide). When it comes to standardization and regulations of testing the battery cells at all levels – it should be introduced to standardize the performance of the batteries and at the end to meet the customers' requirements.

Once the battery has been declared unsuitable for use in its primary application, regulations are needed to promote and encourage battery repurposing (battery second use, or B2U). For instance, batteries which are no longer used in the automotive sector could serve as spinning reserve, peak shaving, renewable energy shift, residential demand management, and storage in decentralized microgrids. Thus, extracting additional services and revenues from the battery in a post-vehicle application can increase the total lifetime of the battery. Meanwhile, the cost of the battery is shared between primary as well as secondary users. The "Battery Passport" would allow us to have access to any battery's state of health, residual useful life, and governing mechanisms, in order to identify the most appropriate B2U opportunities (see **Figure 2**). In addition to the Battery Passport, a minimum set of instructions must be disclosed by the battery manufacturer in terms of handling/disassembly procedures, battery management system (BMS) algorithms, life cycle assessment (LCA) data, and any other information that facilitates repurposing. Without this operative set of instructions, it is hard for companies involved in B2U to minimize reverse engineering practices to figure out the most optimal way to deal with "black-box" or "gray-box" battery systems.

When batteries have reached their end of life and no additional value can be extracted from them, recycling must be prioritized over disposal, as zero waste is the ultimate goal, especially when disposing of hazardous materials. The main limitations for Li-ion battery recycling are their component complexity and the various chemistries and shapes used by different companies, and the high labor intensity of the disassembly process. Therefore, the batteries' end of life should be an equally important consideration when designing the battery (design for recycling), not only focusing on performance and cost. Suggested strategies for the design as well as recycling phases are the following: i) use the minimum number of components to facilitate their separation, ii) avoid toxic and corrosive materials that are hazardous and may damage the reactors, iii) include labels to track the battery cell, chemistry, and identify proper routing, iv) standardize the materials and the cell/pack/module format to ease disassembly, v) automate battery disassembly line to speed up battery recycling process, vi) develop less energy-demanding methods for recovering critical elements and vii) optimize recycling processes to recover all materials and reduce the environmental footprint.

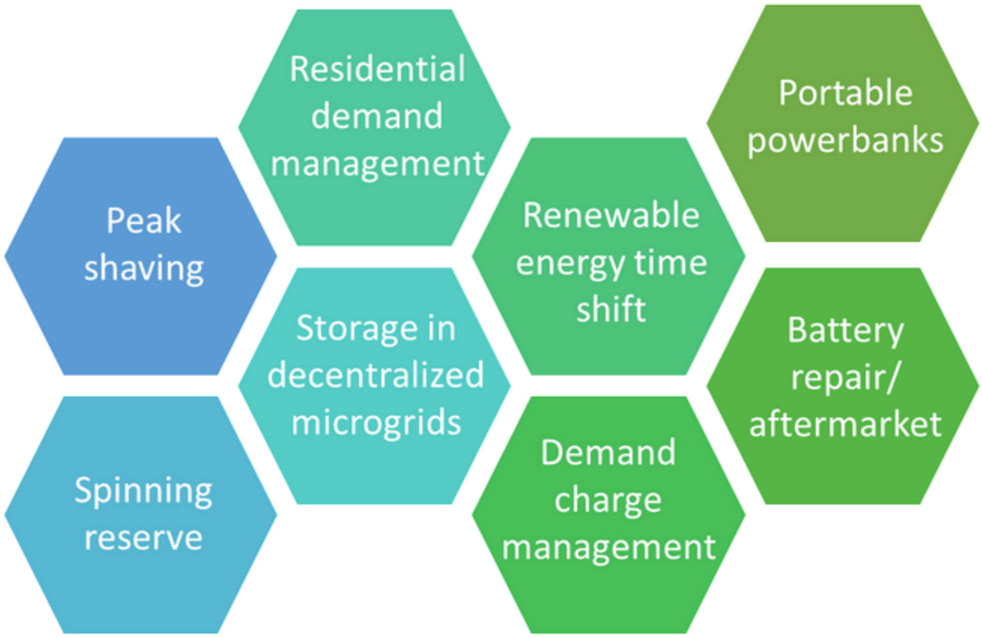


Figure 2. Second-use applications for batteries.

INDUSTRY

The sustainability and circularity of batteries will also be improved by the simplification of production methods in the battery industry, supported by digital management and monitoring technology, focusing on being less dependent on costly and environmentally damaging CRMs or moving to solvent-free electrode fabrication processes, among others. These would simultaneously lower the cost of production and the environmental impact of battery manufacturing. Making use of digital tools and artificial intelligence powered by the data generated across different scales, and using a wide range of complementary approaches, including numerical simulation, material synthesis and characterization, *operando* experiments, and device-level testing, would contribute to new material and battery cell development and allow the optimization of manufacturing processes, consequently reducing overall costs in terms of material, energy, and human resources. Together with price reduction, safety is one of the other major concerns faced by the battery field. State-of-health (SoH) monitoring and testing should be improved for better and more specific data, integrating innovative battery management systems (BMS) that collect information from different battery designs with sensing technology for first and second life applications. The integration of smaller yet more powerful sensors inside batteries would enable the anticipation of any minimum failure and allow the replacement of a single damaged cell when a defect is detected. This information would be crucial when deciding on the possibility of second use, replacement, refurbishment, or recycling of batteries.

The measures outlined above should be integrated in the current and coming Battery Gigafactories. In the last few years, the installation of many more Gigafactories in Europe has been announced. While there is an open competition for battery manufacturers to produce the best battery packs first for electric vehicles, a clear pathway must be defined for a European battery manufacturing strategy based on sustainability, resilience, and circularity through the principles of Industry 5.0. European-wide measures should also be implemented to regulate and support the manufacturing market, as well as regional/local initiatives to ensure a smooth and positive impact of the manufacturing activities in the local and national communities. To achieve this, the political powers must implement action plans and initiatives to pay forward for social and environmental impacts from the activities, as long as the industry will ensure the production of long-lasting and circular battery systems. The disagreement between prolonging the battery life (through self-healing or longer-lasting materials, amongst others) versus pushing for recycling is a political issue, where the viable path might differ with the evolution of market conditions, material availability, and new chemistries, and thus needs to be answered by the European leadership through the development of a roadmap focusing on the environmental impact, energy efficiency, human rights, and circular ecosystem of batteries without compromising future generations.

Another important bottleneck that the battery field is facing arises from the lack of clear communication between academia and industry. The competition towards developing the best battery for the future has led entrepreneurs to underestimate good communication and cooperation needed to bridge the gap between fundamental scientific research and industry demand, which is of crucial importance to achieve high-impact battery development. There is no doubt that industry needs the fundamental insights arising from academic research, while academia would greatly benefit from industrial feedback to guide future research directions. Transparency, better reporting, and open science are also of high importance. Following an overarching aim for zero waste, we must also strive for zero waste in science, following a new practice based on sharing of all results, and not only the ones that are most promising. Sharing information of 'failed' experiments could result in significant cost savings and help to focus on creating new and innovative technologies.

Moreover, special focus should be placed on education. The battery industry will be one of the leading areas of the EU Industry 5.0 initiative. Consequently, it carries responsibilities to reshape our education systems in order to adapt new industrial approaches. The battery industry must have a major presence across different subject areas at higher education level if multidisciplinary teams are to be built, while battery manufacturers should establish schemes for bachelor, master, and PhD students to provide experience of battery research and production, in which mentoring and outreach activities are expected to support young careers.

Figure 3. Needs of the battery industry to build the batteries of the future.

SOCIETY

The battery market has been growing rapidly in the past few years and with the growing demand for different battery technologies, it will continue increasing further. As mentioned above, the ability of education to keep up with technological development is crucial to enable universities, research units, and public institutions to nurture a new generation of young scientists that will accelerate the transition toward a zero-carbon society. The launch of a Europe-wide study program, tailored to the challenges facing the battery field, will be necessary, as well as introduction of new specializations at universities focusing specifically on battery development (electrode materials, electrolytes, post-lithium chemistries, electrochemical testings, analysis principles, etc.). Comprehensive outreach approaches to educate the public on electrification and the value of batteries will be invaluable. For example, the public should be aware of the necessity of battery recycling and disposal, and the impact of not doing it (toxicity of electrolytes, loss of valuable materials). More broadly, additional training for existing professions will also be necessary as our society adapts to the energy transition (for example, firefighters on how to deal with a battery incident, doctors on how to cope with the eventual skin problems after contacting a destroyed/damaged battery).

According to the Fortune Business Inside: *"The global lithium-ion battery market size was USD 36.90 billion in 2020. The market is projected to grow from USD 44.49 billion in 2021 to USD 193.13 billion by 2028, exhibiting a CAGR (compound annual growth rate) of 23.3% during the forecast period from 2021-2028".* This growth will drive innovations in battery production. For example, each battery could be adapted to the specific requirements of a particular application, such as energy density, safety, recyclability, etc., which will help the customer to make an informed decision when selecting a suitable battery. This development could also help to avoid the overproduction of a certain type of battery, thus reducing financial losses and the number of excess batteries to dispose of. The design of the battery specifically for recyclability, modularity, long lifetime, and fast charging can be an pivotal step forward in large-scale production.

Another aspect is the popularization of electrification. According to Hannah Ritchie and Max Roser: *in 1990, around 71% of the world's population had access [to electricity]; this has increased to 87% in 2016*. To reach full electrification, a total change in mindset of our society must be achieved. Public campaigns could be well perceived and could show the necessity of introducing more personal measures within the next few years. Common perceptions and misconceptions related to electric cars could be addressed, for example, around fast charging and autonomy which can be adapted to the use, the material demands of different car sizes, and the global CO_2 emissions from manufacturing to charging electricity source. The cost of electrification must also be reduced, not only to promote individual technologies, but also to make them affordable for everybody including SMEs and rural areas. Unfortunately, current prices are still too high for the average citizen.

Safety concerns are widely discussed and are strongly related to the chemicals used for battery production, the electrolyte and Li dendrites formation. Safety must be considered equally alongside cycling performance, in particular, the aspects of flammability and possible explosions are paramount. New regulations could be implemented on battery checks (*e.g.,* thermal imaging of a car battery every few years to check if the condition of the components is still safe for use). A regulatory framework on the obligatory battery replacement in electric cars should guarantee their circularity requirements, with an eventual shift towards car manufacturers replacing the battery (for a reasonable amount of money) for a recycled or refurbished one.

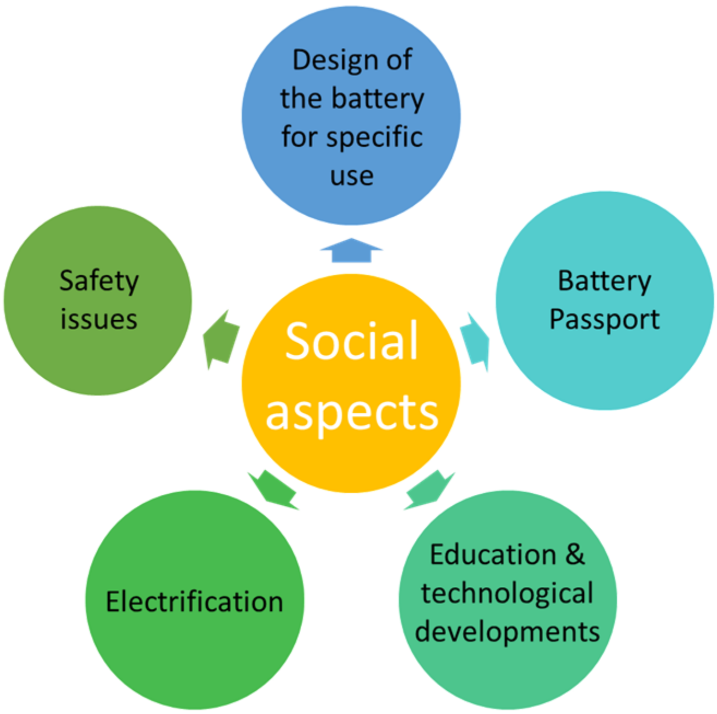


Figure 4. Social aspects around battery field.

CONCLUSIONS

The Young Scientist Event celebrated on the 1st June 2022 in four universities simultaneously (Politecnico di Torino, Uppsala University, Vrije Universiteit Brussels, Warsaw University of Technology) brought into focus our shared concerns about the key drawback and challenges ahead on the battery development journey. The importance of the battery design, from avoiding critical raw materials and utilizing those that are more abundant, to circularity, has shown itself to be one of the most pressing aspects. This has highlighted the need for making more sustainable batteries, and penetrating them in the renewable energy market with the lowest carbon footprint as possible. In order to build a more realistic scenario, the EU should strongly push towards sustainable technologies by implementing more specific regulations, not only for academia, but also for industry. More effective transfer of sustainability progress made at universities and research centers to battery manufacturing Gigafactories would begin with better communication and information exchange between industry needs and academic research. From the Young Scientist battery community, we would like to encourage greater cooperation among universities, research centers, and industry, gathering different research units, building a bridge between academia, industry, and customers (intersectionality) based on trust and responsibility, as together we can create bigger, better, and more useful technology than we could achieve separately. Moreover, in the last and most innovative steps defined towards the batteries of the future, the necessity of researchers from different fields has been identified, in order to cover the knowledge along the whole battery value chain. Creating multidisciplinary teams for the battery production, R&D&I, and recycling industries can make use of already existing scientific and other human resources and provide new innovative perspectives. The Young Scientist Event provided the next generation of battery scientists the opportunity to be proactive and demonstrated how they can be a credible and interesting interlocutor for the European community and for planning the future in the field of batteries. Furthermore, it is of crucial importance to boost Science, Technology, Engineering, Mathematics (STEM) careers in our young society to attract them towards our battery development field. Seminars, workshops or science outreach activities would help to encourage young researchers to enter the field of energy storage. We should not forget that the efforts made today will be the breakthroughs of the future.

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