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The role of critical materials for the energy transition

Challenges and opportunities

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The role of critical materials for the energy transition

Challenges and opportunities

This report summarizes current concerns from experts on increasing risks in the international supply of critical materials for the energy transition, discusses potential implications, challenges and opportunities and makes recommendations for Switzerland.

Table of contents

Key messages

1. Switzerland is strongly dependent on imports

- The strong scaling up of technologies (photovoltaics, electric cars batteries, heat pumps, etc.) leads to increasing concerns about the availability of materials that are of high importance to the clean energy transition and whose supply is at the same time associated with a high risk (e.g. lithium, cobalt, nickel) (chap. 1.1). The rapidly increasing demand of such 'critical' minerals and materials might lead to shortages, also of semi-finished and end products, and increasing costs. This could affect the costs for Swiss companies developing technologies and manufacturing end-products (chap. 2.2).

Recommendation

→ Create a more specific overview on needs with regard to critical minerals.

- Supply risks of future clean energy systems are different from those of current fossil-based systems: the continuous import of fossil fuels is required for the operation of systems and a sudden shortage would quickly have a massive impact on the economy. In contrast, a one-year supply stop for PV modules, for example, would only affect the replacement or expansion of a few per cent of facilities. The shift from a fossil based to a renewable energy system leads to a strong decrease of the overall supply risk for fuel but an increase of supply risks for construction of electricity power installations (chap. 1.3).

Recommendation

→ Reduce demand: diversify technology mix; recovery of raw materials; support product sharing and reuse; prevent planned obsolescence; prevent and avoid waste; sufficiency.

2. Risks of dependence are rather geopolitical than physical

- Supply risks are not primarily induced by global physical scarcity but rather by geopolitical aspects and risks along the supply chain (chap. 1.1). A major geopolitical issue is that both the extraction of raw materials and the processing of these materials tend to be concentrated in a small number of countries. In particular China dominates in many markets, especially for rare earths where it controls most of the supply chain. The EU is completely reliant on imports from China for its solar photovoltaic needs. EU produces only 4% of raw minerals and 12% of processed materials of global PV production and only 2% of raw minerals and 4% of processed materials of global lithium-ion batteries production (chap. 1.2)
- Switzerland depends strongly on import and for the major part these are components or end-products: in 2021 Switzerland imported components for solar energy at 57% from Europe (Germany 22%, Netherlands 18%) and at 38% from China. However, components imported from EU depend themselves on imported materials from China which still makes China a major factor in the supply chain. Wind motors and towers were imported at 48% from Turkey, 30% from Germany and 17% from Italy (chap. 2.1). For Switzerland, due to the focus on PV and electrification of cars, dependances with regard to PV and batteries are more important than those for wind, where the demand is lower and supply is more diverse.

3. Trade and international cooperation are important

- Switzerland plays an important role in trading of commodities and therefore has a facilitated access to corresponding trading platforms. However, the rising awareness and concerns on environmental, social, governance and health challenges of mining activities might direct public attention on the Swiss commodity trading sector and lead to increasing reputation risks for the sector (chap. 2.2).
- Rather than direct access to critical materials, the well-functioning of trade markets and, in the long-term, access to second-life components and materials is essential for the Swiss industry (chap. 2.2).

Recommendation

→ Work together with EU along the entire supply chain; establish secure and sustainable supply chains for Switzerland.

4. Be aware of social consequences of mining

- Largely rising demand of minerals and the extension of corresponding mining leads to social, health and environ-mental issues like GHG emissions, waste, water and soil contamination with corresponding health effects, which should be closely observed. One of the central social issues are states handing out licenses for mining to private companies and thus undermining local land rights. This leads to the destruction of long-term livelihood systems and cultural landscapes, to health problems and to the impoverishment of local communities (chap. 1.4).

Recommendation

→ Support the establishment of and compliance with environmental, social and health standards in mining (and recycling).

5. Technology development and research is needed

- Supply risks can be alleviated by technological innovation reducing material intensity for components for the energy transition (substitution, design optimisation, introduction of new materials, extending lifetime of products) and demand reduction for utilisation as for example reducing size and/or weight of electric cars or car sharing (chap. 1.5).
- Switzerland and its industry and research have a high potential for technological development regarding new/innovative circular processes, recycling minerals and reducing material intensity (chap. 2.3).

Recommendation

→ Promote research/innovation to replace critical minerals; establish recycling infrastructures/chains.

1 Global considerations

1.1 1. Introduction: Concerns about international supply of critical materials

Many countries, including the U.S., EU states, China and India have announced ambitious targets of net-zero emissions by mid-century to meet the Paris 2015 Climate Change Agreement. As part of the Energy Strategy and the Climate and Innovation Act Switzerland has set a similar goal of net zero greenhouse gas emissions by 2050. Aiming at these targets implies an important transformation of current energy systems replacing carbon-based fossil fuels by low CO_2 emissions renewable energy sources. In a global net zero emissions scenario, sales of electric cars would need to account for two-thirds of new car sales by 2030 and global renewable power capacity increases threefold between 2022 and 2030 (IEA 2023b). Scaling up these technologies also implies an increasing demand for transmission and distribution lines in electricity networks and for batteries to store energy.

There are increasing concerns about the availability of materials that are critical or of high importance to the clean energy transition and whose supply is at the same time associated with a high risk (European Commission 2023b, DOE 2023). The European Union classifies in particular gallium, magnesium, rare earth elements,[1] lithium, germanium, cobalt, silicon metal, nickel and copper as critical to meet future demand for the renewable energy and e-mobility sectors (European Commission 2023b). Renewable energy technologies, such as wind and solar energy, require significant quantities of critical materials such as rare-earths elements for permanent magnets and silicon metal for the manufacturing of solar PV thin film modules in particular. EV batteries also require large amounts of lithium, manganese and cobalt. Finally, copper and aluminum are used in important quantities to manufacture electricity transmission lines.

1 Rare earth elements refer to the 17 chemical elements of the 3rd subgroup of the periodic table. These are metals which, with one exception (promethium), are not that rare in the earth's crust or (in the case of cerium, yttrium and neodymium) are even more common than lead or copper, for example. However, larger economically exploitable deposits are rare.

Material supply chain

(European Commission 2023b)

The supply of critical materials is characterized by various steps:

- **Raw Materials:** Extracted, processed and refined raw minerals. Processing operations serve to separate, smelt, refine and purify mined mineral substances
- **Processed materials:** Semi-finished (e.g. metal alloy) products consisting of a combination of several materials (e.g. alloys)
- **Components:** Manufactured small building blocks of a technology (e.g. permanent magnets)
- **(Super)Assemblies:** Set of components put together (e.g. assembled electric motors)

Supply risks are usually not induced by global physical scarcity – mineral reserves are a dynamic concept that depends on exploration, technologies and economic viability (Meinert et al. 2016) – but rather by geopolitical aspects and risks along the supply chain (see Box) making it difficult to ramp up the supply at the required speed and scale to meet the demand.

1.2 Concentration of mining and processing in a few countries

A major geopolitical issue is that both the extraction of raw materials and the processing of these materials tend to be concentrated in a small number of countries with a particular dominance of China in many markets (Leruth et al. 2022, Cool et al. 2020), see Figure 1. The domination of China is particularly important in the market for rare earths, where it controls most of the supply chain. China mines about 60% of the world's rare earth supply and owns almost all refining facilities (USGS 2019). China's key role in critical materials is the result of strategic efforts over the last decades to capture the entire supply chain, using industrial policies and investments in mining projects abroad. In addition, the US stopped most of its rare earth elements mining activities already decades ago although they have substantial resources. While Australia and Chile are responsible for 70% of lithium production, Chinese state-owned companies control a third of the total market (due to monopolistic spodumene refining capacities and Li carbonate to Li hydroxide capacities). The Democratic Republic of Congo produces

Figure 1: Countries accounting for the largest share of global supply of critical materials. Source: European Commission 2023a

almost 70% of global cobalt, but most firms operating cobalt mines – apart from Glencore – are incorporated in China, as the country has actively sought to obtain exclusive mining rights in several African countries as part of the Belt and Road Initiative (Leruth et al. 2022). Finally, Russia is also a key player in the supply of critical materials as it contributes to about 10% of global nickel supply (including 20% of world supply of class I Nickel required for battery production). The recent Russian's invasion of Ukraine has sparked concerns about supply disruptions due to trade and economic sanctions.

Countries with a large demand and sizeable imports of critical materials to feed their clean energy industry are thus largely dependent on a small group of suppliers. The EU is for instance completely reliant on imports from China for its solar photovoltaic needs. Figure 2 shows the steps of the solar PV supply chain: the EU produces only 4% of raw minerals and 12% of processed materials of global production. The situation is worse for lithium-ion batteries, where the EU produces only 2% of raw minerals and 4% of processed materials in global production.

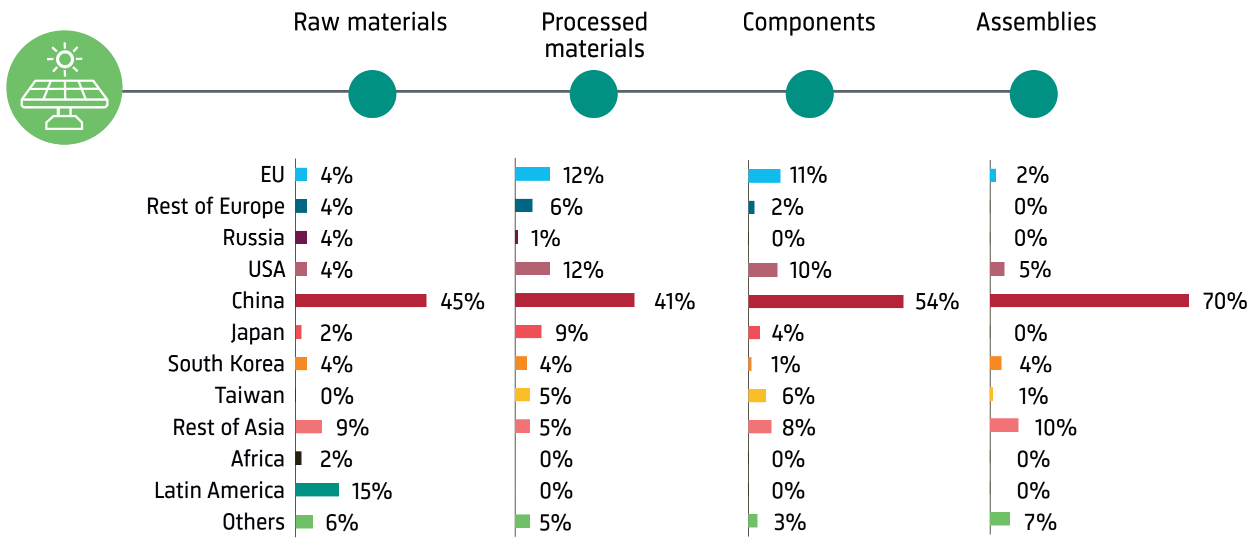

Figure 2: Supply concentration and key players along the supply chain of EU solar PV. Shares indicate average share of each country in global production at each supply-chain stage. Source: European Commission 2023b

Price increases and volatility due to supply restrictions may reverse cost-reduction gains in clean technologies achieved over the last decade and thereby threaten the affordability of the energy transition. While cathode materials (cobalt, nickel and manganese) accounted for less than 5% of battery pack costs around 2015, they now represent 20% of costs. There is evidence that prices of solar PV and lithium-ion batteries have increased between 2020 and 2021 (IEA 2023a) and between 2021 and 2022 (Goldmann Sachs 2023), respectively, after a decade of declining prices. It remains to be seen whether these are only short-term fluctuations, due to current material scarcity or supply chain disruptions still affected by the COVID pandemic, or longer-term trends. Moreover, the economic drivers for mining of some critical raw minerals are in many cases not the minerals itself, but they are byproducts of mining of other commodities. Thus, supply and prices might not necessarily follow their demand.

1.3 Change of supply risks

Supply risks for future clean energy systems are different to those of current fossil-based energy systems: those of fossil systems mainly concern the fuel, which must be constantly supplied to operate an installation, while critical materials are only needed for the construction of installations and these can be operated without further supply of materials (except maybe in case of a damage). Thus, while a sudden shortage of fossil fuels would have an immediate massive impact on the economy (with some possible relief from compulsory stocks of oil products), a supply stop of for example PV modules for one year would 'only' affect the replacement or expansion of a few per cent of the total volume of installations (which have a lifespan of 25 years) and would not threaten production from stocks. Electric cars are imported as a whole and would only have a problem in case of a 'blackout', while gasoline and diesel vehicles would be directly affected by any import ban.

Clean energy systems in general tend to be more mineral-intensive, as clean electricity requires more minerals per kilowatt than fossil-based electricity. The production of an electric car requires also more than 200 kg of minerals per vehicle (among which copper, nickel, lithium, manganese, graphite) compared to 35 kg for a conventional car (mostly copper and manganese) (IEA 2022a). Regarding geopolitical risks, mineral markets are often quite small and the level of concentration is higher than in fossil fuel markets. Compared to oil and gas extraction sites, mineral mines tend to be more concentrated in developing countries with high political risks, due to important reservoirs and also due to lower social opposition – or lacking political consequences of such oppositions – to the opening of mines in these countries. On the other side, the scale of mining activities required for the clean energy transition may end up being less extensive than for fossil-fuels, in particular as minerals have the capacity to be recycled (Nijnens et al. 2023).

To mitigate these risks and future supply disruptions, several countries have started to implement policies to diversify their supply chains. In November 2023 the EU has reached an agreement on the EU Critical Raw Mineral Act which enters into force in 2024. It aims to secure the supply of strategic raw materials (strategic raw materials include aluminum and synthetic graphite) by increasing the 'domestic capacity' of extraction in the EU to cover at least 10% of the EU's annual consumption of strategic raw minerals, increasing processing capacity to cover 40% of EU annual consumption and increasing its recycling capacity to cover at least 25% of the EU's annual consumption. Moreover, imports shall be diversified so that no countries provide more than 65% of EU annual consumption by 2030 (European Commission 2023d). In the US, the Inflation Reduction Act provides tax deductions to electric car and battery manufacturers at the condition that they use a large share of critical materials that is sourced from the US or a country sharing a trade agreement with the US. South Korea has defined strategic minerals for nationally relevant sectors (engines, batteries, semiconductors).

1.4 Adverse impacts of mining on local environment

Additional exploration and mining activities in advanced economies or their trade partners could contribute to raise and diversify the supply of critical minerals. Yet, exploration and extraction are limited by the need to address the environmental and social concerns raised by mining activities. There is mounting evidence on the adverse impacts of mining on the local environment. The extraction of minerals is associated with various environmental issues such as air pollution, local contamination by toxic chemicals, landscape disruption, biodiversity loss and waste generation (Sengupta 2021). Although minerals for renewable energy production or for battery production represent only a fraction of total mining (including fossil extraction) and the transition to renewables will reduce mining activities overall (Krane and Idel 2021, Nijnens et al. 2016), its largely rising demand leads to the extension of corresponding mining. Related social, health and environmental issues should therefore be closely looked at.

The excavation, grinding of ore and transport of material by large diesel trucks is land-, energy- and emissions-intensive, and mining waste and tailings may cause contamination of local water and soil – leading to adverse health effects for exposed population. In addition, mining activities are associated with a host of negative social and governance impacts with severe implications for the livelihoods of communities in the vicinity of mines, including displacement of local population, violation of human rights and contribution to armed conflicts. One of the central problems are colonial and postcolonial legacies of the extractive industries by which local land rights, often common property, have been undermined by states handing out licenses for mining to private companies. This form of commons grabbing often leads not just to pollution, but also to the destruction of local long-term livelihood systems and cultural landscapes with high biodiversity, to health problems and to the impoverishment of local communities (Niederberger et al 2016, Haller 2019, Haller et al (eds.) 2020, Sternberg et al 2022). Corporate social responsibility (CSR) measures are neither sufficient to cover the long term losses nor usually set up in a participatory way (Niederberger et al. 2016, Dolan and Rajak 2022).

Extended mining for green energy production thus entails the danger to further exacerbate the grabbing process with the justification of sustainable and green energy transition and the Sustainable Development Goals (Larsen et al. 2022). Hence aligning the extraction of minerals with energy transition goals will require a profound transformation of production practices by developing clean mining technologies, improving indicators for the traceability of mining and extractive activities and including local communities in decision processes. In many producing countries, data to assess environmental, social and governance impacts are still limited, not standardized or non-existing. The introduction of some kind of a digital product passport could be an option to address this problem. The battery regulation that entered into force in 2023 (European Commission 2023c) is a step in that direction. The IEA's Critical Minerals Policy Tracker (IEA 2022b) tries to provide information on policy developments and ESG (Environmental, Social and Governance) concerns, in addition to working with governments and other stakeholders to develop new policy guidance to reduce the negative impacts of minerals production (IEA 2023c)

1.5 Mitigation of supply risks

Next to opening and regulating mines, technological innovation could greatly contribute to alleviate supply risks by reducing the material intensity of components. Technological substitution, efficiency improvement, design optimisation, the introduction of new materials, or extending the lifetime of products may affect the demand for critical minerals and materials. For instance since 2015, shifts in EV battery chemistry including a higher proportion of lithium ferrophosphate (LFP) have significantly reduced reliance on cobalt and nickel (EERA 2023). The recycling of end-of-life products can improve the future availability of critical materials, although there are still questions about the economic viability of recycling compared to extraction. Introducing mandatory information on environmental footprints of materials could be one route to make recycling more competitive. Moreover, in a world of rapidly growing demand and considering the life-time of cars (10–20 years), wind and PV power-plants (20–30 years) recycling can only marginally contribute to the supply in the short to medium term (Liang et al. 2023), but it is all the more important to set up functioning systems now for the long-term.

Last but not least, supply risks can be reduced by demand reduction for materials for energy using technologies like electric cars by e.g. reducing car size and/or weight or car sharing.

2 Challenges and opportunities for Switzerland

2.1 Challenges for Switzerland

Although Switzerland is a country rich in raw materials, this mainly concerns the construction sector (gravel, sand, etc.). Concerning critical minerals (metals such as cobalt, lithium or rare earths) Switzerland depends mainly on import, often in the form of pre-processed products and semi-finished goods. However, Switzerland plays an important role in trading of commodities (chap. 2.2) and therefore has a facilitated access to corresponding trading platforms. While Switzerland plays an important role worldwide in processing raw gold and trading refined gold and products, this is not the case for other critical minerals. Here Switzerland needs to import either refined material for its companies that develop technologies and manufacture end products (e.g. Gurit, Meyer Burger, ABB) or it imports end products. Rather than direct access to critical materials, the well-functioning of trade markets is essential for the Swiss industry.

Origin of imports in Switzerland
Switzerland only imports a small quantity of raw rare earths but a majority of these (57%) come nowadays from Asia. As of 2021, 26% of rare earths imported in Switzerland come from China, 26% from India and 10% from Indonesia. Europe accounts for 34% of Swiss imports (mostly Germany, France and Austria). The share of Asia has been multiplied by 3 over the last decade since in 2010, Europe represented 73% of Swiss imports, while Asia only accounted for 19%. [2]

A 2016 survey of Swiss firms in the sector of machinery, electric equipment and metals indicated that 20% of firms used rare earths, next to chrome (74%), molybdenum (69%), magnesium (60%), tungsten (57%) and graphite (53%), mainly via indirect provision of intermediary goods given that Swiss companies are situated at the end of the supply chain (Federal Council 2018).

Permanent magnets are a downstream product of rare earths used by Swiss companies. Magnets are used in industrial robots, clocks and watches but also in wind turbines. International trade data show that Asia now accounts for 87% of Swiss imports in permanent magnets (China and Malaysia representing 36 and 47% of imports respectively) compared to 68% in 2010. Over the last decade, the share of Europe in Swiss imports of permanent magnets dropped from 31% to 11% today.

The acceleration of the clean energy transition may raise new challenges. While in the early phase of development of solar energy use Swiss Companies were among the leaders in the world, Switzerland has lost this position and has – like the other European countries – to import most of the end products, although there are still a number of rather small firms producing the panels themselves. The share of solar energy used in Swiss energy consumption is rising very fast (from 3% in 2019 to 6.6% in 2022 and 10% in 2023; BFE 2023) and market growth has multiplied by 6 since 2017 (Swisssolar 2024). Demand will thus continue to grow and imports will largely contribute to the future Swiss solar installed capacity.

As of 2021, components and machinery for solar energy are imported at 38% from China, 22% from Germany and 18% from the Netherlands, while these shares were of 15%, 46% and 7% in 2010. For now, Europe is still the major source of solar components for Switzerland (57%), before Asia (42%), see Figure 3. However, components imported from EU depend themselves on imported materials from China and therefore in the supply chain there is still a major dependance on China. The EU Critical Mineral Act to secure the supply of critical and strategic materials (chap. 1.3), which will enter into force in 2024, might reduce this indirect dependance in the future.

Regarding wind motors and towers, Switzerland imported a majority (51%) of these components from Asia in 2021 (Turkey accounting for 48%, China for 1%, Japan and Vietnam each for 0.4% of imports), the rest being imported from Europe (at 49% – mostly from Germany at 30% and Italy, 17%), see Figure 3. However, for Switzerland, due to the focus on PV and electrification of cars, dependances with regard to PV and batteries are more important than those for wind, where the demand is lower and supply is more diverse.

Shortages, prices and policies
The rapidly increasing demand of critical minerals and materials might lead to shortages worldwide and lead to supply shortage of materials, semi-finished and end products and increasing costs that were not sufficiently anticipated. This could affect the costs for Swiss companies developing technologies and manufacturing end

2 Trade statistics in this section are extracted from the BACI dataset on bilateral trade flows (Gaulier and Zignago 2010) at the product level identified using the Harmonized System (HS 2007 Revision). The percentages are computed using quantity shares of each source country in total Swiss imports (reporting country: Switzerland). The HS codes used for 1) rare earths and permanent magnets are extracted from Mancheri (2015, 2016), 2) for wind energy are borrowed from Subramaniam (2019) and 3) solar energy are extracted from WTO (2022). We thank Ayse Nihal Yilmaz for excellent research assistance on working with the BACI dataset.

Figure 3: Countries from which in 2021 a significant proportion of imports to Switzerland originate for: rare earth elements, permanent magnets and wind power plant motors and towers (which are all components of wind power plants) as well as for PV components. Source: BACI dataset on bilateral trade flows.[2]

products as well as for the energy transition in general and may slow down the transition and therefore decarbonisation of the energy sector. Moreover, due to experiences during the pandemic, recently increasing conflicts and political uncertainties, security of supply has gained much attention and leads to the increasing efforts to enhance manufacturing end products in the own country or at least in Europe. This and increasing efforts to reduce environmental and social impacts of mining might further increase the costs of the energy transition. However, the increasing demand and the desire to reduce costs will be opposed to the request of improving environmental and social standards of mining.

On the political side, additional challenges might be that in Switzerland traditionally there are only few industrial policies to steer securitization measures. Concerning foreign policy, current strategies around the world to negotiate bilateral agreements or even build large networks of commodity rich states via economic diplomacy to be able to absorb international shocks and manage risks of shortage might increase the pressure to 'pick sides' and partly question the traditional policy of neutrality.

2.2 Role of the Swiss commodity trading sector

The commodity trading sector is an important economic sector in Switzerland since it represents 8% of Swiss GDP. In 2020 about 900 companies were active in the sector. It is the largest trading hub for commodities in general. About 60% of the international trade in base metals like zinc, copper and aluminium (Swiss Academy of Sciences 2016) is traded in Switzerland. There are a number of Swiss companies (Glencore, Mercuria, Trafigura among others) that mine, process, ship, and sell metals. Glencore accounts for 19% of the global production of cobalt, 6% of copper, 4% of nickel (Leruth et al. 2022).

Due to this high share of Switzerland in the trading sector, the rising awareness and concerns on environmental, social and health challenges of mining activities will direct public attention on the role of the Swiss commodity trading sector (WRF/MRF 2023). This will create increasing reputation risks for the sector. Switzerland is engaging in improving ESG activities at the multilateral level, and continues to advocate better environmental sovereignty for raw materials. In 2022, Switzerland played a central role in the adoption of the UN resolution on environmental aspects of raw materials which encourages member states and stakeholder groups to align their practices and investments in the mining sector with the 2030 Agenda. On the national level an obligation has been introduced recently to report on the one hand on environmental concerns, working conditions and respect of human rights for large companies and financial institutions, and on the other hand on specific due diligence and reporting obligations in the area of so-called conflict minerals and on combating child labor (Federal Council 2023). But more stringent regulations (Responsible Business Initiative) were rejected in a very tight vote in November 2020 by the Swiss population, i.e. accepted by the entirety of voters but rejected by the majority of cantons. Since 2024, however, reporting requirements on climate risks have been implemented in Switzerland for public companies, banks and insurance companies with 500 or more employees and at least CHF 20 million in total assets or more than CHF 40 million in turnover. Similar discussions are going on in the EU (e.g. European Commission 2022) and the US. Such disclosure policies contribute to steering the financial sector to invest into cleaner practices and technologies helping to maintain secure and sustainable supply chains.

2.3 Opportunities for circularity and technological innovation

Resource scarcity also can drive innovation, as the example of Japan showing high progress in substituting and recycling rare earths after the Rare Earth Crisis. Although being a small country, Switzerland and its industry and research have a high potential for technological development regarding new and innovative circular processes, including the recycling of critical materials from batteries or solar panels, and could build corresponding plants. Switzerland already has a strong record of recycling e-waste, which is ensured by corresponding take-back and recovery regulations. These activities could be further strengthened with more focus on strategic commodities and especially (critical) metals for which processing facilities are missing in Switzerland (CSS 2023). This could be done for example by assuring that the up-scaling of new recycling plants and installations apply the best solutions with regard to extract critical minerals by supporting development and using for example technical standards like ISO-Norms (ISO/DIS 2023).

Additional important innovation goals are to lower the mineral intensity of new energy technologies and diversify the range of technologies with regard to the metals and minerals they use. At the same time new technologies should try to reduce the environmental footprint of the extractive activities for example by water and energy saving. The establishment of databases or labels concerning the toxicity and other ecological footprints might help to promote such efforts.

All these activities can reduce the import dependence. However, another very important aspect in this sense is waste prevention and avoidance, respectively, which is the most effective way of reducing energy demand for and environmental impacts of mining, use and recycling of materials. This also includes demand reduction and sufficiency.

3 Recommendations

3.1 Policy options and final recommendations

First, we have to recognise that the supply of critical minerals as well as the energy transition as a whole are global challenges. That means that even if Switzerland, the EU or the US can secure supply e.g. through bilateral or multilateral agreements, the necessary global decarbonisation of the energy system does not work in case of a global general shortage of critical minerals. Thus, in parallel to strategies and efforts to secure national supply, the focus on developing new technologies to boost efficiency in production, advance recycling and increase the diversity and substitutability of materials will be of key importance.

Second, it seems that efforts in recycling and efficiency will not be able to compensate for the expected rapid increase in demand for renewable energy installations, electric cars, batteries and other clean energy technologies (Liang et al. 2023). This means that a worldwide expansion of mining and production of certain materials will be very likely, especially in the short and medium term, while mining of fossil resources is intended to decrease. In the longer term, innovations in substitute and alternative technologies could alleviate demand.

Third, the rapidly increasing demand together with declining ore grades for cobalt, lithium and graphite will lead to increasing energy consumption for mining and purification and, in combination with likely shortages of supply, to significant price increases. Due to the increasing pressure on supply chains there is a high risk that environmental and social aspects of mining might move into the background, except of more mining taking place in EU and other countries with high standards and controlling. It is nonetheless important to include these aspects when developing strategies to secure supply.

To deal with expectable challenges in critical mineral supply chains, we recommend the following possible fields of action:

– Reduce demand:
  · Promote research and innovation to replace critical elements in technologies for the energy transition (e.g., batteries, PV, wind turbines, electrolysers, catalysts, etc.) by abundant elements or to reduce the required amounts while still achieving the same or even better performance;
  · Diversify technology mix in the country not to over-rely on specific materials;
  · Establish recycling infrastructures and chains
  · Develop a strategy to enhance longevity: prevent planned obsolescence, promote an extended use of ICT products and compatibility of different components;
  · Support social innovation (e.g. sharing and reuse of products);
  · Enhance waste prevention and avoidance;
  · Be aware of rebound effects.

– Work together with EU and/or internationally on innovations along the entire supply chain.

– Create a more specific overview on what critical minerals, materials, products Switzerland needs for the anticipated energy transition, their origin and their corresponding social and environmental costs. Identify 'hot spots' for specific raw materials with high negative ecological, social and economic impacts.

– Establish secure and sustainable supply chains for Switzerland, taking into account European strategies and international cooperation as well as and considering that Switzerland is more likely to import readily made technologies rather than raw materials themselves. This means for example:
  · Choose reliable suppliers and countries for supply agreements;
  · Support or choose mining, processing and production in Europe for higher supply security
  · Evaluate need or possibilities, respectively for support of Swiss industries taking into account the heavy governmental subsidization as in China and US.

– Support the establishment and compliance of environmental, social and health standards in mining:
  · Ensure that mining and technology companies track progress, possibly introducing some labelling or certification including transparent communication, on socioeconomic and environmental conditions

along the whole supply chain e.g. through digital product passports or following transparency requirements of the EU regarding social, health and environment issues.
- Promote best practice and high standards in mine development through the Swiss trading industry.
- Encourage traders to develop financial products taking ESG specifications into account and to draw on their capital to provide finance for (cleaner) mining operations.

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