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The energy-material nexus: CRM demand, CRM footprints, and their interplay

IRTC-Business online workshop

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Introduction

Critical raw materials are needed for the energy transition, and at the same time they require energy themselves across their supply chains. In this workshop, we aim to look at a) the different ways critical raw materials are used for energy production and storage, and the energy and material efficiency of different technologies, and b) the energy needs of critical raw materials, the potential of the circular economy to reduce these, and the interplay of raw material demand and energy requirements. One goal of the workshop is to gather expert opinions on how the "energy balance" of critical raw materials could be calculated and put into context.

Agenda

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11:50	Energy efficiency of different battery types	Naeem Adibi, WeLOOP

b) Energy needs of critical raw materials		
12:05	Energy requirements of CRM extraction and the role of ore grades	Gavin Mudd, RMIT
12:20	Energy sources used in mining operations	Luisa Moreno, Tahuti Global
12:35	Environmental Footprints of Li extraction from brine and ore	Hyunsoo Kim, POSCO
12:50	The influence of demand shifts on REE processing	Alain Rollat, Carester
13:05	Thermodynamic limits of mining and recycling, and optimization of strategies	Markus Reuter, SMS Group
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14:30	End	

1 Critical raw materials contributing to energy supply

1.1 Critical minerals for the clean energy transition

Toru Muta, IEA

Toru Muta is a senior energy analyst at the International Energy Agency (IEA). The IEA was founded after the energy crisis of the 1970s and analyses current energy trends and long-term outlooks, lately with a strong focus on climate aspects.

The IEA developed several energy pathway scenarios, and evaluated the use of critical raw materials in these scenarios:

- Net-zero emissions by 2050 (NZE): Global energy pathway to achieve net-zero emissions by 2050, which is consistent with limiting the global temperature rise by 1.5 degrees Celsius, in line with COP26. This scenario also covers the ambitions of energy-related Sustainable Development Goals (SDGs) (e.g. achieving universal energy access by 2030).
- Sustainable development scenario (SDS): Scenario consistent with limiting the global temperature rise by "well below 2 degrees" (Paris agreement), and it assumes that all energy-related SDGs are met. It requires increased effort to realize near-time emission reductions.
- Stated policies scenario (STEPS): Exploration of energy pathways with current policy settings. A granular and sector-by-sector look is applied to include existing or announced policies.

All scenarios foresee an expansion on the share of renewable energy, which are more mineral intensive than conventional energy technologies: a typical electric car requires six times the mineral inputs of a conventional car, and an offshore wind plant requires thirteen times more mineral resources than a similarly sized gas-fired power plant. Due to an increasing domination of investments in renewable energy technologies in the power generation sector, the average amount of minerals needed for power generation has increased by 50%.

How, and how fast could mineral demand rise? In 2040, the SDS scenario could require 4 times the mineral use of 2020, and the NZE scenario 6 times. Electric vehicles (EVs) and battery storage are the largest driver of the increased mineral use. Other contributors are the required investments in electricity networks and low-carbon power generation technologies. Even though it depends on specific policies and technologies, the demand for lithium is expected to increase in the SDS scenario over 40 times compared to 2020 (graphite 25x, cobalt 21x, nickel 19x, and rare earths 7x).

The share of clean energy technologies in the total demand for minerals in the SDS also strongly increases. In 2040, 90% of the global lithium supply will go to the energy sector (compared to 30% in 2020). A similar trend can be observed for other minerals, although less pronounced than for lithium. Also developments in the cost structure of energy technologies are expected. Learning curves and economies of scale bring down other component costs, making mineral inputs account for an increasingly large share of the total cost of batteries and other key clean energy technologies. Price increases or price volatility could have a significant effect on the costs of the energy transition.

The energy transition will also have a strong effect on the mining industry. Currently, the revenue from coal mining is 10 times larger than the revenue from the mining of energy transition minerals. However, this distribution will change in the SDS scenario, as revenue from energy transition minerals will become more important than from coal before 2040.

The IEA further observed a mismatch between the projected SDS demand and the scheduled supply of minerals in the coming decade, based on today's investment plans. Especially the balance for lithium chemical products, battery-grade nickel, and key rare earth elements seems very tight. New projects could bridge this gap. However, considering long lead times (4-5 years for construction, adding additional time for project preparation and permits), it appears that investors and suppliers are not yet convinced that policymakers put their ambitious targets into action. Policymakers need to set clear milestones for action for near-time clean energy deployment this decade, in order to reduce investment risks and encourage capital flow to new projects.

Over the whole lifecycle, sources of GHG emissions in gasoline fueled cars are dominated by their fuel use. The manufacturing of electric car causes slightly higher GHG emissions than conventional cars, but the main source of GHG emissions is related to the electricity used to charge the car. In the SDS scenario, the global average electricity mix could result in halving the lifecycle GHG emissions of a conventional car. Countries with the cleanest electricity mixes could obtain a reduction of lifecycle GHG emissions of 75%.

IEA also analysed the role of recycling for critical minerals. The analysis showed that recycling can have a significant effect after 2040, and now it is important to implement recycling mechanisms. Other circular models such as car sharing were analysed by studying the effect of behavioural changes in the transition, but this analysis was not directly combined with the study of critical minerals.

The IEA proposes six recommendations for policymakers:

1. Ensure adequate investment in diversified sources of supply – companies should be provided confidence to commit to new supply
2. Promote technology innovation at all points along the value chain – e.g. to reduce mineral intensities and increase substitution
3. Scale up recycling – by 2040, primary supply of copper, lithium, nickel, and cobalt could be reduced by 10% by battery recycling
4. Enhance supply chain resilience and market transparency – e.g. by strategic stockpiling and monitoring supply data
5. Mainstream higher environmental, social, and governance standards
6. Strengthen international collaboration between producers and consumers

1.2 Scenario modelling approaches for critical mineral supply

Stephen Northey, University of Technology Sydney

Stephen Northey is a research fellow at the Institute for Sustainable Futures (UTS) at the University of Technology Sydney.

Whereas historically much emphasis has been on the demand for critical raw materials, Stephen explores the potential supply – e.g. where we can get the materials from, in what form, and where it can be sourced from. Data sources on mineral resources have developed over the last decade, which allows to move to a next stage of sophistication in the modelling of raw material supply.

Raw materials commonly go through commodity supercycles, which are periods through history where there have been structural swings in commodity prices. Such swings are triggered by, for example, major conflict around the world, substantial development in a specific region, or technology implementations. The question is whether the next 20-30 years of renewable energy deployment, or the sustainability transition, will trigger another commodity supercycle, and what this could mean for global material supply.

For many of the major commodities, demand is expected to rapidly increase (e.g. copper, cobalt, nickel, lithium, cadmium, tellurium, see Watari et al. (2020). Where will we get these materials from, and can supply can be upscaled to meet this demand? To avoid that material availability becomes a bottleneck for decarbonization, some degree of predictability is needed. Industries would benefit from guidance on demand projections, which gives them better understand supply requirements at different times and schedule their production accordingly. This allows for more effective investments and an attempt for an orderly transition and avoids short-term decision-making, especially in periods of crises. However, a clear prediction is not possible. Instead, it is helpful to model scenarios that increase our understanding on the elements that influence the behavior of a system and identify key leverage points of this system.

Historically, approaches for scenario modelling of mineral supply were relatively simplistic. There is room to improve the sophistication of the models to allow them to answer more meaningful questions. An example of a more sophisticated model is the Primary Exploration, Mining, and Metal Supply Scenario (PEMMSS) model. This is a transparent, open-source model under development in Python. Demand is calculated by linking a primary supply model to demand scenarios for the SSP scenarios produced by others. The basic goal of the model is to fill the black box for primary supply we often see in scenario models and prospective MFA. Primary commodity demand scenarios can be fed into the model and make estimations on the supply side. The model has the following characteristics:

- It uses the level of data that is actually available (without aggregation), such as deposit sizes, grades, annual production capacity, mineral recovery, and the cost basis and revenue of mineral operations.
- It also allows for modelling of brownfield and greenfield exploration, which as often ignored or simplified in previous models. The model simulates the discovery of new deposits over time based on grade and tonnage probability distributions. These can be modeled as a function of mineral demand, or as background rates of mineral discovery.
- The model furthermore allows for time lags between the moment of discovery and development of production. In many regions the time required for environmental approvals is increasing, and there is large regional variability regarding these time lags.
- The model also considers the simultaneous supply of co-produced minerals, such as nickel and cobalt, copper and gold, copper and molybdenum.
- Randomized elements (e.g. the type of deposits that are discovered) allow for the consideration of uncertainty in mineral supply, after multiple iterations of the model.

Example questions that could be answered by the model are:

- How many mines are required to produce a certain amount of a commodity over time?
- How many deposits need to be discovered, and does it make a difference what type of deposits are discovered?

Such questions go beyond the simplistic question of “will we run out of a mineral” that has been the focus in the past. The presented type of modelling can be used on any primary demand scenario, and could also be adapted to identify specific supply bottlenecks for certain materials by looking at both investment requirements to scale up supply and avoid bottlenecks, and then also do what-if analysis of if supply cannot keep up with demand.

1.3 Energy-material mismatches in global carbon-neutral transition

Peng Wang, Chinese Academy of Sciences

Peng Wang is an associate professor at the Material and Urban Sustainability Research Group at the Institute of Urban Environment of the Chinese Academy of Sciences.

The topic of carbon neutrality is gaining international interest among global countries. More than 120 countries announced to achieve carbon neutrality or net-zero emissions, including China, which aims to become carbon neutral before 2050. The EU aims to move from peak carbon emissions to carbon neutrality in 60 years, the US in 45 years, and China in 30 years.

Carbon neutrality can be achieved via two strategies: CO_2 mitigation and CO_2 offsetting. The energy sector is responsible for the largest share of GHG emissions. However, in this sector, a strong material need is expected when moving to renewable technologies. At the same time, carbon offsetting (by planting trees) conflicts with deforestation practices done by the mining industry, to produce the materials needed in renewable energy technologies. Therefore, a balance needs to be found between the roles of the energy sector as carbon emitter, carbon mitigator, carbon releaser (e.g. due to increased mining) and carbon remover. This balance reflects the material-energy nexus.

The material-energy nexus resembles the theory of five elements from Taoism, in which wood, fire, earth, metal, and water are interconnected. Materials can be consumers and producers of energy, and therefore emitters and mitigators of carbon emissions. This nexus should therefore be evaluated from different perspectives, e.g. life cycle assessment, coupling of systematic linkages between energy and materials, and cross-scale interactions.

The material system can be expressed in different layers of a hierarchy, including technology, energy, business, geosystem, life cycle, and the ecosystem. According to these layers, there are mismatches between energy and the material:

- Scale mismatch: Current reserves do not provide enough metals to support a low-carbon energy transition. At the same time, declining ore grades require more energy to extract raw materials, which is mostly provided by carbon-intensive energy technologies. Many of these technologies are difficult to decarbonize, including material-processing technologies – such as aluminium required for solar panels.
- Spatial mismatch: Countries that need raw materials are increasingly dependent on countries that supply them.
- Temporal mismatch: Production of metals is difficult to scale up. Even if there are enough resources in the earth's crust, there may be not enough capacity to fulfil demand. And even if the materials are recycled, there is a delay in the time of strong demand and the availability of end-of-life products for recycling. Also, the amount of waste produced by renewable energy technologies needs to be anticipated.
- Element mismatch: Co-production of metals (such as rare earth elements) leads to a mismatch between the metal production from the mines and the demand. For example,

mining of REEs is triggered by material use in wind turbines, leading to surpluses of europium of which demand is declining.

- Process mismatch: There is a burden shift from consumption to production, which can be evaluated with a carbon payback period. For solar cells this is around 3 years, but it depends on the energy mix used. For some metals, the energy savings cannot offset the energy induced by metal production. On top of that, burden shifting takes also place to other types of wastes and environmental impacts.
- Impact mismatches: The geographical distribution of environmental impacts is not equal. Impacts are increased in metal producing countries. This is not only regarding GHG emissions, but also water use and pollution, biodiversity, etc. It must be considered how the burden of these impacts can be shared between different stakeholders.

The proposed way forward to bridge these mismatches is a carbon-neutral metal production with carbon-neutral energy via a circular economy, connecting stakeholders from the whole supply chain and taking a global approach.

1.4 Energy efficiency of different battery types

Naeem Adibi, WeLOOP

Naeem Adibi is managing director of WeLOOP, a consultancy company in the field of sustainability, circular economy, and eco-design in France, working on multiple projects in the field of batteries.

Currently, lead-acid batteries have the highest market share with 60%, whereas lithium-ion batteries (LIBs) experience the highest growth and largest share of current investments, probably overtaking the market in the near future. E-mobility (electric vehicles) and industrial applications are the most important users of batteries. For LIBs, up to 70-80% of the costs occur through the use raw materials used.

Over the years 2018-2021 there has been a global tendency to reduce the use of cobalt in LIBs for the car industry (i.e. from NMC (nickel, manganese and cobalt) 111 to NMC 622 and NMC 532). This trend continues after 2021 with the development of NMC 811, as well as an increasing development of LFP (lithium iron phosphate) batteries (e.g. by Tesla, Volkswagen, and Ford). The efforts to reduce cobalt in the batteries leads to an increased use of nickel, whereas the lithium content stays similar. LFP batteries do not rely on critical metals. In some other battery types neodymium is used, although the exact material content is difficult to obtain due to confidentiality and IP limitations.

LFP batteries have a lower energy density and are cheaper than LIB, which make them interesting for lower-cost vehicles. Future technologies are lithium-sulfur (Li-air) technologies, with four times higher energy density than LIB. In the next 5-6 years, we can expect the emergence of solid-state batteries that can store 50% more energy than LIBs and are safer. New-generation LIBs will have similar properties.

According to a study of Montenegro et al. (2021), environmental hotspots (GHG emissions) of most batteries are the production of the cathode, causing about 50% of the impacts. The second contributor is the electricity consumption. In magnesium-sulfur batteries, anodes are more impacting than the cathode. However, these environmental impacts do not consider potential recycling.

The environmental impacts of the recycling of LIBs is strongly dependent on the recycling route (hydrometallurgical, pyrometallurgical, or direct recycling of the cathode). Regarding some impacts or material/energy flows, recycling could be more impactful than primary production. WeLOOP is now involved with multiple projects that aim to improve the process parameters of recycling to decrease its impacts. However, there will always be a delay of 10 years before end-of-life batteries become available for recycling, which makes the potential contribution of recycling to the strongly growing demand for batteries very limited.

2 Energy needs of critical raw materials

2.1 Critical minerals, energy issues & the role of declining ore grades

Gavin Mudd, RMIT

Gavin M. Mudd is associate professor at the Department of Environmental Engineering at RMIT, Australia.

We are more and more transition into a “peak metal” era, analogous to “peak oil”. This is not so much about metal supply running out for society, but rather that individual areas of mining rise and peak and eventually fall away. We then move on to another field, another deposit or region to mine. Compared to the amount of food we consume as a society, the amount of metals used increases over time. The increasing complexity of our society calls for more and more metals from the periodic table used to cover modern technologies.

When looking at any modern technology, it becomes clear very quickly that the metals that are consumed are for a large part base metals, and the critical metals make up only a small part. However, as we have seen already over the last years, this trend is changing and the quantity of minor metals will grow over the next years. Not only is the available overall quantity mostly comparably small, but most of the time these metals are only mined as a co- or by-product. Some examples are rhenium in molybdenum or indium in zinc sulfite. Both of these metals cannot be economically mined on their own.

Environmental impacts, energy intensity, carbon intensity, land footprint and wastes of mining are mostly determined by the ore grade. There is already an extensive amount of data showing that metal ore grades have been declining and will further do so. This causes not only problems in terms of the increased amount of mines that will be needed to cover the same production quantity, but also in terms of energy required to extract the metals from lower-grade ores. The data from the chemical database of Western Australia shows a clear correlation in this regard. For metals like hafnium, gallium or cadmium, where there is no directly reported data, the data for zinc, aluminum or zirconium is used

to derive an estimate. This again comes back to understanding the primary minerals in order to derive data for minor metals.
To understand how such allocations are done, we have to look at sustainability reports where all input, outputs and emissions are recorded. This allows then to see the relationships between the ore grade and the greenhouse gas emissions or carbon intensity. Depending on the energy source (hydro, coal or gas), the GHG emissions will change in quantity. However, carbon intensity will always increase with decreasing ore grades.

The Olympic Dam mine in Australia is one of the largest production mines for copper. It contains various critical metals, such as REEs, cobalt, tellurium, precious metals, and others. Historically though, it was focusing only on copper, uranium, gold and silver, although one third of the value could be found in rare earths, and cobalt could also provide a significant value. However, there is only an extremely minor amount for metals like tellurium which would be one of the easiest to extract from the Olympic Dam.

Lithium hallmarks the transition that we are currently in. Australia used to have one lithium mine in the South of Perth back in 2015. By 2020, there were already 8 mines in total, and lithium has overtaken uranium in terms of the Australian exports. One of the biggest lithium mines is found in the Pilbara region, but compared to the iron ore that is mined there, the lithium quantity is still very low and hence of little concern of the local communities there.

When it comes to recycling of minor metals, we still have a long way to go. When recycling a mobile phone for example, most of its value (70%) comes from the gold inside the phone. There needs to be new ways for business models, policies and also consumer choices in order to make the circular economy work for critical raw materials.

In summary:

- Mining provides the metals, minerals and energy the modern world needs & wants – many of which are increasingly critical
- Most critical minerals are co-/by-products, and often substitutes in primary economic minerals
- Long-term trends for mining are declining ore grades – implications for critical metals are unknown
- Sustainability reporting and life cycle assessment allow us to allocate energy, CO_2, water and other consumption to individual metals
- Many see the 'Circular Economy' as the best way forward; it increases resource security and lowers environmental impact

2.2 Energy sources used in mining operations

Luisa Moreno, Tahuti Global

Luisa Moreno is founder and managing partner of Toronto-based Tahuti Global, a global advisory and consulting firm supplying services to government institutions, investment firms and companies in the mineral resource sector.

While some mining projects are attached to the grid, others are 100% dependent on fossil fuels because their location is more isolated. These fossil fuels can be anything from diesel, natural gas, oil to even coal. However, more and more mining companies are investigating ways to use renewables, including solar, wind, biogas, biomass, or geothermal. Accessing electricity is an important consideration when starting and investing into a new mine project, as the access to a grid could mean less capital and operating costs.

The mining process can be divided into different stages, and each stage has different energy requirements. The exploration stage (e.g. drilling, trenching, lab analysis, sample transportation, etc.), uses fossil fuels for the conventional drilling trucks and excavators. Only the lab analysis of the samples may be facilitated over the electricity grid. The mining process includes activities like blasting, trucking, crushing and grinding. These activities are usually done at the mining site and for mines that are remotely located it often means a 100% dependent on fossil fuels for these activities. The same goes for the processing and refining stages (e.g., floatation and purification) if processing plants are remotely located – moreover depending on the metal and process of extraction, some plants include equipment that is designed to use fossil fuels, like gas fired furnaces and kilns. For wet tailings, often pumps are used, which need to be powered. If there are dry tailings, they are transported via conveyor belts or trucks which both need to be powered or fueled as well. Lastly, even wastewater requires pumping. Every stage of mining and processing requires energy and depending on where the mines are located, GHG (greenhouse gas) emissions will vary.

Oftentimes, the processing stage accounts for 30-50% of the energy consumption. This is especially the case for base metals. However, a lot of the critical materials have similar processes in terms of crushing, grinding and mineral concentration. A significant percentage of energy consumption is used for comminution and floatation which usually happens at the mine site. In this processing step, the material is upgraded, for example from a grade of around 1% to about 6% for lithium oxide. Rare Earths usually have a mineral concentration between 2 and 10% total rare earths (TREO) before floatation, and are upgraded to 40-70% TREO mineral concentration. For graphite, the floatation process alters the concentration from as low as 2%-6% graphitic carbon (Cg) to more than 95% Cg. These differences before and after this process step shows its importance. Considering that these processing steps happen at the mine site, the likely source of energy are often fossil fuels.

When looking at the lithium production as an example, most of it is done in Australia and Chile. In both of these countries, if production sites are remote, operations will depend largely on fossil fuels. Some of the energy can come from renewables but this hasn't been implemented yet on a large scale. Even though in both countries renewables make up a larger part of the energy sources, for the mining production this cannot be directly assumed, since the choice of energy source depends on the region and where the mines are situated.

For cobalt, 71% of its production is conducted in the DRC, where most of its energy comes from hydro power. However, this also cannot be applied to the mining production, as the cobalt mines are sometimes in remote locations and hence dependent on fossil fuels as well. China has a high exposure to fossil fuels of 68% of the grid – which is contributing to the high carbon footprint of many of the raw materials that China produces, like Rare Earths. Brazil that is a major producer of niobium and graphite, does have a large contribution from renewables in their energy grid. However, it is still a large country, and depending on where the mines are situated, they may or may not still be dependent on fossil fuels for production.

What can mining companies and other stakeholders do in order to improve this situation? The mining companies can start monitoring the GHG emissions at the mine and processing plants, understanding where the harmful emissions come from. They should use renewable energy where possible, depending on where mines are situated and the economics. Some locations might have conditions where this is impossible at the moment, but in other places, this might be feasible. Furthermore, power plants could be combined with heat plants. This means that the generated heat from certain processes becomes repurposed within the plant and turned into power. Some of the more modern plants already do that, but older ones may have to be repurpose. Last but not least, mining companies could start using electric vehicles, where feasible.

These improvements are easy to be suggested – however, for most of the mining projects, the reduction of CAPEX and other costs is in the forefront, and a transition to renewable energy sources is not necessarily the cheapest way forward. Hence, it is more feasible for investors and other stakeholders to nudge the change towards more renewable energies. Governments can offer incentives for mining projects to increase their percentage of renewable energy. In Canada, for example, the government has put forward large funds for steel and mining companies to help with the transition. Furthermore, investments funds can favor mines with lower GHG emissions.

Concluding, all the materials that are being produced to reduce GHG emissions are still the cause of a lot of emissions themselves. It is inevitable that we need to change the upstream stages of the supply chain.

2.3 Environmental Footprints in Li Extraction from Brine and Ore

Hyunsoo Kim, POSCO

Hyunsoo Kim is a senior researcher at the Lithium Material Research Group of POSCO. POSCO (Pohang Iron and Steel Company) is an international steel making company that has started to invest in lithium extraction in Argentina and Chile in order to cover the increased lithium hydroxide demand due to the growing electric vehicle market. In order to secure lithium mining, POSCO has started a pilot plant for lithium extraction from brine in Argentina. The salt lake where the demonstration plant is situated has a surface area of 25’000 hectares and lithium reserves of 13 million tons. Additionally, POSCO has signed a joint venture agreement with Pilbara Minerals in Australia from which they expect to get 315’000 tons of lithium concentrate every year. With these two plants combined, POSCO is planning to increase their lithium hydroxide and lithium carbonate production to 22’000 tons per year until 2030. POSCO has started developing their lithium extraction process back in 2010 and has run a pilot plant in Chile and Argentina from 2011 to 2015. Since 2017, they are operating one demonstration plant for the brine production in Argentina and one for the ore production in South Korea. Additionally, POSCO is constructing a production plant which recycles black powder from waste batteries to produce lithium carbonate.

Introduction to the lithium extraction process

For the brine process, impurities are removed after the evaporation process of the brine after which lithium salt is precipitated and separated. The lithium salt is then refined to lithium hydroxide. For the ore process, the ore is heated and dissolved in sulfuric acid to separate the lithium from the ore before the lithium ion is converted into the hydroxide through refining.

In the conventional brine process, impurities are removed before sodium carbonate is added which precipitates lithium carbonate. The lithium carbonate is then converted to lithium hydroxide which is then crystallised. In the case of the conventional ore extraction process, spodumene, the lithium ore, is calcinated at high temperatures and then dissolved in sulfuric acid. The lithium hydroxide is then obtained after several purification and refining steps. When comparing these two processes in terms of their energy use and GHG emissions, higher values for the ore process are expected due to the use of higher temperature processes such as calcination and high temperature roasting.

In their publication, Kelly et. al. (2020) compared the energy consumption of brine and ore processes and illustrate that the ore process uses more electricity and coal and hence has also higher GHG emissions. The coal energy is used to generate the steam and heat for the calcination process. Comparing these two processes, the brine process produces 6.9 tons of CO_2 and the ore process 15.7 tons. Changing to natural gas instead of coal, the later value could be decreased to 13 tons.

However, a POSCO technical report showed different results. They stated for each process similar GHG emissions, arguing that the brine process usually operates in mountain areas, where electricity is produced by using natural gas or diesel, hence leading to higher GHG emissions.

The POSCO process

In case of the POSCO brine process, the lithium is precipitated in form of lithium phosphate because it contains lower impurities. In the refining process, an electrodialysis process is used to transform the lithium sulfate into the hydroxide. However, this increases the electricity consumption. When compared to the conventional process, the POSCO ore process might have higher electricity input but uses a smaller amount of HCL and NaOH and hence has comparable GHG emissions. In the conventional process, high amounts of NaOH are used in the causticization process which produces high amounts of CO_2. In the future, POSCO will gradually switch to more renewable energy, decreasing its GHG emissions.

Summary

Ore process: when producing 1 ton of LHM, the generated CO_2 is 9.49 tons for POSCO, and 9.71 tons for the conventional process. Hence, there is no significant difference in the amount of carbon generated in POSCO and conventional processes for lithium ore extraction. POSCO aims to improve their manufacturing processes to continuously reduce carbon emissions.

Brine process: When producing 1 ton of LiOH, the generated CO2 is 9.5 tons for POSCO, and 9.47 tons for the conventional process. Also here, there is no significant difference in the amount of carbon generated in the POSCO and conventional process for lithium brine extraction. The renewable energy such as solar power or wind power could help to reduce the CO_2 emissions of the POSCO process.

What else could be done to reduce the carbon intensity of spodumene sources? The calcination and roasting process of spodumene uses a huge amount of natural gas. Microwave could be an alternative source to replace the fossil fuel. Spodumene could absorb the microwave efficiently and so the heating rate would be very high. If microwave energy is induced by renewable energy or a non-zero carbon energy source, it can decrease CO_2 emissions. Then the impacts of the calcination and roasting process could be reduced as well.

2.4 The influence of demand shifts on REE processing design and long-term processing viability

Alain Rollat, Carester

Looking at the mega trends of the US market, one can see that the REE market has become a magnet market which will increase even more over the coming years due to the e-mobility rise. Hence, the divergence between the REEs that are needed for these magnets and the other REEs will increase as well in the coming years. In fact, mainly four 4 REEs are used: Pr and Nd among the LRE (light rare earths), and Tb and Dy for the HRE (heavy rare earths). However, when processing the ore, the companies have to deal with all 14 lanthanides and Yttrium. How can the ores be processed to improve processing of the currently four most relevant REEs?

Currently all the HRE separation, including ionic ore separation, is done in China. In La Rochelle, ionic ores were separated until 2000; then this separation unit has been shut down. In Lacq in the South of France, Carester intends to restart such a unit, with a higher flexbility because the feed stock will come from different deposits

In typical REE compositions, almost all the LRE and mixed LRE+HRE deposits contain between 20-30% PrNd content per overall LREs. Only the Yangibana deposit and the ionic ores have a higher PrNd content due to a very specific geological weathered process. Even in that case, at least 50% of the LRE will not have a market in the coming years. This picture is very similar for the HREs. All the mixed LRE/HRE deposits and the pure HRE deposits contain between 10% and 13% TbDy content per overall HREs, i.e. more than 80% of the HREs will not have a market in the coming years. This means, when processing REEs, there will always be either 50% or even 80% of REEs that are not valuable in the coming years. This raises the question whether it is possible to treat only the part which is interesting and valuable, i.e. only the LREs Pr and Nd and the HREs Tb and Dy.

When looking at the process steps from the mine to the magnet, it becomes clear that during the beneficiation, there is no possibility to remove other, non-valuable REEs, and the process will be paid by only the REEs used in magnets. During the second step, the chemical attack, it is possible to remove part of the cerium, which can make up to 50% of the ore. Its removal is possible due to its chemical form (CeIV) and hence its different chemical behaviour compared to the other REEs. During the separation process by solvent extraction, there is the most potential to adapt the separation of REEs and reduce the cost based on the type of REE that is desired to produce magnets.

The REE separation can be done by two routes: chloride or nitrate. With the chloride route, only the acidic molecule HEH(EHP) (PC88A) can be used as a solvent, while with the nitrate route several molecules can be used: PC88A, but also TBP and Aliquat 336. PC88A is selective all along the lanthanides series and can be considered as a universal molecule for REE separation. However, using an acidic molecule requires acidic (HCl or HNO3) and alkaline molecules (NaOH or NH4OH) to operate. This increases the carbon footprint. The other possible molecules used with the nitrate route have a lower carbon footprint, but none of them can be used for all the REE separations and all require to be used in combination for an overall RRE separation due to their lower selectivity.

At the end, there will always be a trade-off using either of the two routes in regards of OPEX and CAPEX. The more LREs in the feed, the shorter the payback time between the nitrate and chloride route. This is due to the smaller OPEX but higher CAPEX for the nitrate route.

In order to adapt the separation process to the REE imbalance, the separation process flow diagram has to be considered. For the case of LREs, 4 separation extraction batteries are usually used in order to separate pure La, Ce, Pr and Nd. When only Pr and Nd shall be extracted, (or even only the mixture PrNd which is called didymium), one (or two) of the solvent extraction batteries (the one to separate La from Ce and the one to separate Pr from Nd) can be removed. This is one possibility to reduce OPEX and CAPEX.

For the case of the HREs, China has developed a process to separate all HREs into pure Sm, Eu, Gd, Tb, Dy and Y. Up to 2015, all these REE had a market and were mainly dedicated to the phosphors and magnets market. However, today the phosphors market is almost dead as well as the market for most of the other HREs, except for Tb and Dy used in magnets. The separation process shows a high complexity due to the high number of elements to be separated and the very different HRE distribution depending on the type of ore. This complexity makes it very difficult to adapt and optimize the process so that only the elements Tb and Dy are extracted. In fact, it can only be done with the use of a software which takes into account all the capabilities of the various extractants. Carester has developed in cooperation with the French Atomic Energy Research Center (CEA) such a software that is able to design and optimize the separation process with all the REEs and all the different types of organic

extractants. For example it can be used to design the process for extracting Pr, Nd, Tb and Dy whatever the feed stock.
Currently, most of the current RE mining and separation projects are based on LRE or mixed LRE/HRE deposits with low HRE content. The expertise for the HRE separation is very rare outside of China. With the experience of his experts and this software, Carester has the expertise to design and operate any type of LRE and HRE separation process. The software, which provides the REE profiles in aqueous and organic for each stage, can be adapted to any type of ore whatever the RE distribution, from the LRE+SEG rich composition (type monazite) to the HRE reach composition like xenotime. Any type of parameter can be modified, such as flowrates, composition, etc. The software provides the modification of the profiles over time, and users are able to adapt the parameters to keep the steady state profile.

Considering that most of the current separation projects include only the LRE separation keeping the HRE as a concentrate which should be sent to China, Carester is now building in the south of France a hub dedicated to the HRE separation which should be in operation by the end of 2024/beginning of 2025 and will be run on a tolling basis for all the future non Chinese RE separators.

In the production of neodymium iron boron magnets, there are two main steps of the process where the energy consumption is important: the solvent extraction step (SX) producing purified RE oxides, and the metal making. The two main SX processes for making the separation are the nitrate and the chloride routes. Carester has performed a life cycle assessments comparing the two routes for the End of Life magnets recycling, but probably the conclusions can be applied to virgin ores as well. The nitrate route consumes mainly energy, while the chloride route consumes caustic soda and hydrochloric acid. The LCA shows that the carbon footprint of the chloride route is higher than that of the nitrate route. This is because the energy contained in the caustic soda and the hydrochloric acids is higher than the energy needed for the nitrate route. So one way to reduce the energy footprint of the separation is probably to focus on the nitrate route, especially for the light rare earths. The second point is the metal making. Here, the energy used is the electricity needed for the electrolysis. Of course, the CO_2 footprint will depend on the energy mix of the country where it is done. But one important point is that the current type of technology, which is used everywhere – in China and in Japan as well – is a is a technology using the so-called Molten Salt electrolysis which in addition to the electricity itself releases high amounts of CO_2. There are several teams in the world working on the improvement of this process with the target to avoid the CO_2 release and lower the electricity consumption. The overall quantity of rare earth production is not huge, so in terms of global CO_2 release, the impact will be minor. But related to the rare earths, it is a significant step to improve this part of the carbon footprint linked to the NdFeB magnet-making.

2.5 Thermodynamic limits of mining and recycling, and optimization strategies

Markus Reuter, SMS Group

Prof. Markus Reuter is a chief expert as SMS Group GmbH. From a process engineering perspective, the use of simulations helps to understand the material-energy nexus. When assessing the criticality of different elements, it is always important to look at the whole material mixtures. There are complex mixtures in geological deposits but also at the end of life of products.

Considering the energy nexus with the example of a PV cell, we have to evaluate the energies that are interacting with the material. The material is in fact an energy flow in terms of the first law of thermodynamics, i.e. it has an enthalpy value measured in kilowatt. When the system works, it is also creating entropy which is dissipating from the system boundary. This dissipation can be quantified in terms of exergy, also using the measurement unit of kilowatt. Once the system is broken down to that level, one can start optimizing it and understand the material losses and the exergy dissipated in that process, all in terms of kilowatt. The use of simulation helps estimating the mass balance, the energy balance and also ethe exergy flow of the system. With these estimations, in addition to the kilowatts, it is then possible to calculate the carbon footprint.

Generally, these simulations consider all the thermodynamic linkages between the carrier elements and the minor elements in different chemistry mixtures, either from primary or secondary resources, in order to produce the metals and ultimately bring them back into the cycle. The Metal Wheel expresses these linkages.

When considering the material-energy nexus, the key point is to look at different disciplines together to create a reasonable model to understand how the energy infrastructure of supplying the energy and the chemical processing and the different stakeholders in the circular economy behave. The digital twin of such a circular economy system would then link the energy system to the material system, using the unit of kilowatt to quantify all flows of material and energy, both in terms of the first and second laws of thermodynamics.

The concrete example of Photovoltaic Cells (PV) cells can illustrate how this works (see Bartie et al. (2021) for details). When simulating such a complex system, different processes are compared. This example compares three PV cells: a PERC cell, which is silicon-based with 217 W per square meter, a perovskite-type cell which is lead-based and with fairly complex compounds that are integrated on different layers that are connected to each other, and thirdly a PERC-perovskite tandem cell, which is a combination of the first two that achieves a higher efficiency rate.

In order to build a simulation flowsheet for a tandem cell system, all steps in the life cycle have to be integrated, from primary processing, the manufacturing up to the recycling. Only if everything is integrated into the simulation, the system and the true losses can be understood. Even the exergetic loss which is mostly hidden otherwise should be considered to see the effect on the economics of the system and in the end make the complete system work. Each step in such a circular life cycle system has barriers to the next one, i.e. factors that affect the material flow between them. These could be market forces, policy & legislation or consumer decisions, etc. All these streams get quantified in terms of enthalpy, entropy in its full composition. These are then combined with the process streams, e.g. the use of all the furnaces in one process step.

Once all different stakeholders and process steps are considered, the exergy dissipation can be simulated in terms of kWh/h thus kilowatt, and it becomes obvious that the loop can never be fully closed – dissipation always takes place. One has to evaluate different types of flowsheets to understand the interactions. Such an evaluation could help to identify, in the example of PV cells, which cell is optimal. The flow sheet can be adapted according to different regions of the world, leading to a different footprint of the whole system overall.

If the goal is to reduce the carbon footprint, considering the whole supply chain gets more and more important. The discussed flowsheets could show, for example, the effect of EOL recycling onto the emissions. There will always be an optimum between the amount of what is being recycled and how many emissions are being produced. This optimum further depends on the location of the whole system with its full complexity. It is important to acknowledge the law of physics to which everything is bound to and which is at the heart of mixing and unmixing elements.

Finally, the recovery of the different elements and the percentage of revenue can be calculated as a function of all the compounds in the system. With the entire flow sheet established, the optimization of the system becomes possible, taking into account different scenarios.

3 Discussion

3.1 Energy use for extraction as a limiting factor in the energy transition

Two major aspects play a role in the energy demand of critical raw materials: the usage of energy itself as well as the carbon emissions to generate energy. From a company perspective, cost is a prime metric. Energy costs matter, but so do capital costs (and time to implement). One could imagine situations where a process with higher energy use (but lower capital and faster deployment) might be favored over a more energy efficient process (with higher capital and longer deployment). To understand these mechanisms in more detail, the quality of energy and materials has to be considered, which includes ore grade and product complexity that all affect the “unmixing” chemistry, in which especially the second Law of Thermodynamics plays a key role. However, as transport is electrified, primary energy efficiency increases, and less primary energy is required. By switching to renewables, the lower ERoEI (energy return on energy invested) is offset from many renewable energy technologies. Furthermore, many of the metals we need for the energy transition are already being mined for primary metals, so the energy allocation to by-products is small on a mass or value basis. By-production, however, makes a projection of future supply complicated, and might oversee possible bottlenecks of supply that might slow down the energy transition. Substitution and new technologies are difficult to predict, such as the changing compositions of NMC batteries. Sketching different pathways is critical here, as shown in the talk of Toru Muta.
If fossil fuel systems are to be completely replaced by renewables, the currently known reserves in the ground are not even sufficient to make the first generation of batteries. Batteries needed for stationary power storage will be eight or nine times the amount of batteries for electric vehicles. At the moment, NMC chemistries seem to be the battery material for the foreseeable future, and governments are silent partners for investments that go into billions for these raw materials. Our ability to substitute has

a number of practical limitations, not the least of which is the mineral supply. The job in front of us is enormous and emerged very quickly. There already are structural deficit supply issues with battery raw materials, and we run into a risk that deposits and mines could be nationalized, in a way that e.g. Saudi Arabia or Norway manage their oil reserves. If raw materials are required for nation states to function and survive, and if the value of them goes up dramatically, current agreements could be broken, and the energy transition seriously hampered.

Regarding scenarios, many estimations are not taking into account that there will be a transition to much smaller and more efficient systems. Estimations should be made by looking outside of growth-based economics (see GTK (2021)), and include assumptive changes in material intensity.

3.2 Should energy demand and availability be part of criticality methodologies?

While some participants emphasize that criticality methodologies should not be mixed too much with other approaches, others have the opinion that it would add great value to incorporate energy aspects into criticality methodologies, since energy is a scarce «commodity», and since questions of quantities should be combined with impacts. Until now, energy is seen as a cost and does not play an important role. Criticality is often seen as a measure of how a player could lose competitiveness in comparison to other players that could enjoy lower costs and/or privileged access to CRMs. However, from the discussion today, it seems that everybody could have similar problems in terms of "not enough energy" to cope with. There might be a role for certain kinds of assessments to focus less on competition and more on common bottlenecks that could inhibit or slow down implementation of low-carbon technologies on a global level.

It is also emphasized that material streams must be present in full compound form so that their enthalpy can be calculated to get a handle on their energy flows. One indirect way in which the energy sector is included in criticality methodologies already today is via vulnerability assessment: a low-carbon energy sector requires different materials than a fossil fuel-based energy sector, leading to different sector splits for metals, which in turn affects the vulnerability to disruptions. It is suggested that LCA with a cradle to gate approach could be useful to integrate into criticality assessments, because it provides a wider view and does not only focus on energy criticality. Another factor that should be regarded is the role of energy and environmental policies (such as policies in China implemented to regulate emissions of REE production) that could add to supply risks.

We can calculate the carbon payback time of certain technologies, but we also use these raw materials in other applications that have nothing to do with low carbon technologies. Should we prioritize the use of energy-materials in low-carbon technologies (and minimize the use in gadgets, for example), or will this be regulated by the market? If yes, who should be the body to make this prioritization? The answer to this question is still open.

3.3 The role of energy for mining industries

The economic viability of mining is strongly dependent on commodity prices. If prices increase, energy investments of companies follow. While mining technology can sometimes adapt to volatile prices of by-products, it does not often happen in practice.

Experience from the Australian mining industry shows that energy consumption is a high-priority topic. Especially in grinding, decreasing ore grades make energy costs going up, while unit cost of the energy is also increasing. Mineralogically, grains get smaller, so grinding efficiency is decreasing as well. The relationship is exponential, so over time, much more energy is required to extract the same amount of metal. Accordingly, the productivity index of mining in Australia dropped by 50% over a 12 year period. That means that twice the work had to be done to produce the same amount of metal across the whole Australian mining industry. Many ways were tried to reduce energy consumption despite of decreasing grain size, without success. It was therefore decided that process plants must include energy efficiency components in feasibility studies. On top of energy, with grain sizes decreasing, more potable water is needed, which is a problem in many regions such as South America. In 2020, for example, some mining operations in Chile were interrupted due to water shortages.

The shift towards lower grade ores is partially also caused because of the difficulties to get new projects developed. If no new greenfield sites can be developed, the ones left are the lower grade sites or those surrounding existing ore bodies. This issue touches on social and environmental issues and the social license to operate.

3.4 Electrification of mining and processing

The localization and complete electrification of mining could be a way towards mining with a smaller carbon footprint, as well as completely switching to renewable energy. The scale of implementation of electrification in mining depends on its economic attractiveness. This is dependent on the relation of cost for changing the process and the benefits of carbon reduction of emissions. Also, it can only take place where renewables are sufficiently available and cheap. A full electrification is difficult for metals, but also for building materials such as concrete. The localization and complete electrification of mining could be a way towards mining with a smaller carbon footprint, as well as completely switching to renewable energy. Complete net zero mining, however, will not realistically be implemented in the foreseeable future.

Electrifying mining demands knowledge of the geometry of the deposit and similar information. For example, for crushing and condensing, trucks are replaced by conveyor belts. Even if mines are well connected, there might be a need for diesel generators for some equipment, for example because the power poles on site might not be able to support very high point loads. Most processing operations and mining operations run 24 hours, with only maybe a day or two of downtime per year. They are dependent on constant energy supply without fluctuations. Having an electric infrastructure might thus not always be sufficient to actually enable full electrification.

3.5 Potential of the circular economy to reduce the energy footprint of CRMs

In most cases, secondary supply will only start becoming significant after the demand is stable (2040-2050) (see also presentation of Peng Wang). But in the long run, circularity it is a necessity in for sustainable material supply, and raw material supply from secondary sourcing should be a priority. Recycling rates could be substantially improved by better policies and economic settings. The available data and accounting for recycling for the huge number of alloys is very poor in comparison to the primary data available for mineral resources and mining. It is an area where we need to work out how to get better systematic data to better understand, quantify and model the circular economy. The focus should also be on reuse and remanufacturing. For example, for batteries, instead of consuming a significant amount of energy to extract elements, recovering intermediate parts should have priority.

Instead of targeting recycling of cobalt and losing, for example, graphite and other elements, NMC can directly be recovered from black mass. However, there are hurdles regarding potentially decreased functionality of directly recycled raw materials compared to virgin production, and an evolving composition (for example NMC 1:1:1 versus 8:1:1) – direct recycling only works if the composition of the cathode does not change over time, except for scrap and defects. In case of technological change – for example a shift from NMC to sulfur-based batteries – investments with a high CAPEX can thus be risky in the long term.

It is also emphasized that the time delay for incoming secondary raw materials from stocks has to be filled with primary mining in a way that market reaches a stable level.

3.6 «Energy bottlenecks» in the supply chain

If we look at the question of reducing total energy use in the raw materials sectors, the mass metals Fe, Al, Cu mostly matter at the moment. However, with the energy transition, minor metals get more and more in the focus. While the recycling rates for aluminium – extremely energy intensive in primary sourcing – for example, are high, recycling rates of gallium as a by-product of aluminium mining are close to zero. Niobium and other refractory metals such as steel alloys elements have high end-of-life recycling rates due to steel recycling but very low recovery rate in the remelting processing. The recent energy crisis makes it very difficult to prepare future recycling structures for energy-intensive materials. It may be important to emphasise such an issue to the general audience.

It is important not to only talk about minor metals. While an increase in lithium demand of 1000% is a lot, it is possible for supply to react accordingly. However, to double for example steel production, where we talk about close to 2000 million tons, is going to be extremely difficult. Already a 10% quick increase would require extremely large investments and heavy burdens on the environment. Thus, absolute amounts have to be considered, not only the percentage increases.

The generation of electricity is limited, and the reduction of carbon footprints makes a big shift to solar and wind power energy, but the efficiency is still low. Energy is required in metal mining, refining, and smelting, whereas smelting has the highest energy share. The most pronounced bottleneck is energy transportation from where it is generated to where it is used, especially in case of remote mines. Extracting and processing from ore to the metallic precursor is identified as another bottleneck.

3.7 The role of energy prices

Higher energy price volatility that is expected with higher use of renewable energies and carbon taxes could pose supply bottlenecks for CRMs. We already see huge electricity price changes throughout the day and in dependence of the weather in many European electricity markets. High price volatility may hinder investments even if average energy prices are low.

All mining sites have a business model which is based on a conventional formula, with assumptions of an average day at an average production of metal per month. Even though there might be some variations, the economics of the business model is based around this. But what happens in reality is that the mine can only determine the actual average and associated costs in retrospective on an aggregate mean level. When there are volatilities in terms of the cost of operation, the net revenue decreases. When a mine starts with a high investment, stakeholders do not care about the technical realities, but about cost and revenues. However, there is a difference for the by-product elements. For example, the price of indium by-produced from zinc might vary a lot, but the actual production of indium is dependent on the prices of its base metal. This has to be untangled first before the mechanisms can be fully understood.

3.8 Strategies to reduce energy consumption of raw materials

High performance materials properties are often dependent on extremely rare or critical elements, which include high energy and carbon densities. Each process must be investigated and analyzed for its energy efficiency to determine waste energy or low efficiency. Today's talks showed some new and innovative methods can reduce the energy consumption. Such methods must continue to be developed, applied to other CRMs, and upscaled. For example, the reuse of waste heat (fatal heat) from the smelting process is one way to reduce energy consumption. There are ways to use this also in applications outside mining, such as for heating greenhouses for food production. Renewable energy should be used to process raw materials as well as to recover waste energy from the processing materials. Trade-offs of lower energy consumption could be higher cost and lower quality. Internalization of the environmental cost and green mining innovation could help to limit burden shifting from global CO_2 emissions to local pollution. Overall goals should include using less materials, less energy intensive materials, and increasing recycling (which will only be significant once markets have stabilized). Design for recycling is fundamental. However, the dissipative uses of metals or uses that make metals impossible to recycle are even a bigger problem, for example platinum in road dust from catalysts, or copper from overhead power lines at railroads.

It is important to note that e.g. not all zinc mines do even try to extract indium, or copper mines other by-products. It would be interesting to study how many operations are actually taking care of the by-products, and identify the potentials for further by-product mining.

The largest reduction could be achieved by using less primary materials overall. The faster we mine, the more rapid ore grades decline, and the more expensive energy sources we use.

3.9 Calculating the "energy balance" of raw materials

Using LCA, the energy "costs" of producing critical materials could be allocated based on either proportional mass or value. A cost value could give a better representation as ultimately, society uses financial value to account for things (rightly or wrongly). Another approach is the Energy Returned on Energy Invested (EroEI), which shows that renewable energy technologies are clearly strongly energy positive over their expected life time. As manufacturing gets better and more efficient, and new technologies are commercialized (e.g. new solar panel types, bigger-stronger wind turbines), the energy "returns" will improve even more. Furthermore, it is suggested to move to establish an exergy-based metric where there is a unit that includes some form of equity, which is embedded energy in context of its reference environment. If we can get to something like that, all operations can be brought on to a level playing field from mining to recycling. Thus, the opportunity to compare processes against each other is provided. Furthermore, when there are availability problems with energy – as fossil fuels are stepping out and renewables are not coming in fast enough – we have a useful metric for planning. LCA could be integrated directly or via primary energy demand. Material needs for low-carbon developments and LCA should be connected, and it should be discussed how this can be used to complement criticality assessments. However, many LCAs in the context of energy transition assume that electricity will (one day) be 100% renewable and carbon free. Yet, this is not the case today, and even in the future it is all to be understood and proven, so guidance to LCA practitioners should be given on how to model this, for example, by scenario-based ex-ante LCAs using Shared Socioeconomic Pathways (SSP) based energy mixes.

More parametrized and generic datasets for different geologies, processing steps and technologies are needed; a sort of modular LCA dataset for different metal production routes with factors and parameters in the background. International standards such as the carbon footprints could be applied, also to see how recycled materials can minimize this footprint. The EU should consider to add scores on how much energy is saved by CRM recycling/reuse as compared with standard mining. Customers could then refer to such scores listed on electrical appliance etc. However, the data basis is still insufficient to provide comprehensive information on this.

To conclude, it is stressed that it is important to note that many countries have pledged net zero by 2050 but do not even yet have concrete policies for implementation until 2030. Current policy targets are far from what is needed to implement what we have agreed on. Government must make strong commitments and establish concrete policies which push companies to invest more in the decarbonization of mining sectors. This will make companies more confident that GHG emissions in countries with these policies will decrease in the coming years, and will provide incentives to reduce the footprints of the materials needed for the energy transition.

4 Next steps

IRTC will continue to work on this topic: what has to be taken into account for calculating the energy balance of raw materials, and how can it can be managed so that we can reach the sustainability goals we have agreed on? If there are concrete ideas for further research on this topic within the IRTC framework, please send an e-mail.

On April 2022 is the official launch of the next IRTC series, called IRTC-Training. The 3-years project, funded by EIT RawMaterials, will again be supported by a broad international network of experts in criticality from academia and industry. It will establish trainings on raw materials risk management for professionals and an annual conference, the first of which will take place in Lille, France, on February 17-19.

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