European Commission

JRC CONFERENCE AND WORKSHOP REPORT

IMPROVING THE RESILIENCE OF THE COMPLETE CLEAN ENERGY SUPPLY CHAINS

Jointly organized by the European Commission's Joint Research Centre and the IEA's Experts Group on Research and Development

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Joint Research Centre

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Abstract

On 12 and 13 December 2023, JRC-Petten hosted the workshop 'Improving the resilience of the complete clean energy supply chains – from raw materials to advanced materials, manufacturing and end-of-life', organised jointly by the European Commission's Joint Research Centre and the IEA's Experts Group on Research and Development. The workshop consisted of 13 invited presentations by experts and four discussion sessions, and attracted more than 60 in-person and online participants from all over the world.

The aim of the workshop was to provide a better understanding of the state-of-the-art solutions available for managing and increasing the resilience of clean energy materials supply chains and to define R&I needs for addressing the related policy challenges.

The main focus of discussion was the role of research and innovation in increasing the overall resilience of these critical supply chains; for example modelling and analysing the supply chains, providing innovative solutions to improve sustainability and circularity, and discovering new advanced materials and components which could reduce our dependence on critical raw materials.

Executive summary

On 12 and 13 December 2023, JRC-Petten hosted the workshop, 'Improving the resilience of the complete clean energy supply chains – from raw materials to advanced materials, manufacturing and end-of-life', organised jointly by the European Commission's Joint Research Centre and the International Energy Agency's Experts Group on Research and Development.

The workshop centred on the role of cutting-edge technologies and targeted policy initiatives to promote resilient supply chains. A clear indication from the discussion is that policy initiatives must target the whole supply chains (from mining, refining and processing materials to manufacturing components; from assembling the final products to their end of life and recycling). Some participants clearly voiced their preference for a "bottom-up" approach in developing policies, although clear guidelines from policymakers are also seen as fundamental to define the work of scientific organisations in support of policy.

The role of foresight initiatives was deemed essential to make sure that no new criticalities are introduced in the process of addressing existing ones, and that the technologies we will rely on are future-proof. In particular, anticipating the implications of potential policy choices is seen as crucial, even when the magnitude of potential problems is difficult to estimate.

Finally, it was agreed that international cooperation must be fostered and accelerated at all levels. The importance was emphasized of building strategic capacities through projects in the EU internationally. Both national action and international cooperation are needed to address materials challenges, in terms of access to funding and collaboration in research. In particular, data handling and data sharing were highlighted as two of the most important positive aspects to mobilise a greater exchange of ideas and knowledge, for example on new approaches to advanced material characterisation.

1 Introduction

The energy transition, which is taking place globally in order to achieve the Paris 1.5 degrees target, is bringing a paradigm shift to our energy system: the main focus is moving from fuel to clean energy technologies, to the manufacturing of components, and to materials. That's why it is said that the energy transition is a materials transition.

Clean energy materials, such as lithium, graphite, manganese, nickel and cobalt for our batteries, and rare earth metals for our wind turbine generators and electric vehicle motors, are scarce and sometimes heavily concentrated in one or two countries and regions. This creates dependencies and increases the risk of supply chain disruptions, putting the progress of the whole energy transition at risk. Against this backdrop, governments have come up with measures such as the Critical Raw Materials Act in the EU and the Inflation Reduction Act in the US, as well as critical materials strategies such as those of the EU, US, Australia and Japan.

Both the International Energy Agency (IEA) and the European Commission's Joint Research Centre (EC-JRC) have analysed the materials demand and supply chain bottlenecks of clean energy technology value chains. They have produced landmark reports underpinning debate with robust scientific evidence and supported the needs of policymakers and decision-makers internationally.

In addition to policy, administrative and regulatory measures, it has also become clear that research and innovation (R&I) can and should play a central role in strengthening the resilience of clean energy supply chains. The International Energy Agency's Experts Group on Research and Development (IEA-EGRD) therefore joined forces with the European Commission's Joint Research Centre (EC-JRC) to organise a workshop, in December 2023, examining the role of R&I in clean energy materials and their supply chains.

The workshop offered solutions for improving the resilience of complete supply chains – from raw, refined and processed materials to the manufacturing of components, assemblies and systems, reaching the end-of-life stage and, ultimately, recycling.

The workshop was hosted by the Directorate for Energy, Mobility and Climate of the JRC in its premises in Petten, the Netherlands. It included 13 invited presentations by renowned experts from across the globe dealing with clean energy materials and supply chains, and attracted more than 60 in-person and online participants from all over the world. The two main objectives were:

a) to provide a better understanding of the state-of-the-art solutions available for managing and increasing the resilience of clean energy materials supply chains;

b) to define the R&I needs for addressing the policy challenges related to clean energy supply chains, and assess ways towards fulfilling them.

The workshop was divided into four sessions, each tackling specific issues relevant for the policy challenges in the field, e.g. the role of research and innovation in increasing the overall resilience of critical supply chains; modelling and analysing the supply chains, providing innovative solutions to improve sustainability and circularity, and discovering new advanced materials and components which could reduce our dependence on critical raw materials. Each session was focused on the guiding questions listed below.

1) What are our future needs in clean energy materials and how can we diversify their sourcing? Can demand-side management play a key role in striking the right balance between materials demand and supply?

2) How can we secure the energy transition by increasing the resilience of supply chains and mitigating the disruption risk?

3) How can we ensure sustainability and address environmental, social and governance (ESG) challenges along the whole value chain, and how can R&I help to resolve the challenges of circularity and increase its role in materials supply?

4) What innovative and advanced materials do we need in order to substitute expensive and difficult-to-access strategic materials in clean energy technology value chains?

This report offers a short summary of the key messages of each presentation as well as the main topics discussed during the workshop. The workshop agenda and the slide decks which the speakers agreed to share can be downloaded from the event page: https://www.iea.org/events/improving-the-resilience-of-the-complete-clean-energy-supply-chains-from-raw-materials-to-advanced-materials-manufacturing-and-end-of-life

2 Key messages presented and discussed during each workshop session

2.1 Session I: Materials challenges in the clean energy transition

2.1.1 The European Critical Raw Materials Act – Madalina Ivanica (European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs)

The presentation focused on the current and planned European Commission (EC) policy activities in the context of raw materials, specifically on the Critical Raw Materials (CRM) Act. Considering the material requirements of the twin transition and aimed at ensuring a secure and sustainable supply of CRMs, the Act is structured around 3 policy objectives: better monitoring the risks of disruption; building strong circularity and sustainability; and reducing strategic dependencies.

The speaker highlighted the ambitious 2030 goals and benchmarks set out in the CRM Act, emphasizing the non-binding nature of the targets and the adjustments that proved necessary to finalise the Act (e.g. the inclusion in the EC CRM list of bauxite/aluminium, natural and synthetic graphite, battery grade nickel; and the revision of permitting times defined as 27 months for mining and 15 months for processing).

As for the implementation, the importance was underlined of carrying out strategic projects both in the EU and cross-border to build strategic capacities; the primary focus will be on the better utilisation of existing funding opportunities. The speaker also highlighted the need for an early warning system with integration of real-time monitoring and stress testing to mitigate the risk of disruption. Other important points touched on in the presentation were strategic stocks (requiring coordination efforts), joint purchasing (including the facilitation of offtake agreements), national exploration programmes (to be implemented by Member States for the proper assessment of mineral reserves), assessments of the raw materials market, sustainability and the importance of research & innovation (with a total budget of EUR 800 million to support projects in extraction, processing, refining and recycling).

On governance, the advisory role of the EC and the development of strategic partnerships were underlined. The EC will continue to encourage the conclusion of agreements (such as the recently established partnerships with Canada, Ukraine, Kazakhstan, Namibia, Chile, Argentina, DRC, Zambia and Greenland, as well as the ongoing discussions with Norway and Australia) to contribute to greater diversification of supply.

2.1.2 The Role of Research & Innovation to Strengthen Clean Energy Supply Chains – Kathryn Peretti (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy)

The presentation focused on the US policy context, priority themes and core activities in the area of CRMs. It highlighted the role of research & innovation to develop next-generation solutions for mining, processing, and manufacturing, guided by the requirements of sustainability and environmental compliance.

The speaker outlined the goals and ambitions of CRM policies, which include increasing the efficiency of processes and circularity, and decreasing environmental impacts and health impacts. These are deemed to be of fundamental importance for businesses to operate effectively in the US and remain competitive globally. The existence of longstanding programmes on supply chains and CRM materials was emphasized (USD 11 million budget for research and USD 8 billion for infrastructure); the Inflation Reduction Act further supports these commitments with tax benefits for CRM extraction, processing and recycling.

The speaker referred to the earlier work of the US Department of Energy (DoE) which established the strengths and weaknesses of 11 strategic supply chains and covered crosscutting topics such as commercialisation and competitiveness as well as cybersecurity and digital components. The recent announcement of the creation of a White House Council on Supply Chain Resilience was also noted, as well as new cross-governmental supply chain data-sharing capabilities.

The U.S. Critical Minerals & Materials Program was presented, which aims to integrate applied research, development, and demonstration (RD&D) to accelerate the development of domestic critical material supply chains. This is stimulating the development of The Critical Materials Collaborative (CMC), a new office within the DoE, which will focus on largescale programmes in addition to a general interagency coordination role, also acting as an essential interface with other parties and stakeholders.

The speaker concluded by highlighting the key policy areas and actions within the DoE strategy on critical minerals and materials (diversifying & expanding supply; developing alternatives; material & manufacturing efficiency, also in the context of the Bipartisan Infrastructure Law investments; circular economy; and enabling activities including education) and by giving a glimpse of the possible next steps: a CRM roadmap to define RD&D priorities and the Critical Materials Accelerator Funding Opportunity announcement.

2.1.3 Materials Challenges in the Clean Energy Transition – Peter Levi (International Energy Agency, Energy Technology Policy Division)

This presentation focused on the general challenges of the transition towards a low carbon energy system outlined in the IEA special report, Net Zero by 2050: A Roadmap for the Global Energy Sector [IEA 2021]. Improving energy security is a major focus for 2030, with long lead times for upstream projects raising significant concerns for the transformation of the energy system, under scenarios where, for example, power generation from renewables increases to 90%. The speaker identified five crucial pillars to keep the 1.5 degree goal alive: installed renewables, energy intensity improvements, reduced emissions from fossil fuels, reduced methane emissions, and clean energy investments.

The IEA assessment metrics have considered diverse aspects such as:

- Regional concentration (of mining and critical mineral processing, material production (e.g steel and aluminium); and technology manufacturing (batteries, wind, solar, PV, heat pumps, electrolysers)).
- Project pipeline (based on announced manufacturing capacities), noting that technologies are developing at different paces (the main additions to capacity are in solar PV, with only minor capacity additions in wind and heat pumps).
- International trade (with the analysis of the share of trade in global technology deployment showing the dominance of China in solar PV modules, wind and EV batteries).

The speaker raised some points of concern, such as the lack of robustness of the development pipeline (only a small fraction of the announced projects can be considered committed) and the cost competitiveness of hydrogen production from electrolysis (with likely variations across the globe based on electricity and production costs, where China and the US would have a competitive advantage against EU and Japan). In general, government incentives have proved necessary to achieve development goals.

To facilitate the transition to a more sustainable energy system, a wide-ranging R&D effort is required. Innovation is a key facilitator of the progress needed in the heavy industries (iron and steel, chemical, cement) which account for 70% of emissions; net-zero emission routes such as hydrogen-based technologies and CCUS could play a key role in reducing the emissions of iron and clinker production. In general, the persistence of cost competitiveness gaps indicate the need for strategic partnerships and collaboration.

2.2 Session II: Modelling and analysis of supply chains, Resilience, and Mitigation of disruption risk

2.2.1 Supply chain analysis and materials demand forecast in strategic technologies and sectors in the EU – Michalis Christou (European Commission, Joint Research Centre)

The speaker presented the main results of the Joint Research Centre's supply chain analysis of 15 technologies strategic for the twin transition and EU security, published in a foresight study [JRC 2023] which provided scientific input to the CRM Act. The study forecasts an unprecedented increase in demand for the key materials necessary to a successful twin transition.

For onshore and offshore wind turbines, demand for rare earth metals is expected to increase 4.5 times by 2030 and 5.5 times by 2050, while the batteries powering our electric vehicles are forecast to drive up demand for lithium 11 times by 2030 and 17 times by 2050. Demand for other critical materials, such as cobalt, nickel, manganese and natural graphite is projected to skyrocket in the EU and worldwide.

The analysis also reveals the EU's heavy dependence on a very limited number of suppliers for all the strategic technologies examined, in several stages of their supply chains. For some technologies, this dependence applies to the entire value chain. The raw materials step is systematically critical for all technologies, while the EU is stronger in the manufacturing of final technologies.

Meeting the EU's ambitious policy targets will drive an unprecedented increase in materials demand in the run up to 2030 and 2050, and this will also be the case globally. While CRM markets are demand driven, there is often a delay in new development projects. This raises concerns about a potential gap between demand and supply for many raw materials.

The speaker outlined a number of possible strategies to strengthen supply chains, such as diversifying material supply sources, increasing domestic manufacturing capacity, enhancing recycling and reuse for a stronger circular economy, and exploring possibilities for substitution.

2.2.2 Critical Raw Materials for Electric Vehicles – Martin Beermann (Joanneum Research)

The speaker presented the results of Task 40 of the IEA Hybrid and Electric Vehicle Technology Collaboration Programme (HEV TCP). The Task's objective was to gather an integrated view of the future supply of critical raw materials for electric vehicles, including battery technology developments, scenarios of global electric vehicle fleets, primary raw material supply, recycling technologies, and supply bottlenecks.

The global supply and demand scenarios were calculated for selected CRMs. The availability of nickel for EV batteries by 2030 could reach a maximum of 1.2 million tonnes per year. Cobalt may be less problematic, with (new nickel) Indonesian sources showing great potential, and scaled-up potential from the DRC. Nevertheless, considering all factors, a shift towards the elimination of both Ni and Co from battery chemistries would be required. Very large resources of lithium are available (and will be further extended), but short term supply shortages are possible.

Graphite shows great potential for additional mining, and synthetic graphite would be available to cover the gaps. With silicon-graphite anodes, the graphite content will be reduced (solid state battery anodes do not use graphite). As for phosphate, deficits on the global supply side are unlikely. Considering additional phosphate production driven by fertiliser production, the share of future demand for batteries might be around 10%.

Finally, due to the challenges related to establishing additional supply production of rare earths, alternative motor solutions will most likely be implemented for electric vehicles.

For battery recycling, hydrometallurgy is seen as the most likely technology in the medium term in order to reach EU recycling targets. Largescale NMC-recycling can be expected to be in place by 2030, whereas largescale LFP-recycling (less cost-efficient) can be expected to be in place later.

In terms of battery research, the development of sodium-ion technology and other technologies with reduced demand for critical raw materials should be seen as a priority, since this would lead to a reduced risk of supply deficits and geopolitical dependencies. However, sodium ion has reduced energy capacities compared to “close-to-ideal” materials, so new combinations of cathode / anode / electrolyte materials should also be developed.

Finally, the dynamics of the transition of global economics towards climate-neutral transport and production systems should be modelled within the short timeframe of 20 to 30 years. The Life Cycle Assessment method should be further developed to better assess the circularity potential of products and services.

2.2.3 Advancing Sustainable Battery Recycling: Towards a Circular Battery System – Tilmann Vahle (Systemiq)

The speaker presented the key findings of Systemiq’s recent report, 'Advancing Sustainable Battery Recycling: Towards a Circular Battery System' [Systemiq 2023], which focuses on the environmental and social impacts of recycling EV lithium-ion batteries and discusses its sustainability prospects. The study unveils the ongoing development of a whole new industry growing up around EV battery recycling, as the global stock of passenger EVs is forecast to increase exponentially and the strategic and regulatory importance of secondary materials becomes more and more evident.

The focus on recycling must necessarily be understood as part of a wider circular economy framework; other steps such as transport and collection (as well as the usage of the recycled content) need to be optimised for sustainability (e.g. by electrification of transport modalities). The speaker put all this in the context of a battery circularity hierarchy, which would also include strategies like battery reduction, reuse, and design for circularity.

Battery recycling is a technically complex feat which demands a multi-step approach; each of the five archetypal routes analysed in the report involves a series of trade-offs, not only from the operational input (energy usage, water, auxiliary material) and the operational output (resource recovery, emissions to air, waste), but also in terms of health, safety and economic feasibility.

Despite the divergence in battery recycling technologies and approaches, the speaker proposed a list of ten universal sustainability principles which could be applied. These include the prioritisation of stringent health and safety standards, the maximisation of materials and energy recovery while minimising waste streams, and need to incorporate sustainability impact assessments when selecting battery recycling technologies and processes.

The speaker concluded by recalling some open debate topics in sustainable battery recycling that need further industry alignment, such as the classification of black mass, the trade of end-of-life batteries, and the co-production of primary and secondary materials.

2.2.4 Primary and Secondary Metals and Minerals Supply Risk & Sustainability Analyses – David Pennington (European Commission, Joint Research Centre)

The speaker presented the European Commission Raw Materials Information System and its potential to provide timely information in response to EU-level knowledge needs arising, e.g. in terms of foresight of supply risks.

The global supply-demand graphs over time for several materials (eg lithium, cobalt, palladium) were shown as examples. In the case of palladium, supply is forecast to surpass demand by 2025, and this supply trend will continue increasing until 2030. In contrast, a threefold increase in demand for cobalt between 2021 and 2032 highlights the risk that supply may not be enough to cover demand towards the end of this decade.

A geopolitical risks forecast was introduced by analysing the countries which will supply the capacity of cobalt by 2025 and 2030. This shows that DRC may keep the control of around 60% of global reserves (while the already limited EU capacity decreases), but also forecasts an increase in the role of other players such as Australia.

2.3 Session III: Sustainability, ESG and Circularity - Challenges and Innovation in recycling

2.3.1 Navigating towards an **'all**-cir**cular' Plastics & Carbon Economy**: CO_2 as renewable feedstock and new industrial commodity – Reinhold Lang (Johannes Kepler University, Institute of Polymeric Materials and Testing)

This presentation focused on the circularity of CO_2 as a "renewable" feedstock, through the combustion of plastic materials and the subsequent use of the CO_2 generated. This stems from the capital importance that plastics has, and will have, in the industrial ecosystem, as well as from the need to pursue climate change mitigation. However, the speaker pointed out that a realignment of the plastics industry and market is necessary to ensure that it contributes to sustainable development and operates within planetary boundaries.

The speaker presented industrial carbon circularity as an essential factor in achieving sustainable development and our circular economy goals. He proposed a terminology shift from "decarbonisation" to "defossilisation", in order to better reflect the need for sustainable carbon management across all relevant sectors. In this context, the convergence of the polymer industry and the oil-gas industry in the next transformation stage of the global energy system was also stressed as a necessity.

Five key messages were proposed:

1. Carbon circularity is essential for circular economy and sustainable development;
2. Plastics waste incineration coupled with Carbon Capture & Use (CCU) – as a viable "chemical recycling" route for plastics waste – paves the way for a "sustainable" all-circular plastics sector;
3. For the industrial transition, a focus on green hydrogen (H_2) is important, but green forms of methane (CH_4), methanol (CH_3OH), and ammonia (NH_3) are also fundamental;
4. Hard-to-abate industries (such as steel, cement, plastics & chemicals, waste incineration) must spearhead CCU technology development and large-scale implementation;
5. Regional collaboration and transnational partnerships are essential.

2.3.2 Creating sustainable and responsible critical minerals supply chains: Guidance for policymakers – Alexandra Hegarty (International Energy Agency)

The speaker opened the presentation by stressing that in order to make critical minerals supply chains more secure, it is crucial to ensure that they are sustainable and responsible. Specifically, as the critical minerals sector is under growing pressure to develop new mines, processing facilities, and refineries, it is fundamental to minimise any risk of harm to the environment, workers, communities, indigenous peoples and societies. Failure to address these risks can limit market access (or create legal barriers when regulatory requirements cannot be met), discourage investment in new projects, and increase the likelihood of opposition from local communities and other stakeholders, leading to possible acute supply disruptions and reputational damage for the actors involved.

The recent IEA report on this topic [IEA 2023] includes five key recommendations for policymakers to ensure the sustainability and responsibility of supply chains:

1) Ensure legal and regulatory protections for the environment, workers, indigenous peoples and communities, supported by sufficient means of implementation and enforcement regimes;
2) Channel public spending to encourage the development of better practices and to incentivise good performance;
3) Strengthen the collection and reporting of granular and standardised data to enable benchmarking and progress tracking across the industry and throughout the supply chain;
4) Ensure companies improve transparency throughout the supply chain, including by enhancing traceability, undertaking due diligence and reporting publicly on risks and mitigation actions;
5) Support the development of initiatives that help companies demonstrate that their operations are sustainable and responsible while ensuring cross-compatibility and interoperability.

Finally, the speaker mentioned the 2023 update of IEA's Critical Minerals Policy Tracker, which analyses the status of sustainable and responsible practices (eg environmental standards, transparency norms and inclusivity policies) in 35 countries.

2.3.3 Circularity and sustainability as a means to build resilient and responsible value chains: the example of batteries – Fabrice Mathieux (European Commission, Joint Research Centre)

This presentation discussed how circularity and sustainability can help to build resilient and responsible value chains, and how batteries can be a starting point for such a journey. In particular, the speaker focused on the EU Battery Regulation, framing it as a valuable opportunity to take a holistic approach to lifecycle thinking, circularity and key critical/strategic raw materials. The regulation is based on the whole life cycle, targeting different aspects and stages (such as raw material supply, manufacturing and end-of-life) as well as introducing several game-changing entry-market requirements (such as carbon footprint and recycled content, performance, durability, and safety). Companies that place batteries on the EU market will have to put in place a due diligence system for the lithium, cobalt, nickel, and natural graphite contained in them, operating a system of controls and transparency over the supply chain and identifying and responding to environmental and social risks.

The speaker stressed that data and intelligence are key to increasing the circularity of critical raw materials. The JRC's Raw Materials Information System (RMIS) serves this purpose. It includes a rich dataset on batteries which was used to support the Battery Regulation, for example by helping to identify new market trends.

The JRC also proposes:

1) calculation rules in support of collection targets for waste portable batteries and light-means-of-transport batteries;
2) harmonised calculation and verification rules for recycling efficiency rates and recovery of materials rates;
3) a methodology for the calculation and verification of the percentage share of Co, Ni and Li recovered from battery manufacturing waste or post-consumer waste, as well as for Pb recovered from waste batteries;
4) an initial set of rules for accounting and declaring carbon footprints.

The speaker closed the presentation by hinting at the possibility of implementing the manipulated / extended dataset for the Battery Regulation back in the RMIS, and mentioned the JRC's work with the Horizon Europe project FutuRAM to define the types of data (in terms of scenarios, granularity, etc.) which are best suited to policy support.

2.4 Session IV: New Innovative and Advanced materials for Substitution of CRMs

2.4.1 Materials for new energy technologies – Pekka Pohjanne (VTT Technical Research Centre of Finland)

This presentation included details on the activities and business solutions provided by VTT in the area of materials for energy technologies. Particular attention was paid to sustainability, and the creation of new materials, innovative technologies, and processes. The speaker promoted a holistic approach to materials challenges, taking in the complete supply chain and all its interactions. In addition to metal and mineral cycles, water loops are also critical aspects of sustainability.

Cross-value chains are defined to encompass extraction, refining and recycling on top of demand reduction measures. Substitution will be most relevant for maximising the efficient use of resources and should include the assessment of opportunities to replace individual materials in some applications in order to make them more available for use in others (e.g. reducing the use of cobalt in hard metals in order to free it up for use in batteries). Material system analysis and material flow modelling should consider the life cycle process losses and the impacts of repurposing and remanufacturing.

The speaker reiterated the importance of resource efficiency to safeguard a secure supply of raw materials. Measures should include minimising consumption and losses, substitution, new processing and manufacturing. One key aspect is to identify needs for novel materials and speed up their adoption in strategic areas. Examples include coatings, components, functional addition (e.g. catalytic powders for electrolysers) and aspects related to circularity.

The speaker noted that substitution, though it is not new, needs a higher profile. Materials Acceleration Platforms (MAPs) are a global hot topic with genuine added value for the exchange of information on advanced materials and new developments, opening up possibilities for substitution. By deploying computational power and data sciences, making use of active learning tools, dynamic modelling, and physics-based simulations, the time it takes to develop new materials could potentially be shortened by 90%. Such ambitious objectives require the collaboration of various institutions, services, and other actors.

2.4.2 Completing the loop: Increasing resilience of lithium ion supply chains through an improved circular economy of batteries – Gavin Harper (Birmingham University)

This presentation revolved around the subject of recycling and recycling potentials, critically reviewing existing technologies and discussing ways to achieve better follow-up and greater efficiency. It focused on batteries, reflecting on the legitimate concerns around waste management, and the need for “design for recycling” and smart automated disassembly.

The speaker highlighted the mismatch between battery recycling infrastructure investments and the realisation of waste streams for recycling. With lots of new entrants in this space (outstanding capacity in China but also in Europe and the West), assets are currently somewhat strained. In addition to the fact that sufficient volumes for recycling are not yet available, the industry is not settled into a uniform configuration and better practices will only be made possible when the market is more mature.

The speaker noted the challenges facing the recycling industry and recalled the need for operations to evolve. Smart automation is of the utmost importance from the point of view of critical raw materials, and it is imperative to ensure the highest effort on the dismantling of complex end-of-life products. For recycling, it has typically been difficult to separate the multiple layers of a battery cell, which, in addition to a significant variety in pack designs, has enhanced the adoption of pyrometallurgy by the industry. A more efficient approach to recycling should begin with product design. The use of adhesives that can be removed upon application of an external stimulus (e.g. magnetic, ultrasound, UV light) allowing the layers to separate, was mentioned as an example of suitable design.

Design for recycling should aim to reduce the complexity of the current systems and be a major source of simplification. Digitalisation of LIB recycling was also highlighted as a key aspect on the way forward. Robotics and automation are also key to address sustainability concerns around the materials, and to tackle other aspects such as aging and degradation.

In this context recycling can take new forms and the technology pipeline could evolve from pyrometallurgy and hydrometallurgy towards recycling aided by cell disassembly, finally reaching the stage of redesigning cells for recycling.

The speaker also referred to the importance of geospatial modelling for unlocking the potentials for efficient recycling. Appropriate site selection and the optimisation of the industrial configuration, considering the proximity to waste flows, for example, should be a guiding principle for developing the recycling industry of the future.

2.4.3 Alternate Materials & Technologies for Clean Energy – Kumar Sadayappan (Office of Energy Research and Development, Canada)

This presentation provided insights into substitution options for critical materials in certain applications. The speaker highlighted the importance of Material Acceleration Platforms, launched in 2019 under Mission Innovation to better integrate of all aspects of material development (testing, characterisation, data analysis and new processes).

The substitution of critical materials in applications such as conductors, magnets and motor technologies need to be given higher priority. Grid infrastructure, construction and EV components (eg rotors and charging stations) have very high requirements for conductors made of aluminium or copper. Given the potential risks to copper supply in the future, aluminium could be used instead of copper in applications where conductivity requirements are not so strict. Improvements to aluminium strength and conductivity can be achieved through alloy developments such as the addition of Sc or Sc + Ce or Al-graphite with improved conductivity.

Rare earths demand, on the other hand, is dominated to a large extent (43%) by permanent magnets deployed in EV motors and wind turbines, along with consumer electronics and individual motors. With regard to motors for electric vehicles, multiple options are available. Advantages are to be found in induction motors which use soft magnetic materials (windings) in both stator and rotor, eliminating the requirement for permanent magnets, though at the expense of power density and efficiency.

The speaker concluded by promoting a holistic approach to policy development to support the industry's response to supply chain challenges. All applications and end-markets should be considered for each material.

3 Conclusions

The role of cutting-edge technologies and initiatives to promote resilient supply chains emerged as key themes of the workshop. In addition, the discussion sessions produced three key takeaways:

- Policy initiatives must target the whole supply chains – from mining, refining, and processing materials to manufacturing components; from assembling the final products to their end of life and recycling.
    - Some participants voiced their preference for a bottom-up approach in developing policies, rather than the prevailing top-down approach (where thresholds tend to be fixed on a political basis rather than a technical/scientific basis). However, it was also noted that clear requests and guidelines from policymakers are fundamental to defining the work of scientific organisations in support of policy.
    - Stockpiling was discussed, with some participants highlighting confidentiality requirements with respect to company stocks and the fact that stockpiling obligations cannot be imposed. The EU CRM Act requires large companies to assess their supply chains and report on the degree of preparedness for possible emergencies, informed by a sound and comprehensive knowledge across all stages of the value chain (beyond current knowledge which at present seems very limited in scope to the immediate suppliers).
    - In some cases, market forces may limit the potential for more sustainable choices out of economic considerations; for example, it was argued that some existing rare-earth-free magnets may already perform as well as their rare-earth-based counterparts in some specific applications where a high energy product is not strictly necessary, but are held back by a lack of incentive for producers to replace them.
- Foresight is essential to make sure that no new criticalities are introduced in the process of addressing existing ones, and that the technologies we will rely on are future-proof.
    - The value of certain materials (for example, cobalt in EV batteries) was mentioned as a driving force behind efforts to make recycling more effective and efficient. Design for recycling is therefore seen as a high priority; progress on this front will be fundamental to increase the recovery of high-value materials, since the recycling industry needs to operate at certain scales to reduce costs (as well as other environmental impacts).
    - The role of CCUS and its challenges were also discussed, with participants acknowledging the importance of both geological storage and utilisation and foreseeing a prominent role for CCUS in abating emissions in certain industries (e.g. cement), unless novel production processes become feasible.
    - While it is difficult to predict the magnitude of certain problems, science has an obligation to anticipate the implications of potential choices; the growing concern around microplastics was brought forward as an example.
- There is a lot of room for international cooperation at all levels, which must be fostered and accelerated.

- Both national action and international cooperation are needed to address materials challenges, in terms of access to funding and research cooperation.
- The importance was emphasized of building strategic capacities through projects at regional and international levels.
- Data handling and data sharing were highlighted as two of the most important positive outcomes of Materials Acceleration Platforms. Mobilising a greater exchange of ideas and cooperation on new approaches to material characterisation, including performance evaluations and properties, is seen as crucial to accelerate the Platforms' operational development.

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