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Critical materials as key factor providing efficiency in energy engineering

DUMITRA LUCAN[1,2*], CLAUDIA SAMARINEANU[1], GHEORGHIȚA JINESCU[2,3]

[1]Institute for Nuclear Research, Campului no.1, Mioveni, POB 78, Arges, Romania
[2]Technical Sciences Academy of Romania ASTR, Dacia Avenue no.26, Bucharest, Romania
[3]Politehnica University of Bucharest, Polizu Street no. 1-7, Bucharest, Romania

Abstract. The energy transition should be planned with critical materials in mind to avoid unforeseen delays. This planning relates to both supply and demand aspects. Better public data are needed regarding the capacity to ramp up mining of primary materials in the coming years. Also, the potential of innovation to avoid or minimise use of critical materials needs to be better understood.
This paper will assess how the growth of different types of energy (including nuclear) will put critical materials at the centre of the energy transformation at the international level, with the objective of highlighting the criticalities related to the sector and of identifying how technological developments and innovation can positively reduce geopolitical risks. For Europe's ambition to deliver the Green Deal the access to resources is a strategic security question. The EU's open strategic autonomy in these sectors will therefore need to continue to be anchored in diversified and undistorted access to global markets for raw materials. The paper also presents a case study of the exploitation of Romania natural resources.

Keywords: critical materials, energy engineering, performance, efficiency, effectiveness, natural resources

1. Introduction

Efficiency is an input and transformation process question, defined as the ratio between resources expected to be consumed and actually consumed. *Effectiveness*, which involves doing the right things, at the right time, with the right quality etc., can be defined as the ratio between actual output and expected output, Fig. 1 [1].

*Correspondence address: dumitra.lucan@nuclear.ro

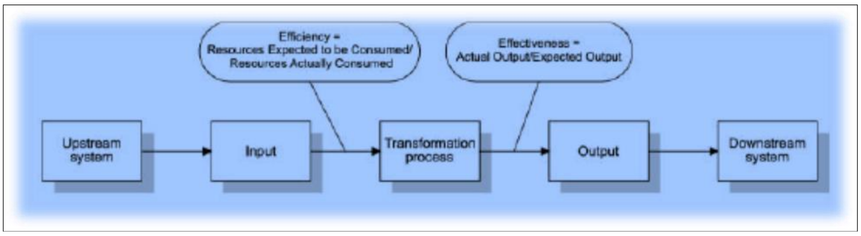

Fig. 1. Efficiency and effectiveness.

The energy should be safe, clean, cheap and efficient and that means performance. Performance is the umbrella term of excellence and includes profitability and productivity as well as other non-cost factors such as quality, speed, delivery and flexibility, Fig.2 [2].

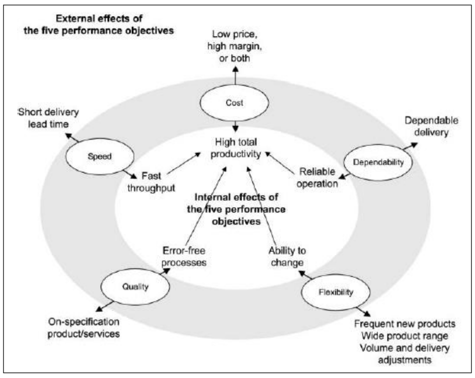

Fig. 2. Performance objectives.

A schematic view of how common terms within this field might be used is illustrated by the triple-P model, Fig.3 [3].

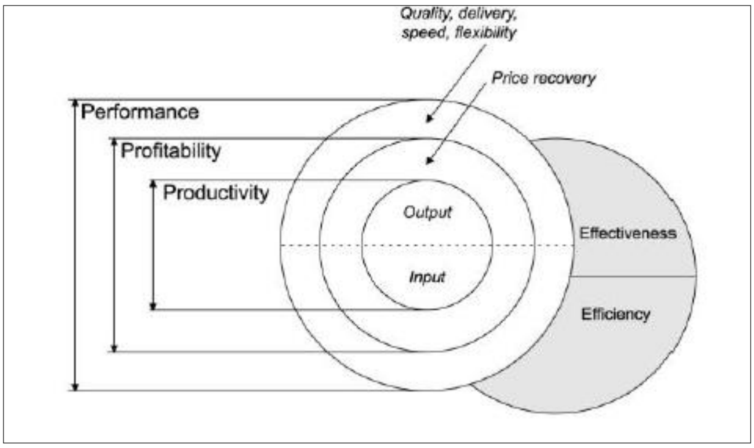

Fig. 3. The Triple P model.

The two terms *effectiveness* and *efficiency* are somewhat cross-functional when it comes to the other three terms (*Performance, Profitability, Productivity*). *Effectiveness* represents the degree to which desired results are achieved and *efficiency* represents how well the resources of the transformation process are utilized.
Clean electricity plays a central role in the energy transition, and we need to make the switch as soon as possible. Electricity must become the main source of final energy and the main feedstock for clean energy carriers such as hydrogen.
The world needs an energy transition. This transition will be based on three main pillars: renewable energy supply, electrification of end use and efficient use of energy. It will entail a fundamental shift in power generation, where the share of solar and wind power needs to increase substantially. Such a transition is daunting. One strand of critique regarding the feasibility of such a transition relates to the availability of the necessary minerals and metals: the future access to those *critical materials*, the ability to ramp up the materials supply and production fast enough, the rising cost of such materials, and the geopolitical and strategic implications of new resource dependencies. Some even talk of a possible "cold war" over critical materials. Demand for materials may also grow due to other aspects of energy transition. This paper will assess how the growth of renewables will put critical materials at the centre of the energy transformation, with the objective of highlighting the criticalities related to the sector and of identifying how technological developments and innovation can positively reduce geopolitical risks, [4]÷[10].

2. What are critical materials?

There is the question of what determines criticality. Generally, attention has focused on minerals and metals that require a significant extraction effort, where the production is concentrated in a few countries, where the quality of natural resources is declining, where a massive ramp-up of supply will be needed and where prices have shown large fluctuations that reflect supply-demand imbalances.
Certain materials have been used in growing quantities for decades or centuries, and their growing supply does not face constraints. For example, steel and concrete are generally not considered to be critical materials, despite recent concerns regarding sand and gravel availability for concrete in parts of the world.
Also, aluminium is not considered to be critical, despite a need for a massive ramp-up of supply: the resource is in place and widely distributed.
A review of recent literature suggests there is little consensus on what materials are critical. But some materials are included in most assessment studies, and those are the focus of this paper: cobalt, copper, nickel, lithium, rare earth metals, notably neodymium and dysprosium.
A much longer list of critical materials is given in one or more of these studies: aluminium, chromium, gallium, germanium, graphite, indium, iron, lanthanum, lead, manganese, molybdenum, platinum, rhenium, ruthenium, scandium, silver,

vanadium, tantalum, titanium, yttrium and zinc. For the sake of this paper, they will not be discussed in more detail. But their listing points to the fact that the definition of "critical material" is somewhat fluid and that new developments can change the critical materials list [11].

Metals dominate the list. This is not surprising, as metals dominate the periodic table of elements. But not all critical materials are metals (e.g. graphite). *The term "critical materials" refers to the processed output; sometimes the term "minerals" is also used, which refers to the mined commodities. For the sake of this paper, we will use the term "critical materials".* For some of the critical materials, the field of applications is limited. In other cases, the application is rather pervasive. For example, demand for lithium, cobalt and nickel is closely related to demand for lithium-ion batteries. Demand for neodymium and dysprosium is closely related to the use of permanent magnets in electric motors and generators. However, copper is used in all three fields of application: in renewable power generation, in power grids and in electric end use applications such as EVs.

3. Strategies to mitigate critical materials dependencies

A number of strategies exist to reduce supply risks related to critical materials. These strategies are well known from circular economy concepts and industrial ecology [11], [12].

• ***Ramp up supply and ensure a global free market.*** A market that has sufficient depth without dominant parties on the supply and demand side can prevent disruptions. Diversifying supply thus reduces dependence on one or a few dominant suppliers. However, this is easier said than done. Large-scale mining projects often take years to develop, and a successful outcome is not guaranteed. The interests of national governments that hold resources, the local interests and the project developer's interests often do not coincide, and dialogue is essential to find mutually agreeable solutions.

• ***Develop national supply.*** This may come at a certain cost, as such supply may be more expensive due to the resource being of lesser quality or the scale of mining operations being smaller. In a free market, such a solution cannot be forced; it likely requires government intervention in the market and some form of standards and certification, as well as market regulation, to ensure uptake. The experience with global supply chain disruptions caused by COVID-19 has emphasised the vulnerabilities that come with dependency.

• ***Substitute critical materials with other less critical materials.*** This strategy has been deployed, for example, in the case of battery cathode design. Often, there is a trade-off between technical performance and the criticality of materials supply. Equipment suppliers will respond to criticality with adjustments in their product design. However, such adjustments may take time as production lines and supply chains need to be adjusted. A structured inclusion of materials criticality in energy transition decision-making processes can help avoid problems in the future.

• ***Develop stockpiles and long-term supply contracts for critical materials.*** Physical stockpiles and contractual arrangements can help prevent sudden disruptions. Enterprises are used to hedge commodity price disruptions. Governments hold strategic oil and gas reserves; they could extend this approach to hold strategic reserves of critical materials. However, such reserves are suited to disruptions on a scale of months; they are not a solution for longer term structural issues. It should also be noted that some countries such as the United States had strategic materials stockpiles in the past.

• ***Raise the efficiency of materials use.*** For example, efforts are ongoing to reduce the rare earth element content of permanent magnets through enhancements in the production process. Also, the silver content of solar photovoltaic (PV) has significant room for improvements in materials efficiency. Normally, suppliers will seek such solutions as they also help reduce manufacturing costs, but greater public and private research, design and development efforts can help accelerate such efficiency gains.

4. Critical raw materials for renewable technologies in the EU

The transition towards a low-carbon society will come with a large-scale deployment of renewable technologies such as wind and solar PV. By 2050, more than 80% of electricity produced in the EU is expected to come from renewable energy sources, with electricity providing for half of the final energy demand in the EU, Fig.4 [12].

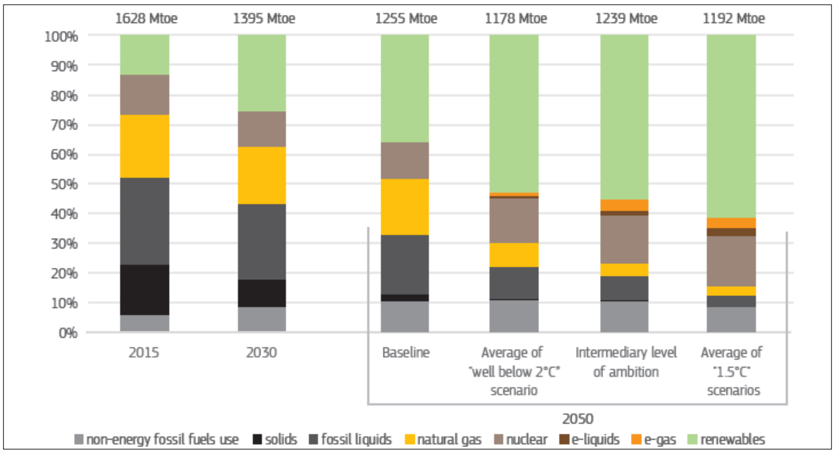

Fig. 4. Gross inland consumption of energy in the EU for various timelines and scenarios.

The shift to low-carbon energy systems will imply massive changes in the raw materials requirements, due to the deployment of the technologies involved in this process. For example, some critical rare earth elements (REEs) such as neodymium, dysprosium and praseodymium, are key ingredients of permanent magnets used in high - performance wind turbines. Critical raw materials - CRMs such as borates, gallium, germanium, indium and silicon metal are needed in solar PV, robotics and digital technologies. Batteries employ CRMs such as cobalt and natural graphite, which are also required in 3DP and digital technologies. Platinum is used as a catalyst in FCs and in digital applications, for example for hard disk drives. Overall, the renewable sector requires many raw materials ranging from very high to low supply risk with the split among technologies as shown in Fig.5 [12].

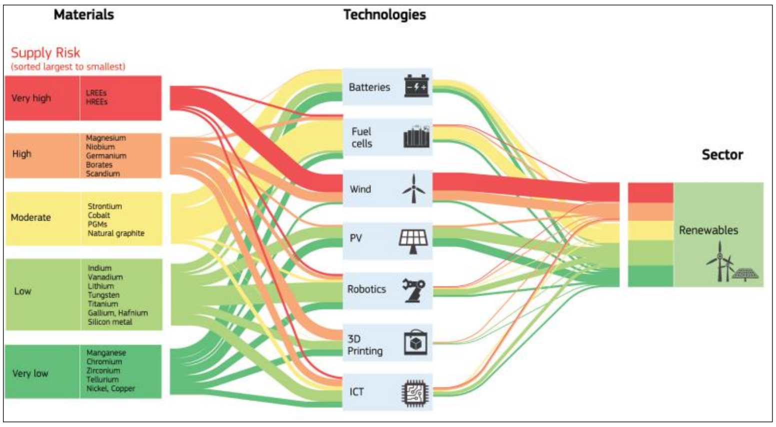

Fig. 5 Materials and technologies relevant to the renewable energy sector.

A renewable energy system is more than just renewable electricity production; it also requires technologies for energy storage, new infrastructure, automation and smart/digital technologies. The EU is dependent on imports of many of the raw materials used in these technologies and is susceptible to supply interruption for materials characterised by high and very high supply risk such as Rare Earth Elements - REEs, magnesium, niobium, germanium, borates and scandium. For some of these raw materials the EU lacks domestic primary production.

Based on the long-term decarbonisation scenarios for the scale-up production of the renewable generation technologies such as wind and solar PV, the demand for several materials will increase significantly by 2050. EU demand for the the raw materials used in wind turbines, in particular REEs in Permanent Magnets - PMs, is expected to increase by up to six times in 2030 and up to 15 times in 2050 in addition to current EU consumption in the most severe scenario.

When looking at the supply chain, the raw materials step is the most vulnerable for most technologies used in renewable sector, in particular for energy storage and enabling technologies (e.g. robotics and 3D Printing -3DP). This is followed by the assembly step, in particular for the energy storage technologies, and the components step. The EU appears less susceptible to supply bottlenecks for processing materials, although there are significant gaps as in the case of processed materials used in battery applications.

5. Case study in Romania

A painful example of the evolution of this industry in Romania is the exploitation of gold and platinum from Roșia Montană, in connection with which the question arises, how valuable are these ores in the end? Romanian geologists who have a solid knowledge of the Roșia Montană deposit state that it is not gold and silver that are the most valuable products, but rare metal deposits, Fig.6 [13].

Fig. 6. Ores containing rare metals at Roșia Montană.

The rare precious metals in the area are arsenic, gallium, germanium, molybdenum, titanium, vanadium and tungsten.

These rare metals can be used as follows:

- Arsenic is used in the manufacture of alloys, increasing their hardness, in electronics, for semiconductors, in pyrotechnics, in the paint industry as a pigment for royal yellow paint and in tanning;
- Gallium is a metal used almost entirely in the electronics industry and very little in the production of medicines;
- Germanium is a metal that is found in small quantities in nature and has semiconductor properties, being used in the manufacture of semiconductors;
- Molybdenum is mainly used in alloys to increase the hardness of steel, then in various chemical applications, fertilizer for certain types of plants, the oil industry, catalyst for sulfur removal, production of halogen lamps, aircraft components;
- Titanium can be used in alloys, in the medical industry, the military, industrial processes (chemical, petrochemical, desalination plants), jewelry, mobile phones, nuclear energy;
- Vanadium is used to make steel products for high speed machinery or a catalyst for the production of sulfuric acid.
- Tungsten is used for light bulbs, electrodes, X-ray tubes.

In conclusion, in addition to gold, there are other treasures hidden in Roșia Montană.

It is now up to us to make wise decisions dedicated to using these resources sustainably, without harming the environment in a harmful way.

The specialists of the Research Institute for Rare Metals claim that Romania could become an important provider of resources at European level.
For the field of nuclear energy, it can be appreciated that the grandiose Nuclear Program of Romania regarding the provision of strategic materials necessary for the manufacture of nuclear fuel (zirconium alloys) and the closure of the nuclear cycle by the final storage of burned fuel (titanium alloys) went into decline and only environmental problems remained. Instead of earning billions of euros, the government is spending hundreds of thousands of euros to close quarries with precious deposits. If before our country competed with the great powers of the world in the processing of rare metals for nuclear purposes, now, in the field of high technology, there is no concern and lacks the economic support that would have been so necessary.
In May 2003, according to the Government Decision no. 537, S.C. Research and Design Institute for Rare and Radioactive Metals Bucharest S.A. (ICPMRR) has become a national institute under the name of the National Research and Development Institute for Metals and Radioactive Resources (INCDMRR) - ICPMRR Bucharest, whose field of activity is scientific research, as well as engineering and technological development in the field of metals and radioactive resources. INCDMRR also has the role to participate in the elaboration of the development strategy of the activity in the field and to achieve scientific and technical objectives set by the National Programs of Research, Development, Innovation, to carry out consultancy and engineering activities in order to solve the problems in the field of recovery of uranium resources and processing of other rare, radioactive and precious metals. Without a concrete program and consistent financial support, this institution will not be able to fulfill its ambitious mission so necessary for Romania [13]÷[15].

6. Conclusions

Energy transition is critical for the future of humankind. The risks associated with climate change dwarf those associated with *critical materials supply*, and the current discourse on materials scarcity as a showstopper is misleading.
Every mineral and metal is different in terms of its supply issues, its demand side potential for substitution and its likely demand growth due to energy transition. There is a need to better understand the *material requirements* of the energy transition in the light of the rapid innovations that are taking place on the production side.
Projections of future critical material needs are subject to much uncertainty. However, this often comes at a cost in *economic, efficient or effectiveness terms*. For many critical materials, a significant ramp-up will be needed if the market takes off as expected, and it is likely that the sources of supply will change.
Whereas *recycling* is often touted as a solution to the problem of access to *critical materials*, this notion is misguided. Recycling can help avoid waste management problems, and it can help develop *circular economy* concepts on a timescale of

decades or centuries, but it cannot be the source of supply needed to build up the materials stock required for the global economy in the coming years.

The topic of *critical materials* has been on government agendas for some time. All major economies have study groups and try to develop strategies to reduce dependencies. However, these are not developed in concert and often they obstruct one another, for example in developing access to strategic supply sources.

Access to critical materials is clearly an issue of rising geopolitical importance. Therefore, a global approach to strategic minerals makes sense but is currently lacking.

Currently, EU industry is largely dependent on imports for many raw materials and in some cases is highly exposed to vulnerabilities along the supply chain. Following the global energy transition, the consumption of metallic raw materials necessary for the manufacture of wind turbines, PV panels, batteries and hydrogen production and storage, and other systems will drastically increase. A strategy must developed to avoid exposure to the risk of missing these critical materials.

*For Romania***,** in the current context of the energy transition, which places particular emphasis on providing critical raw materials, there is a need for a better understanding of data on the capacity to intensify the exploitation of raw materials in the coming years. The potential for innovation also needs to be better understood, both in terms of avoiding or minimizing the use of critical materials and in terms of the geopolitical implications and possible strategies developed to deal with potential risks. Romania's development will fundamentally depend on making wise and fair decisions regarding the provision of these critical materials.

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