Minerals for the green agenda, implications, stalemates and alternatives

Minerals for the green agenda, implications, ...

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Abstract: The green agenda aims to preserve the environment and climate, reduce CO_2 emissions and replace fossil fuels with renewable energy. It relies on electric vehicles, storage, solar and wind power plants. It requires an order of magnitude higher amount of critical minerals, poorly represented in the earth's crust, with problematic recycling, with extraction requiring considerable amounts of energy, fossil fuels and causing unacceptable damage to people and nature in countries that supply raw materials. The increase in the global average temperature demonstrates that the overall effects of decarbonization have been insufficient. The time frame of profit-oriented planning is too short and cannot respect the dynamics of the energy sector. Together with market uncertainty, regulations and incentives did not encourage investors to take all the steps we had hoped for. The long-term needs and availability of key minerals are considered together with an overview of the financial and environmental conditions offered to the population in the countries where mining is carried out. Growing popular resistance to cheap and environmentally damaging mining and increasing demand for critical minerals may call into question the sustainability of current practices. The development of new technologies must be geared towards solutions that use abundant minerals in the Earth's crust, while long-term sustainability requires that fair conditions be offered to the population of countries that supply critical minerals.

Contents

Graphical Abstract:
Coltan mine in Rubaya, Democratic Republic of Congo
(taken from WikiPedia, https://en.wikipedia.org/wiki/Rubaya_mines)

Keywords: Critical minerals, low-carbon technologies, green agenda, mining, solar, wind power plants, battery powered electrical vehicles, sustainability.

Introduction

The global average surface air temperature during the first nine months of 2024 [1] exceeded pre-industrial levels by 1.54 °C. At the same time, global annual energy consumption from fossil fuels is growing several times faster than the combined growth of energy from solar and wind power plants [2], while CO_2 emissions have reached a historic maximum. These disturbing data speak of insufficient and/or inadequate measures being taken to mitigate climate change. The largest global emitters of CO_2 are the energy and transportation [3], which brought electric vehicles, solar power plants, wind farms and grid storage in the backbone of low-carbon technologies [4]. While phasing out fossil fuels is quite slow, the backbone solutions listed require much greater consumption of critical raw materials [5], [6], geochemically scarce minerals that are present in the earth's crust in an amount considerably less than 0.01%. Already existing crisis in the supply of essential minerals is aggravated by the decline in the ore grade, which increases the energy intensity, and by the neglect of socio-environmental aspects [7]. The latter increases the resistance of the local population to companies that practice cheap mining at the expense of the environment, with harmful effects on the living world and public health. An unfavorable series of events and circumstances further increases China's already large dominance in the field of mineral procurement. Meanwhile, green agenda could increase demand of critical minerals up to 9 times in the electricity sector and up to 7 times in the transport sector [8]. Faced with the laws of physics, the aforementioned actions encounter insurmountable obstacles, which is where the cause of the failures so far should be sought. All such policies and strategies which only consider one aspect could bring about severe problems in other areas.

While the world is faced with significant risks brought about by climate change, the regions that provide the world with minerals for low-carbon technologies are additionally threatened by multifold increased exploitation in unfavorable financial and environmental conditions. Limited reserves [9] and the growth in energy intensity of key minerals reveal that many devices and systems that were called renewable cannot be renewed and rebuilt due to the scarcity of minerals. Many of recent technologies are facing bottlenecks in their supply chain that has raised concern for their future use [10]. A study of the quantities of critical minerals needed for green agenda devices and key mineral reserves highlights the need to review low-carbon technologies and eliminate the negative consequences of current mineral procurement practices. The second section of this document provides an overview of contemporary low-carbon solutions and an estimate of required quantities of critical minerals, sufficient to achieve climate neutrality by 2050. An estimate of the grid storage capacity necessary for the integration of solar and wind power plants by 2050 is also provided. The third section presents the current availability of critical minerals, an overview of their reserves, resources, energy intensity and prospects for their long-term availability. The considerations in the fourth section start from the goals of net-zero emissions in 2050 and give the aggregate quantities of batteries, electric vehicles, solar power plants and wind power plants that need to be produced for this purpose. Based on this, the necessary amounts of critical minerals are determined and then expressed as a share of global reserves as well as multiples of current annual demand. The fifth section presents the general experiences of mineral resource exploitation in various countries and regions around the world. As a characteristic and illustrative example, the sixth section is dedicated to the financial, environmental, social and political implications of the planned exploitation of lithium, boron and other essential minerals in Serbia, including the Jadar River Valley, which is expected to supply the EU and thus reduce dependence on China. The summary of the key findings, proposed remedies and feasible solutions are given in Section seven, along with conclusions.

2. Contemporary low-carbon technologies and their needs for critical minerals

Data on trends in energy consumption, changes in the energy mix and CO_2 emissions can be found in accessible and mutually consistent sources [2], [11], [12], [13]. The global annual primary energy reaches 659 EJ, with less than 18% supplied from solar, wind, biofuels, hydropower and traditional biomass. The amount of energy from fossil fuels exhibits an annual growth of 7.37 EJ, considerably larger than the most optimistic estimate (2.32 EJ) of combined growth in solar and wind from 2022 to 2023 (objective estimates state 1.21 EJ). Relative share of coal, natural gas and oil in fossil fuels is 0.342, 0.316 and 0.342, respectively. Road transportation and air transport use 0.144 and 0.028 of the energy from fossil fuels. As a consequence, total CO_2 emissions exceeded 40 $GtCO_2$ (41.6), thus reaching historical maximum, with fossil fuel CO_2 reaching 37.4 $GtCO_2$, and the rest from deforestation and other sources.

The global need for critical minerals depends on the quantity and ratings of low-carbon devices, such as electrical vehicles (EV), solar and wind power plants. It also depends on the specific amount of minerals needed to build an individual unit-rated devices. Based on net-zero emission scenario of [2], Table I summarizes predicted rise in annual production of electrical energy and predicted increase in annual production from grid-connected solar and wind power plants. The required installed capacity of the corresponding plants is calculated using capacity factors obtained as a global average, calculated from global annual energy production and installed power in 2022. The value *RES Total* (*Renewable Energy Sources Total*) of Table I is larger than *RES*(*electrical*) due to a relatively small but finite share of wind and sun energy used off-grid. The last column in Table I (*New capacity*) represents the difference between globally installed capacity in 2050 and globally installed capacity in 2022. The number of units that will need to be produced by 2050 is greater than the *New capacity* due to the replacement of many existing sources that will have reached the end of their useful life in the meantime. This addition is not taken into account in subsequent calculations, so all estimates of the necessary amounts of critical minerals that will follow in the subsequent considerations should be considered as a lower limit.

TABLE I: ENERGY AND INSTALLED POWER FROM WIND AND SOLAR ELECTRICAL POWER PLANTS 2022-2050

	Electricity [TWh]			Installed power [GW]			RESe in 2050 =	RESe in 2050/	RES	New capacity
TWh	2022	2030	2050	2022	2030	2050	=Wind(e)+Sun(e)	/Electricity	Total	2022-2050
Wind(e)	2125	7070	23442	933	3104	10292	54679	0.7116	67791	9359 GW
Sun(e)	1291	8177	31237	1134	7180	27430				26296 GW
Electricity	29033	38207	76838							

Wind(a) and Sun(e) figures reflect global annual electrical energy production and installed power capacity of grid-connected wind and solar power plants. The last row *Electricity* designates global annual production of electrical energy. The figure *RES Total* is larger than *RESe* due to a share of wind and sun energy used off-grid, for production of hydrogen or other purposes. The last column *New capacity* corresponds to the new wind and solar power plants connected to the grid.

In addition to decarbonisation in the energy sector, there are plans to replace internal combustion engine (ICE) vehicles with electric vehicles. The global share of electric vehicles has reached 3%, which corresponds to a number of about 40 million. Of the approximately 82 million cars sold annually, about 8% are battery-powered electric cars, about 16% are hybrid cars, while about 76% of cars have an IC-Engine. Replacing all existing ICE-powered cars with battery-powered electric vehicles (BEV) would require the production of over 1.4 billion (1.4e9) EVs. Key materials required for making one BEV are obtained from [14] and listed in Table IIA. The cars with ICE engines require considerably lower quantities of the key minerals. Among the critical minerals listed in Table IIA, they need just 12 kg of copper and some 1 kg of manganese. The data in Table IIB was obtained in a different way, by summing the critical minerals necessary for the production of an EV battery [15], and adding the critical materials used in the glider and in the electric motor. Some 12 kg of copper and 2 kg of manganese are required for the electric motor, and also some 16 kg of copper and 10 kg of manganese for the glider. With minor differences, there is a good match between the two tables.

TABLE IIA: KEY MATERIALS FOR ONE TYPICAL BATTERY POWERED ELECTRIC VEHICLE [14]

Cu	Li	Ni	Mn	Co	Graphite	Rare Earths (total)	Neodymium
53 kg	9.1 kg	40.1 kg	24 kg	12.8 kg	66.7 kg	1.5 kg	0.5 kg

Data collected from [14] and relevant references.

TABLE IIB: KEY MATERIALS FOR ONE TYPICAL BATTERY POWERED ELECTRIC VEHICLE [15]

Cu (battery)	Cu (car)	Li(battery)	Ni(battery)	Mn (battery)	Mn(total)	Co(battery)	Graphite(battery)	Neodymium(car)
25 kg	53 kg	9	39 kg	12 kg	24 kg	14 kg	67 kg	0.5 kg

Data obtained by using the figures related to the battery [15] and adding some 12 kg of copper and 2 kg of manganese for the motor and some 16 kg of copper and 10 kg of manganese for the glider.

From [14] and [15], the required key minerals for wind and solar power plants are given in Table III. While the estimates for the first seven minerals are taken from IEA publication [14], the quantity of neodymium is obtained by averaging the most recent designs, with reduced quantity of Nd. Therefore, the ratio between the Nd and the rare earth mixture, taken from Table III, differs from the expected one. Namely, in advanced designs of wind turbines, the quantity of rare earth mixture is lower than 243 kg/MW. It is important to notice that many older on-shore wind-turbines use gear boxes and doubly-fed induction generators, hence, and the figures of Table III for rare earths and neodymium do not apply for them.

TABLE III: KEY MATERIALS FOR WIND AND SOLAR POWER PLANTS IN [KG/MW]

	Copper	Nickel	Manganese	Chromium	Molybdenum	Zinc	Rare Earths (total)	Neodymium (*)
Off shore	7852	296	741	518	148	5407	243	50
On shore	2889	444	741	518	111	5407	243 (***)	50
	Copper	Silicon	Silver (**)					
Solar	2814	3926	40					

Data collected from [14] and relevant references. (*) The quantity of Nd is calculated as lower average of most recent installations, and it is not in expected proportion . Similar data can be obtained by using the figures related to the battery [15] and adding some 12 kg of copper and 2 kg of manganese for the motor and some 16 kg of copper and 10 kg of manganese for the glider. (**) The quantity of Ag is calculated as lower average of most recent installations, taking into account most recent savings in silver usage in PV. (***) Older on-shore wind-turbines use gears and doubly-fed induction generators which do not use permanent magnets.

Electrification raises demand for key minerals from 2 to 7 times by 2030 [2]. Annual demand for Cu for electrification alone is expected to increase from 5.8 Mt to 12.2 Mt, most of it used for expanding transmission and distribution grids. Annual demand for Si would rise from 0.8 Mt to 2 Mt, mostly for solar panels [2]. Recent developments have reduced the quantity of silver used in solar panels below 8 gr/m^2, thus reducing the requirements from 80 t of Ag for each installed GW of solar panels down to 40 t/GW.

The increasing share of solar and wind power plants creates a need for grid-connected energy storage. Wind and solar power cannot be controlled at will, and therefore excess energy must be stored and used in “dunkelflaute” intervals with no wind and no sun.

One of the storage systems promoted within the green agenda are utility-grade battery storage, although there are other solutions such as reversible hydroelectric plants, compressed air storage, thermal storage technologies and others. It is necessary to estimate the total amount of grid storage that may be needed by 2050. In an electric power system with a total source power p_{SRC}, a total load p_{LOAD}, and a power p_{INTER} arriving via interconnections with neighboring systems, the power of energy exchange with the storage p_{STOR} is given by Eq. (1), and it represents the first derivative of the stored energy W_{STOR}. The power p_{SRC} corresponds to the aggregate power of controllable and uncontrollable production (2). For the purposes of this calculation, the instantaneous power $p_{SRC}(t)$ is presented in a simplified form, as a sum of 7 groups that differ in controllability, peak power, total annual energy, dependence on weather conditions, dynamics and characteristic time intervals. The seven components in (3) correspond to the instantaneous power of baseload sources (p_{BASE}), wind power plants (p_{WIND}), solar power plants (p_{SUN}), run-of-river hydropower plants (p_{HE_ROR}), dam hydropower plants (p_{HE_DAM}), combined cycle and cogeneration gas power plants (p_{GASC}), and open cycle gas power plants (p_{GASO}). The power p_{LOAD} (3) corresponds to the aggregate power of controllable and uncontrollable consumption. The calculation assumes that part of the load $p_{CONT}(t)$ is flexible part of the demand, and it is modeled as the energy consumption that can be planned, managed, increased, reduced, or shifted in time if needed. Load control can help reduce the storage capacity needed. From now on, the highest flexibility targets set so far are assumed to be achieved by 2050, whether on an hourly, daily, weekly or seasonal scale. It is also assumed that the power of the interconnections p_{INTER} is not limited, that is to say, all necessary interconnections will be built and power limitations will never restrict energy exchanges where a surplus in one system coincides with a deficit in the other, at all technically and economically justifiable distances. By the nature of the changes in production and consumption, exchanges in the east-west direction are primarily on a daily basis, while exchanges in the north-south direction also include a seasonal component.

The overall calculation of minimum storage capacities is reduced to a base period of one year, performed with a 10-minute resolution. It consists of determining technically, economically and logistically feasible vectors of the instantaneous power of controllable sources (p_{BASE}, p_{GASO}, p_{GASC}, p_{HE_ROR} and p_{HE_DAM}) for a period of one year and with a resolution of 10 minutes, along with planning the changes in controllable part of the load $p_{CONT}(t)$, so as to obtain the minimum required energy storage capacity, i.e. the minimum difference between the extreme values of $W_{STOR}(t)$ in equation (4). It has to be noted that hydropower plant management is restricted and conditioned by inflows, while for base sources, periodic repairs must be planned and carried out. The calculation is based on the seemingly optimistic, but still partly realistic, assumption that all changes in wind and solar power, changes in power consumption, and changes in hydroelectric power plant inflows for the observed year will be known at the very beginning of the year. This assumption significantly reduces the time required to find optimal vectors using modern Matlab tools.

$$p_{STOR}(t) = \frac{\mathrm{d}W_{STOR}(t)}{\mathrm{d}t} = p_{SRC}(t) - p_{LOAD}(t) + p_{INTER}(t). \tag{1}$$

$$p_{SRC}(t) = p_{BASE}(t) + p_{WIND}(t) + p_{SUN}(t) + p_{HE\_ROR}(t) + p_{HE\_DAM}(t) + p_{GASO}(t) + p_{GASC}(t). \tag{2}$$

$$p_{LOAD}(t) = p_{NONC}(t) + p_{CONT}(t). \tag{3}$$

$$W_{STOR}(t) = \int p_{STOR}(t)\cdot \mathrm{d}t = \int \left(p_{SRC}(t) - p_{LOAD}(t) + p_{INTER}(t)\right)\cdot \mathrm{d}t. \tag{4}$$

The calculation results yield the annual change in $p_{STOR}(t)$ and $W_{STOR}(t)$ in the case of optimal control of sources and loads. The obtained results allow determining the power and capacity for each of the storage technologies that need to be implemented. For each of the storage technologies, there are two basic parameters that define them, namely the storage capacity (i.e. the maximum energy that can be stored in them) and the storage power (i.e. the maximum rate of change of said energy). The dependence of the required storage capacity on the share of solar and wind power plants is shown in Fig. 1. The discontinuous character of the curve shown results from the fact that it is not a representation of an analytical expression, but rather a set of points obtained through individual optimization for each of the given quotas of wind and solar energy (on the abscissa). The optimization includes variables of a binary nature as well as variables with discontinuous change. For the share of wind and solar power plants planned for 2050 [2] in the scenario with zero net emissions, and for the projected annual electricity production, the total necessary storage capacity exceeds 6000 TWh, some 8% of the global annual electricity.

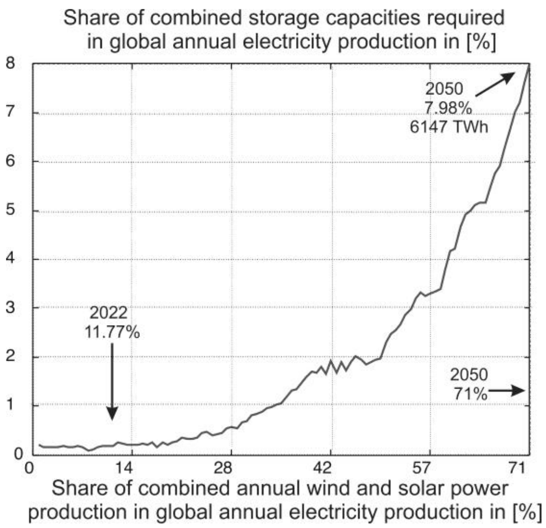

Fig. 1: Combined storage capacity of a well-interconnected system based on the share of wind and solar energy in total electricity production.

Important conclusions about the most suitable storage technologies can be obtained starting from the vector of calculated storage power $p_{STOR}(t)$ for a period of about a year, whose 10-minute samples need to be arranged i n decreasing amplitudes. The corresponding results are shown in Fig. 2, for 2022 (left) and 2050 (right). The maximum storage power in 2050 will be 3,2 times larger than the average annual power of the considered electrical network. It can be seen that the intervals with the extreme charging and extreme discharging power will be relatively short, suggesting that such needs can be met by battery storage.

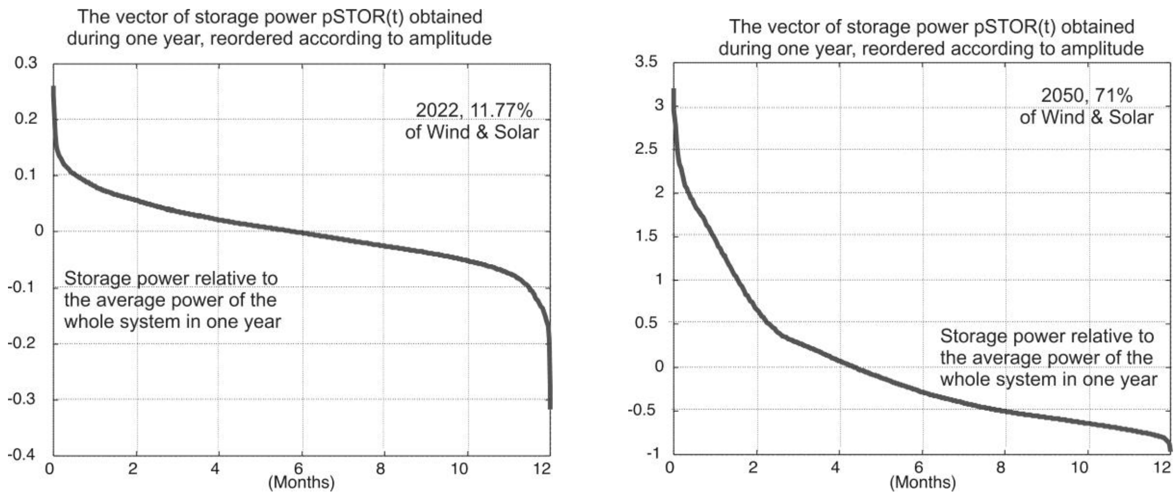

Fig. 2: Storage power vector reordered and sorted according to its amplitudes. In 2050, according to zero net emissions scenario, annual electricity production is close to 77 PWh, which corresponds to average power (1) of 8790 GW.

In order to verify the viability of the present low-carbon solutions, it is of interest to study the availability of Cu, Ni, Mn, Cr, Mo, Zn, rare earths, Nd, Si, Ag, Li, Co, graphite and other critical materials.

3. Availability of critical minerals and prospective of their reserves and recycling

Most critical minerals are considerably more abundant in earth’s crust than in sea water. There are also critical minerals in the magma, but their concentration is too low to justify their exploitation with available technologies. The most significant source of minerals is, for now, the continental part of the earth's crust. A particularly valuable insight into the availability of minerals from the earth's crust was provided in [16]. Within 10-50 km of depth, at least traces are available for 88 chemical elements. Only 12 elements are present at levels above 0.1% by weight, and these are O, Si, Al, Fe, Ca, Mg, Na, K, Ti, H, Mn and P. These elements are considered geochemically abundant, and they were widely used in traditional industries. Notwithstanding steadily-declining grade of ore, geochemically abundant minerals will be readily available and there are no major technological barriers in their extraction.

Other elements (Zn, Cr, Ni, Cu, Co, U, Sn, Ag, Au...) are considered geochemically scarce, yet many of them are used in low-carbon devices and systems. The exploitation of scarce minerals is further complicated by the nature of their distribution in the earth's crust. They rarely form separate minerals in common rocks, and vast majority of their content is represented as randomly distributed atoms [16] trapped by isomorphous substitution where a scarce atom replaces and atom of an abundant element. A very small fraction of the total scarce mineral content is found in geologically limited volumes with higher concentration. These volumes are the result of some rather rare circumstances in which scarce mineral compounds occur with much higher concentrations than in areas with isomorphous atomic substitutes. An example is Pb, which represents 0.001% of the continental crust, while it is obtained from ores containing at least 2% Pb. Proven Pb ore reserves are more than 100 000 times smaller than the total amount of Pb in earth’s crust.

When these very small amounts of scarce minerals are depleted, the remaining portions of scarce minerals will be present as isomorphic atomic substitutions, very difficult to exploit. When the reduction in ore grade falls below the level called mineralogical barrier, the ore it is not amenable for exploitation due to logistic barriers, technological problems, and considerable increase in energy intensity. Excluding special cases (Au, U, Ga ...), the barrier lies somewhere between 0.01 and 0.1%. In the case of scarce minerals other than Pb, it of interest to estimate their share available in concentrations higher than the mineralogical barrier, ruling out their presence as isomorphic atomic substitutes at very low concentrations.

The report [17] establishes mineralogical barrier for Cu at 0.1%, and it states that only 0.01% of total Cu in the continental crust is found with ore grades above 0.1%. For most scarce minerals, the share of their content in the earth’s crust beyond corresponding mineralogical barrier falls between 0.001% and 0.01%. Once the barrier is reached, previously used concentration, smelting and refining can no longer be employed, and the energy demand for alternative processes can jump by a factor of 100 to 1000 times [16]. Therefore, exploitation of ore grades below the mineralogical barrier seems rather unlikely. A visible decline in the ore grade of Au, Ag and several other metal ores has already begun.

An overview of critical minerals is given in Table IV, largely based on [9], [10], [14], [15], [16], [17] and [18], including the relevant resources, reserves, annual demand and energy intensity (that is, the total internal and external energy consumption required to obtain the unit quantity of the desired mineral).

TABLE IV: CRITICAL MINERALS: DEMAND, RESERVES, RESOURCES AND ENERGY INTENSITY

Mineral (name)	Resources [Mt]	Reserves [Mt]	Demand [Mt/year]	Energy [MWh/t]	W1Y [TWh] for 1 yr sply.	W1Y versus Welectric	W1Y versus Wprimary
Copper	5600	1000	28	10.2	285.6	0.009837	0.001561
Nickel	350	130	3.6	48	172.8	0.005952	0.000944
Manganese	∞	1900	20	8	160	0.005511	0.000874
Graphite	800	280	1.6	31	49.6	0.001708	0.000271
Neodymium	32	8	0.057	16	0.912	3.14E-05	4.98E-06
Chromium	12000	560	41	20	820	0.028244	0.004481
Molibdenum	25.40	15	0.284	20	5.68	0.000196	3.1E-05
Zinc	1900	220	13	14.4	187.2	0.006448	0.001023
Argentum	1.74	0.61	0.026	416	10.816	0.000373	5.91E-05
Lithium	105	28	0.18	×	×	×	×
Li2CO3	from spodumene		0.92	60.5	55.66	0.001917	0.000304
Li2CO3	from brine		0.92	9.1	8.372	0.000288	4.57E-05
Cobalt	120	11	0.23	245	56.35	0.001941	0.000308
Rare Earth	478	110	0.164	16	2.624	9.04E-05	1.43E-05
Hi grade Si	∞	∞	9	410	3690	0.127097	0.020164

A certain impermanence of estimated reserves arises from their definition of being economically exploitable now or in the near future, from their dependence on the results of geological exploration and with economic factors, and from the innate volatility of technological, legal and market studies. Since the resources are defined as concentrations of minerals in the earth's crust that have reasonable prospects for eventual economic extraction in the future, they are closely related to mineralogical barrier, presumed acceptable depth of ore bodies, new explorations, projected changes of the ore grade, and borderline energy intensity. In all cases where there are different estimates, the higher values are entered in Table IV, such as, 1000 Mt of copper reserves instead of commonly cited 886 Mt, 1.74 Mt of silver resorces instead of 1.3 Mt [16] and similar.

In column 4, current annual demand is expressed in [Mt/year]. Based on available data on energy intensity in [MWh/t], energy W1Y is calculated, which represents the total energy expenditure for the annual production of considered mineral. For reference, the W1Y quantity is also presented as a share of annual global electricity consumption, as well as a share of global primary energy. The energy required to produce lithium carbonate from spodumene is over six times greater than the energy required to produce lithium from brine [19]. The total energy required to obtain the annual lithium consumption was calculated in two ways, first assuming that all lithium is obtained from spodumene and then assuming that all lithium is obtained from brine. Reserve and resource data are given for lithium content, while energy consumption calculations are based on equivalent lithium carbonate.

Recycling can reduce critical mineral supply problems [14]. The rate of recycling depends on the logistical problems in collection of the worn out devices, on the energy required for recycling and on the market price of recycled minerals. The recycling rate of gold, platinum and silver exceeds 80%, 60% and 50%, respectively. Recycling rates for Cu and Al exceed 40%, while Cr, Zn and Co have recycling rates in excess of 30% [14]. Recycling requires significant amounts of energy, particularly when the devices to be recycled have not been designed to facilitate recycling. Therefore, recycling may reduce resource depletion problems but cannot eliminate the need to use significant amounts of energy to extract minerals [2], [13], [14]. According to predictions published in [14] for 2040, recycling and reuse of EV and storage batteries could reduce the primary supply requirement for minerals by only 12%, while the share of recycled minerals could reach 8%, both figures being a rather modest results. The current practice of designing and optimizing key devices also has a negative impact on the mineral recycling potential. As an example, solar panels are being designed to achieve higher efficiency, greater robustness and durability, and lower cost. The possibility of recycling used panels is not taken into account during design, which significantly reduces the chances of recycling with reasonable energy consumption. In the long term, it makes sense to focus development efforts on technologies and devices that use minerals abundantly available in the earth's crust.

4. Increased share of EV, solar & wind power: Case studies and minerals expenditure

About 97% of existing cars still use ICE engines. As part of the decarbonization of transport, it is planned to replace them with battery-powered electric cars (EV) that do not use fossil fuels. After replacing all ICE-engine cars with battery-powered EV, EV will continue to be produced to replace worn out vehicles. The amount of key minerals needed to produce one typical battery-powered EV is given in Table II. Based on the estimate that there are about 1.47 billion cars in the world today, it is possible to determine the amount of minerals needed for the "first generation" of battery powered EV. The described calculation does not take into account later needs for minerals for the replacement of worn out EV and their batteries. The results of the calculations are given in Table V. The necessary total quantities of Li, Co, graphite and rare earths exceed the current annual production from 38 to 81 times, while the required amount of cobalt is 1.71 times larger than available reserves.

TABLE V: KEY MATERIALS FOR MANUFACTURING BATTERY POWERED EV

Required Mineral	Required mx [Mt]	mx as a share of reserves	mx as a share of annual demand	Energy in TWh to produce mx
Li	13.38	0.478	74.317	466
Ni	58.95	0.453	16.374	2829
Co	18.82	1.711	81.809	4610
Mn	35.28	0.019	1.764	282
Cu	77.91	0.078	2.783	795
Graphite	98.05	0.350	61.281	3040
Rare Earths	2.21	0.020	38.684	35

The calculation of the amount of minerals for the production of EVs can be estimated in an alternative way, starting from the specific amount for each of battery-minerals expressed in kg for each kWh of battery capacity. Based on the information published in [2], [13], [14] and [15], it is possible to estimate the necessary specific amounts expressed in [kg/kWh]. These data are given in the second column of Table VI. With energy consumption of 1/6 [kWh/km] and with required autonomy of 300 km, one EV would need a battery of 50 kWh. With the EV battery capacity of 50 kWh, it is possible to calculate the total amount of required minerals in [Mt], which is given in the third column. The calculation takes into account the "first generation" of battery powered EVs, so the need to replace EVs that have reached the end of their useful life is not taken into account here. The data in first 3 columns of Table VI do not take into account the amounts of copper and manganese required for the glider and the electric motor. These amounts are, approximately, 28 kg of copper and 12 kg of manganese for each EV. In total, the figure *my* in the fourth column of Table VI includes 41.1

Mt of copper and 17.64 Mt of manganese. Notice that data in the last 3 columns of Table VI consider quantity *mx* (battery only) and not *my*. Required amounts of battery-materials Li, Co and graphite are more than 40 times larger than the actual annual production, the amount of cobalt is larger than the available reserves, and the main conclusions are similar to those derived from Table V. Due to the significantly increased amount of material, the extrapolated effects of falling ore grade and the consequent increase in energy needed to obtain minerals should be taken into account, which was not done on this occasion.

TABLE VI: KEY MATERIALS FOR MANUFACTURING BATTERY POWERED EV

Required Mineral	Specific kg/kWh	Required mx [Mt] for battery only	Required my [Mt] for battery + glider + motor	mx as a share of reserves	mx as a share of annual demand	Energy in TWh to produce mx
Li	0.1	7.35	7.35	0.263	40.833	256
Ni	1.2	88.20	88.20	0.678	24.500	4234
Co	0.15	11.03	11.03	1.002	47.935	2701
Mn	0.15	11.03	28.67	0.006	0.551	88
Cu	1	73.50	114.6	0.074	2.625	750
Graphite	1	73.50	73.50	0.263	45.938	2279
Nd	0.5 kg/car		0.74	0.092	12.895	11.76

It is also of interest to estimate the amount of critical materials required for the construction of grid-connected battery storage, and to add such figures to the ones obtained for EV batteries (Table VI). In addition to batteries, utility storage also include compressed air technology, reversible hydroelectric power plants, thermal storage, and other technologies. According to the estimate obtained for 2050, shown in Figs. 1 and 2, the overall, cumulative capacity and power of all the utility storage technologies reach 6147 TWh and 3.2 * 8790 = 28128 GW. Batteries represent only one part of these figures, most often dedicated to short-term storage, where the instantaneous power exchange $p_{STOR}(t)$ is significant and it covers considerable part of the peak power needs plotted in Fig. 2. The capacity (energy) of battery storage is planned to be relatively small compared to other technologies, much smaller than the total storage capacity required, because the most common battery-based storing and recovering processes are shorter than 2-4 hours. In exceptional cases, such as in India, where solar energy makes a considerable contribution during the daytime, batteries would have to withstand charge (or discharge) times of up to 10 hours [13]. To increase the durability of batteries and avoid too frequent replacement of modules or cells, it is beneficial to specify a higher capacity and thus reduce changes in the relative charge of the battery. To this aim, a good practice is to install the battery with a rated capacity between 1.5 and 2 times greater than the load variation under normal operating conditions.

Batteries are planned to provide up to 1/3 of the total short-term flexibility of the grid [2], [13]. Forecasts for battery storage needed in 2050 are constantly increasing. According to the publication World Energy Outlook [2], [13] for 2022, 2023 and 2024, the prognosis of battery power required in 2050 reached 3860 GW in World Energy Outlook 2022, increased to 4199 GW in 2023 and reached 5512 GW in 2024 [13]. If we assume that the batteries will provide only 1/3 of the peak power required to integrate wind and solar power plants in 2050 (Fig. 2), and that their rated discharge time will be specified as 8 hours, then the required grid-connected battery storage capacity is calculated as 75 TWh. Data on the materials needed to manufacture such batteries are taken from column two of Table VI, where they are expressed in [kg/kWh]. Critical mineral resources required to manufacture utility-grade storage batteries, to be installed by 2050, are detailed in column 3 of Table VII, expressed in [Mt].

TABLE VII: KEY MATERIALS FOR UTILITY-STORAGE BATTERIES AND EV BATTERIES IN 2050

Required Mineral	Specific kg/kWh	[Mt] for utility batteries only	[Mt] for EV batteries only	mx [Mt] = EV+ +utility batteries	mx as a share of reserves	mx as a share of annual demand	Energy in TWh to produce mx
Li	0.1	7.50	7.35	14.85	0.530	82.500	517
Ni	1.2	90.00	88.20	178.20	1.371	49.500	8554
Co	0.15	11.25	11.03	22.28	2.025	96.848	5457
Mn	0.15	11.25	11.03	22.28	0.012	1.114	178
Cu	1	75.00	73.50	148.50	0.149	5.304	1515
Graphite	1	75.00	73.50	148.50	0.530	92.813	4604

The results suggest that, for all materials except manganese, the quantities required exceed current annual production by an order of magnitude, up to 96 times. In the case of nickel and cobalt the required quantities are significantly higher than global reserves. Since the data in Table VII represents an optimistic estimate that does not take into account the need to replace worn-out cells and batteries, nor does it consider the fact that ore grade will decline, the conclusion is that the planned decarbonization trajectory is unlikely to be achieved.

The data in Table VIII show the necessary quantities of critical minerals for the production of solar panels planned for 2050. According to the data given in Table I, achieving net-zero-emissions of CO_2 by 2050 requires that the total installed power of solar power plants be increased by 26296 GW. The specific quantities of key minerals for the construction of solar power plants are given in Table III and expressed in kg per each MW of installed power, [kg/MW]. The total amount of required materials is given in Table VIII. As in the previous Table, the data presented do not take into account the need to replace solar panels that have reached the end-of-life. Implementing the current decarbonization plan would require a total amount of silver more than 40 times greater than current annual demand, exceeding global reserves by more than 1.7 times. The energy required to produce solar-grade silicon is nearly twice the current annual global electricity use.

TABLE VIII: KEY MATERIALS FOR PLANNED SOLAR POWER PLANTS

Required Mineral	Required mx [Mt]	mx as a share of reserves	mx as a share of annual demand	Energy in TWh to produce mx
Copper	74.00	0.074	2.643	754.8
Silicon	103.24	very low	very low	42327
Silver	1.05	1.724	40.456	437.6

In order to achieve net-zero-emissions of CO_2 by 2050, the plan we currently rely on (Table I) requires that the total installed power of wind power plants be increased by 9359 GW. The specific quantities of key minerals for the construction of wind power plants are given in Table III and expressed in [kg/MW]. The total amount of required materials is given in Table IX.

The first two rows in Table IX show copper consumption first for the case when all new installations would be on-shore, and then for the case when all new installations would be off-shore. Currently, the ratio of the former and the latter is 12:1, but it is planned that it will change to around 2:1 by 2050. Therefore, the total consumption of copper will be higher than shown in the first row, and lower than shown in the second row of Table IX. Rare earths aside, the consumption of remaining minerals for onshore and offshore power plants is not too different. Rare earths and neodymium enable the construction of directly coupled light generators without gearboxes, so that high-power wind turbines can be manufactured with relatively low weight and without excessive investment in supports and construction.

However, a significant number of existing on-shore wind power plants still use traditional doubly-fed induction generators (DFIG) with gearboxes, which are still planned for low-power plants. Therefore, it should be noted that the total consumption of rare earths and neodymium in Table IX will actually be lower than it is shown, to the extent that lower power turbines with gearboxes and DFIGs are retained.

TABLE IX: KEY MATERIALS FOR PLANNED WIND POWER PLANTS

Required Mineral	Specific kg/MW	Required mx [Mt]	mx as a share of reserves	mx as a share of annual demand	Energy in TWh to produce mx
Cu-on shore	2889	27.04	0.027	0.966	276
Cu-off shore	7852	73.49	0.073	2.625	750
Nickel	444	4.16	0.032	1.155	200
Manganese	741	6.93	0.004	0.347	55
Chromium	518	4.85	0.009	0.118	97
Molibdenum	111	1.04	0.069	3.661	21
Zinc	5407	50.61	0.230	3.893	729
Rare Earths	243	2.27	0.021	13.868	36
Neodymium	50	0.47	0.058	8.210	7

Unlike the unattainable quantities of minerals required for the construction of solar power plants, electric vehicles and batteries (Tables V-VIII), the situation is somewhat more favorable for wind power plants. The need for molybdenum and zinc is less than four years' current production, while the energy consumption shown for obtaining the minerals is quite achievable. The need for rare earths is very significant, exceeding their current annual production by 13 times. If the needs for rare earths required for the production of EVs are added (Table V), then the total needs would reach an amount 52 times higher than the current annual production.

From the presented results, it can be concluded that the planned production of key devices required for the green agenda will be faced with very serious problems in obtaining critical minerals. The needs for silver and cobalt significantly exceed the available global reserves, while the needs for other minerals are up to 60-70 times higher than the current annual production, which makes the possibility of obtaining them questionable due to logistical problems, problems of ore grade decline and the increasing energy consumption in the processes extraction and refining. Over the past twelve years, considerable efforts have been devoted to studying the energy consumption of mining and refining as a function of the decline in ore quality [20]. Developed models [21], feasible solutions for sustainable resource management [22] and to estimates of the energy intensity of critical minerals [23] prove that a drop in ore grade causes a significant increase in the energy intensity of critical minerals, which can create irresolvable problems in obtaining them in larger quantities. Current practices appear to be unsustainable, which would render our renewable devices non-renewable and could force us to divert our developments and technologies towards the use of abundant minerals. A viable solution for critical minerals could be [24] one where they are not sold, but rented or leased, with strict conditions regarding recycling.

5. Countries that supply mineral raw materials - current practices

Significantly increased quantities of critical minerals create the need to open numerous new mines. The European Union sees the need to open new mines in member states where resistance to mining is relatively low, as well as in the countries it influences. Recent legislation in Serbia creates the possibility of opening more than 40 mines, mostly in areas with a vibrant rural population, profitable agriculture, and strategic water reserves. It is of interest to study the willingness and interest of the countries from which the mineral raw materials are sourced to agree to the opening of new mines. If there is resistance to mining, it may gradually cease or it may become stronger over time and threaten the security of mineral supplies. One way to make such an assessment is to look at past experiences.

The distribution of critical mineral resources is very uneven. About 70% of the total amount of cobalt comes from Congo, while about 3/4 of lithium and rare earths are found in the three countries that are the richest in these resources. China refines about 35% of nickel, 54% of lithium, 72% of cobalt and 90% of rare earths [2]. About 79% of the global production of equipment for solar power plants, 64% of equipment for wind power plants, 68% of batteries, 33% of electrolyzers and about 30% of heat pumps are produced in China. China's dominance in the field of obtaining mineral resources increasingly includes Africa and South America, which complicates the position of the industry in the West. A large part of minerals is found in third world countries such as Botswana, Guinea, Suriname, Congo, Zambia, Mali, Guyana, Namibia, Peru, Kyrgyzstan and others. It is of great importance to study the approach and manner in which China is steadily suppressing other companies and gradually taking over resources in third world countries. There are indications that other mining companies' operations in third world countries offer unfavourable financial and environmental conditions to the local population. Although these phenomena are difficult to quantify, this section and the next one are dedicated to studying the problem.

The Democratic Republic of Congo (DRC) supplies the world with over 70% of cobalt and significant amounts of copper. Despite vast natural resources, the DRC is one of the poorest countries in the world. Already very small, the GDP of 649 USD per capita is more an indication of the value of the minerals brought out of Congo than it is of tangible benefit to the people of the DRC. There are indications [25] that the manual work of people, and very often children, is used for the collection and separation of ore, which brings unprotected workers into contact with toxic substances, exposes them to the risks of landslides and rockfalls, and causes illness and loss of life. The average human lifespan in Congo is about 20 years shorter than the global average, and about 30 years shorter than in Italy. Disintegration of the national economy, dysfunctional transport and unavailability of electricity are cited [26] as the main problem in maintaining reliable exploitation of mineral resources in the DRC. The expansion of industrial-scale cobalt and copper mines in the DRC has led to the forced eviction of entire communities and grievous human rights abuses including sexual assault, arson and beatings [27].

It is necessary to study and understand the objectives of multinational mining companies that come to third world countries to exploit critical minerals. Past experience shows that mining companies are interested in operating in countries with high corruption potential, dysfunctional democracy, and governments that abuse institutions and do not respect the separation of judicial, executive and legislative affairs [25], [26], [27]. Stable institutions, functional democracy and a high level of environmental protection largely prevent traditional and cheap mining. Traditional 19th century mining involves the construction of tailings and process waste dumps, the use of large amounts of fossil fuels, insufficient electrification, and the practice of releasing often problematic waters and gasses into the environment. In most cases, mining is much cheaper in countries where an autocratic government has been established, as they can be persuaded to accept 19th century mining. In exchange for political support or for lucrative reasons, key autocratic leaders may be willing to enter into non-transparent contracts and agreements that are fundamentally unfavorable to the general population. The final outcome is the exploitation of mineral resources for a negligible compensation, but with the thorough devastation of water, land, air and the living world. Unwanted effects of this approach are the rebellion of the local population, which can lead to a halt in exploitation, but also to armed conflicts and civil war [28]. What is not sufficiently appreciated is the fact that the traditional approach of companies from the West increases China's room for expansion, which offers the local population of African countries somewhat more favourable financial conditions and, if necessary and convenient, a significantly higher level of environmental protection, thanks to which it gradually takes over key supplies of critical minerals.

Recourse to traditional, low-cost mining with landfills provides significant savings to the investor and makes mineral exploitation much more profitable. Namely, although new technologies enable mining without tailings dumps and without releasing problematic water and gases into the environment, they are, for the time being, considerably more expensive. Instead of implementing new technologies and accepting significant costs of remediation and crop recovery, an investor can choose a completely different way to do business in third world countries. In countries with high corruption potential, investor could focus on establishing mutual understanding with local political leaders. By funding media campaigns, it is possible to try to persuade local people to accept harmful traditional mining without rebelling and without hurting the public image of local autocrats. The described approach prevails in plenty of cases. In the long run, it can significantly threaten the security of mineral supply. Despite political statements and promises that the EU will guarantee the environment, human rights and health of people in the countries from which it sources minerals, and despite the EU’s commitment to a fair distribution of mining profits, leading European companies continue to use minerals from the Managem mine in Morocco, as well as from DRC, where there is environmental devastation, water pollution, child abuse and endangering of basic human rights. The described practice be more profitable, but it does not ensure security of supply in the long term and it paves the way for Chinese investors.

Chinese investors are ready to offer more advanced and environmentally friendly forms of mining wherever this approach gives them an advantage, puts them in a favorable position and allows them to acquire and control new mineral reserves. However, in cases where respect for the environment is not a requirement or does not bring them adequate benefits, they too resort to traditional mining with tailing dumps, landfills, with releasing of toxic waters and with thorough destruction of the environment. An illustrative example of dire consequences of traditional mining is evident in the east of Serbia, in Bor and Majdanpek, towns where Chinese investors operate copper mines and a processing plant.

Mining and smelting basin Bor (RTB) is the only producer of copper and precious metals (gold and silver) in Serbia. It produces cathode copper and high-quality precious metals. As of December 2018, operations are in the hands of a Chinese investor, who has already tripled production and announces a new increase of up to 5 times compared to the initial. The increase in production is accompanied by excessive emissions of toxic substances up to 40 times above the limit values. At the same time, the income of the host country is insignificant. Based on the market value of copper (currently 9188 EUR/t) and known quantities of copper obtained from Bor and Majdanpek on an annual basis (close to 240 000 t), the gross income from the sale of copper amounts to 2205 million EUR. Available data for 2021 show that Serbia received only 13.6 million euros in mining rent.. Due to the unavailability of reliable data, it is difficult to determine the exact total revenues of Serbia from RTB, which include direct and indirect taxes and allocations on other grounds, but the total revenues are estimated to be between 50 and 60 million EUR, i.e. 2.72% of the market value of copper obtained. If the calculation base also included the value of gold, other precious metals and valuable minerals that the investor exports from Serbia in the form of concentrates, then the share of Serbia's income in the value of the minerals obtained would be significantly lower than 2.72%.

Fig. 3: Copper mining and processing in Bor and Majdanpek is carried out without land rehabilitation and reclamation, with pollution of watercourses to the extent that the Bor River is dead in every respect, and with the consent of the authorities that the investor carries out work with permanent pollution that exceeds the limits by several dozen times.

The Chinese investor exports a significant part of the ore concentrate that is further processed outside of Serbia, so the total amount of precious metals and valuable minerals is not known, at least not to the general public. It is known that Serbia has the possibility to buy gold mined on its territory with a discount of 3% compared to the market price.

It is becoming increasingly common for smelters to process arsenic-rich concentrate. According to report 1411-24 dated May 15, 2024, made in the laboratories of the Institute of Mining and Metallurgy in Bor, the concentration of cadmium in PM_{10} particles exceeded the limit value 35 times, while the corresponding concentration of arsenic exceeded the limit value 23 times. Relevant (and alarming) data on the average annual concentrations of cadmium and arsenic can be found in the paper [29].

During 2022, about 4,000 records of oncology patients were counted in the health center in the city of Bor. According to data from the National Institute for Public Health of Serbia, Dr. Milan Jovanovic Batut, about 800 new patients in Bor are diagnosed with cancer every year. Data on the number of patients in 2023 and 2024 are not readily available, while the government-controlled media diminish the problem and state that the total number of oncology patients in Bor is five times smaller than it actually is. Despite the alarming levels of pollution, the operations in Bor do not stop, under the pretext that jobs would be lost. About 6,000 Serbian citizens and a significantly larger number of Chinese citizens, estimated at 22,000, currently work in Bor. The arrival of Chinese investor led to the closing of jobs in smaller companies and subcontractors that employed Serbian citizens and provided specialized services to the RTB complex.

Certain mines are supplied with technical water from the city's water supply system, where they have priority, so that the population remains without water during the summer months. Since a part of the Chinese workers come to work in Serbia under penalty, there is also a Chinese law enforcement group in Bor that controls parts of the territory. The Chinese workforce often comes to Serbia without the necessary qualifications, with the intention of obtaining basic training and learning from mistakes.

In Bor, the number of Serbian citizens decreased by 20% during the past decade, while according to predictions for the year 2050, it will be further halved. Despite the departure of Chinese citizens who complete their training at RTB, the number of Chinese citizens who live in Bor is constantly increasing. The overall picture of Bor and Majdanpek is changing in a very unfavorable way. Practically, almost all economic activities except mining and mining-associated activities have been suspended. The remaining population is shrinking, and living without perspective and hope. There is also a lack of ability and will for the citizens of Bor to recognize, articulate and defend their vital interests. Instead of being the subjects of social dynamics, they are reduced to mere objects and therefore victims. The population that remains passive in the face of mining practices such as those carried out in Bor is in line with the interests of investors and it meets the interests of the autocratic government. Although in Europe, images from Bor and Majdanpek correspond in many ways to scenes from Congo, Morocco or Papua New Guinea.

Most examples of mining in third world countries imply a scenario similar to the experience in Bor. Large mining companies take the concentrate or minerals out of the country, leaving negligible income for the local population and the state. Traditional mining with landfills is used, which leads to devastating pollution of land, water and air, destroys biocenoses, leads to serious diseases in the population, and leaves no room for a productive life of any kind other than mining. As a consequence, strong and negative reactions of the local population are frequent, threatening the security of global mineral supply.

6. Financial, environmental, social and political implications of Jadar project

The efforts of EU countries, primarily Germany, to reduce dependence on China by sourcing minerals in Serbia have been met with public resistance. The following study of the "Jadar project" goes beyond a narrowly professional discussion, but nevertheless contains information and conclusions of importance for the main goals and messages of this paper. In what follows, a brief discussion will ensue on (i) Newly adopted Serbian laws that favor mining companies at the expense of the interests of the population, (ii) Financial effects of jadarit mining, (iii) Environmental risks of the Jadar project, (iv) Views, plans and attitudes of investors, (v) Threat to water supply, (vi) EU policy so far, followed by (vii) Adverse impacts of project Jadar on relations between Serbia and the EU.

Fig. 4. Jadar Valley: One of the rare examples where agricultural production enables the flourishing of a traditional village, schools filled to capacity, and a large number of young people who plan to stay in the village. The area shown lies on an aquifer system of crucial importance for the Republic of Serbia.

6.1. Laws favoring mineral exploitation

Over the past years, the laws of the Republic of Serbia have been changed in a way that suits the international mining companies very well, but which does not suit the citizens of

Serbia. In the context of the basic messages of this work, it is of interest to study the circumstances under which the Jadar project is being prepared. According to the current law on mining and geological research [30], national institutions are prevented from engaging in mineral research. This is only possible for them by order of the Government of Serbia, and such an order has not been issued once since the passing of the law. Mineral research and exploration is available to private companies, which are listed as owned or controlled by international mining companies. The legal provisions of the same law grant the priority right of exploitation to companies that conduct research and find minerals, without obligation of calling an international tender in order to obtain the most favorable offer. In short, the practical consequences of the adopted law are the granting of exploration and exploitation rights exclusively to international mining companies or affiliated companies. A discussion of the motives and interests of those responsible for this law is beyond the scope of this article. The law was based on the corresponding legislation of Congo and Mongolia, which contains elements inappropriate for the EU, but its adoption was not opposed by EU representatives in charge of Serbia's accession process.

There is a clearly expressed interest of international mining companies to, among other things, exploit borates and nickel in Serbia. An excessive amount of boron in the soil prevents the growth of plants [31], while an excessive amount of nickel makes the water unsuitable for drinking. At the beginning of the 21th century, Serbia had regulations that limit the maximum amount of boron in the soil, which could oblige mining companies to apply modern mining technologies without landfills and without the risk of unwanted release of toxic water. However, the newly adopted regulation [32] excludes boron from the list of soil pollutants, and abolishes all previous restrictions, so that investors are enabled to exploit boron and borates without fear of exceeding the limit values of soil pollution. Similarly, increased nickel concentrations in water will no longer be used to determine the chemical status of water [33], which could remove any need for large mining companies in Serbia to invest in equipment that would prevent or limit nickel pollution of water. In short, conditions have been created in Serbia for mining companies to work in a traditional way, with tailings and waste dumps, and with the release of toxic contents into the environment, without bearing any consequences, which is already happening in eastern Serbia, in Bor and Majdanpek.

Fig. 5. The photo was taken in the Jadar Valley, near exploratory wells where toxic groundwaters reaches the surface. Due to the significant concentration of boron and other toxic content, the living world near the well is affected beyond repair and exterminated.

6.2. Financial effects of jadarit mining

Major investors who have arrived in western Serbia have expressed their intention to exploit boron. In the Jadar valley, deposits of the mineral jadarite have been identified, which, in addition to boron, also contains lithium. Although lithium and boron in the Jadar valley were first discovered by Serbian scientists [34] in 1999, the state missed the opportunity to become the sole owner of exploitation rights. The mineral Jadarite was formally characterized in 2007 [35]. In the final outcome, the priority right to exploit jadarite was not given to national institutions and companies.

Data on the potential financial effects of the Jadar project and on environmental risks are available from several sources whose claims differ widely. Leading Serbian politicians and promoters of the Jadar project state that Serbia's GDP will be increased by 10-12 billion euros, that lithium will primarily be used for the long promised production of battery electric vehicles in Serbia, that 20,000 new jobs will be created, and that exploitation will take place in accordance with the green agenda and with the "highest standards of life protection environment". Serbian political leaders also stated that Serbian lithium reserves reach 10% of the global lithium reserves, although they actually represents only about 1% of global reserves [37].

Experts working on behalf of investor [38] claim that Serbia's GDP will increase by 695 million instead of 10-12 billion, 4,500 new jobs will be created instead of 20,000, and only 40 million EUR will be collected annually in royalties when the incentive period expires, implying in this way unconfirmed information that Serbia will provide incentives to international mining companies.

Leading European representatives express the need to obtain raw materials from Serbia, thus denying claims by Serbian politicians that lithium will be used for EV manufacturing in Serbia. They also confirm that the EU is trying to obtain minerals from Serbia in order to free itself from dependence on minerals from China [39]. While EU politicians work on coercing Serbia into lithium mining, prof. Claudia Kemfert [40], [41], a German energy economist, confirms that EU countries have high environmental protection standards, which do not have to be respected in countries outside the European Union. This makes mining in the EU too expensive and introduces the tacit policy of sourcing critical minerals elsewhere. Her statements contradict with the Serbian authorities' claims that project Jadar will be carried out to the highest standards, they confirm that mining lithium in Serbia is problematic, and that the potential environmental damage can be serious. Lithium mining can contaminate groundwater with heavy metals and pollute drinking water. It is confirmed [40], [41] that Serbian environmental protection organizations have long rightly pointed out that the potential investors’ record of complying with environmental standards is not encouraging, and that Germany's intentions to obtain critical minerals in Serbia are simply shifting the potential environmental damage elsewhere.

Fig. 6. In an effort to repair the damage shown in Fig. 5, contaminated soil near the exploratory wells was removed and improperly disposed of next to a nearby pond. The water in the otherwise vibrant pond soon showed visible signs of serious contamination.

A group of independent Serbian economic experts [42], including the former governor of the National Bank and renowned university professors, argue that the Jadar project is not justified and should be stopped. They state that Serbia would have negligible net income from that project on all grounds: 17,4 million euros per year, which represents 2,6 euros per capita. According to independent experts [43], endangered income from agricultural activities is estimated at 81,96 million euros per year, and it exceeds, by far, the potential effective revenues from mining activities. Under favourable conditions, raspberries from Western Serbia contribute to exports of more than 400 million euros a year. The subjective reluctance of potential buyers to opt for raspberries from the mining region can reduce sales and prices if the Jadar project is launched.

Experts noted [42] that techniques of diminishing Serbia's net income include unfounded indirect subsidies to companies linked to investors, transfers of assets and taxable flows to the tax jurisdiction of other countries, and purchase of goods, services and often questionable consultancies almost exclusively from foreign suppliers. These are some of the reasons why mining in Serbia, on behalf of large international companies, generates insignificant revenues does not benefit to Serbia, something that can already be seen in Bor and is predicted by independent experts [42] in Jadar. Moreover, foreign investors operating through a Serbia-based limited liability subsidiary gives them the opportunity to earn income but avoid liability for damages, the cost of remediation and reclamation of contaminated land, and the cost of decommissioning.

6.3. Environmental risks of the Jadar project

Scientific paper [43] contains fact-supported analyzes that confirm the existence of an unacceptable eco-chemical risk of jadarite mining and lithium extraction due to questionable technology solutions, and because of the specific aquifer terrain unsuitable for mining activities. The mentioned work was subjected to strict peer review, usual for reputable scientific publications. In addition, the article has resisted serious efforts to deny the facts presented and to have the article retracted. After double checking, the published claims should be given the importance of scientifically confirmed facts. Publication [43] argues that the Jadar project threatens the water supply of 2.5 million people, it would occupy a territory where 20 000 people live, among which several thousands of farmers would lose their jobs. They state that, despite the proposed announced new technology, the company has been unable to meet legal limit values for boron in soil and water [44]. Unfortunately for the citizens of Serbia, the regulation [44] from 1994 was recently withdrawn, and according to the new one, the maximum content of boron in the soil is not prescribed, so it is possible to exploit jadarite and destroy large areas of land without violating the current Serbian regulation.

Fig. 7. The Jadar Valley is frequently exposed to flooding, which makes the idea of building landfills containing significant amounts of boron unacceptable due to the imminent risk of large-scale soil contamination.

Along with the data on the share of water-soluble boron and overall boron quantities toxic to the soil, it has been pointed out in [43] that the Jadar project would lead to degradation of the soil and desertification. In addition to toxins in the planned tailing dumps and landfills, toxic waters in the orebody zone bring boron, arsenic and lithium to the surface. Scientists [43] indicate that the planned mine at Jadar, similar to 19th century mines, will have tailings and waste dumps and landfills, and will discharge water into the environment. At the same time, modern and already used technologies include zero liquid discharge solutions [45]. It is also possible to reinject water into geological layers of the ore body, slightly away from the mine, or otherwise below the sealing layer [46]. Scientists [43] point to the already visible negative effects of land destruction around existing wells, and emphasize the mobility of boron, the high proportion of water-soluble boron and the significant, visible effects of devastation on the surrounding land. Their conclusion is that the optimal solution for the Jadar project is its cancellation.

6.4. Views and plans of large investors

The investor's attitude towards environmental issues can also be seen from public appearances of their representatives. During nationally broadcasted conversation between concerned local residents and directors and engineers of potential investors interested in the Jadar project [47], the investor's engineers stated that the principle of engineering rationality prevents them from implementing the Jadar project in a way that would never release toxic water into the environment. They confirmed that some of the toxic water will be released under conditions of heavy, “accidental” rainfall that was characterized as “100-year waters” [47], which takes for granted that in the event of a 100-year flood, it is acceptable to expose the fertile land of western Serbia to toxic substances including boron, arsenic and lithium. To make matters worse, the incidents described will occur much more often than once every 100 years. Due to climate change, there is a tendency for very significant amounts of precipitation to fall in an extremely short period of time. In recent years, the maximum monthly precipitation in Serbia exceeded 480 mm, the maximum daily precipitation exceeded 210 mm, and the three-day precipitation in the Jadar Valley basin exceeded 250 mm, in line with global changes [48], indicating significantly higher maximum hourly rainfall. Milutin Stefanović from the Jaroslav Černi Water Management Institute, stated that 100-year floods has been occurring almost every year since 2014. Considering the intentions of investors [47], the same frequency would be observed in the spillage of toxic boron, arsenic and lithium, diluted in water, onto the fertile soil of the Jadar Valley if the Jadar project is implemented.

Although it is cheaper and fits with "engineering rationality", the aforementioned investors' plan violates Article 19 of the Land Protection Law [49], which prohibits the discharge and disposal of polluting, harmful and hazardous substances and wastewater onto the land surface and into the soil. After any of these planned "accidental" spills of toxic water, the Articles 20 and 21 of the same law require the immediate closure of the plant and the cessation of all mining and processing operations, while the costs of damage repairs, remediation and recultivation would fall on the investor. Unfortunately, the state of Serbia does not apply the aforementioned laws if the sanctions are directed at foreign investors. Previous experience suggests that the aforementioned closure will not occur, that remediation will not be undertaken, and that polluting mining will continue uninterrupted until the next storm.

The investors’ engineers justified [47] the “accidental” release of toxic water into the environment by the fact that, in conditions of heavy rainfall, the toxins would be diluted with large quantities of clean water brought in by precipitations. The intention of diluting hazardous and toxic substances with clean substances is contrary to environmental principles. Although inconsistently applied, even the Law on Waste Management of the Republic of Serbia [50] in its Articles 26, 38, 43 and 44 prohibits the mixing of hazardous substances with water and prohibits any dilution of hazardous substances. That is, as a principle, hazardous substances should not be diluted to reduce the concentration of toxins in an attempt to characterize the result as non-hazardous. Numerous experiences around the world indicate that insensitivity to environmental problems may be a sign that investors are inclined to cooperate closely with authoritarian regimes in order to avoid costly compliance with environmental rules, principles and regulations.

An illustrative and worrying example is the investors’ statements about their intention to learn from mistakes, as well as the statements of collaborators that operations could be suspended if a major incident occurs. The promise to learn from mistakes suggests that complete undertaking is an experiment with an uncertain outcome. Since the planned operation in the Jadar Valley would be the first example of jadarit mining, it would be carried out without previous experience in mines and plants of similar type, size and purpose. Unfortunately, each of the mistakes that should be learned from would create permanent and irreparable damage [43] to people, living world, environment and water supplies.

The Jadar project envisages the transport of materials on the surface of the earth [51], using fossil fuels and releasing harmfull dust, instead of using the already widespread underground transport of materials using electric power. In cases where the implementation of electrification would bring the project closer to the goals of the Green Agenda, the use of large amounts of fossil fuels is envisaged instead, which will lead to significant CO_2 emissions and increase Serbia's total emissions. According to Table IV, the energy intensity of lithium obtained from an underground ore deposit is more than six times greater than the energy required to obtain lithium from brine in salt lakes [19]. From publicly available data on the Jadar project [51] it is possible to estimate, directly or indirectly, related quantities of fossil fuels and other explicit and intrinsic energy inputs of the Jadar project. The outcome shows that the energy intensity of lithium extraction from underground jadarite ore would be, similar to the lithium obtained from spodumene, several times larger than the energy intensity of lithium extracted from salt lake brine.

Although the value of materials and goods is commonly expressed in terms of market price, long-term considerations are more reliable if values are based on energy invested and minerals consumed to produce relevant goods. The fact that much less energy is required to extract lithium from saltwater suggests that other methods of obtaining lithium are inferior. The above considerations are one of the reasons for the sevenfold drop in the price of lithium recorded since November 2022. This circumstance calls into question the prospects for earnings from the sale of lithium from Jadar, and emphasizes the importance of the original intentions of investors, which is the exploitation of boron and other critical minerals. This brings into focus the potential devastation of the soil and waters due to the release of rather mobile boron with a large proportion of water-soluble fraction, the risks which goes unsanctioned in Serbia (Fig. 5, Fig. 6), and that would not be tolerated in the EU.

The attitude of large investors currently working in Serbia regarding environmental protection often reflects the belief in the cultural and civilizational inferiority of the local population. This attitude is reinforced by the fact that laws are enacted that are contrary to the interests of citizens, and that even these laws are not respected when they act against the interests of large investors. There are about 250 mining landfills in Serbia, and none of them have been rehabilitated and recultivated, while violations of regulations by mining companies are controlled by a symbolic number of inspectors.

6.5. Threat to water supply

In [43], the authors argue that the Jadar project would threaten the water supply of 2.5 million people. Of the three major water supply systems, the Mačva region, with which the Jadar valley is closely connected, is the most important one. In this region there is a unique configuration of sand and gravel deposits. They are located several tens of meters underground, with a high degree of porosity and large quantities of pottable water. Deposits are running along the Drina River and directly connected to the entire terrain of the Mačva and Jadar region. The greatest thickness of the deposit is found along the course of the Drina River, ranging from 50 to 75 m, while in the rest of Mačva it ranges from 20 to 40 m. This area represents the most important groundwater reserve in western Serbia [52]. The authors [43] predict that the Jadar project and its wastewater would pose a high risk of endangering water systems on a larger scale. The destruction of Serbia's most important water system will put the water supply for a large part of the Serbian population at risk. The impact of mining activities on water supply and groundwater resources is well studied [53-58]. The studies suggest that in aquifer systems and complex geological structures such as those in Mačva and Jadar, mineral extraction and exploration boreholes should not be carried out under any circumstances, while all drilling to significant depths may be permitted only for the purposes of monitoring groundwater quality. Similar conclusion was drawn by Serbian scientists in 2021, where it is suggested that mining should not be allowed in populated areas with fertile soil, strategic supplies of drinking water, profitable agriculture, and favorable demographics.

On 6-7 May 2021, the scientific conference "Jadar Project: What is Known" was held in Serbian Academy of Sciences and Arts [59]. The conference brought together leading scientists, qualified experts, government representatives, experts and managers of potential investors, as well as representatives of third parties cooperating with investors. The main results of the conference were published in the conference proceedings, with conclusion section on pages 17 and 18 (translation in English in [60]), stating in brief that, the Jadar project would lead to massive devastation of space, permanent changes in the character of the landscape, degradation of biodiversity, soil, forests, surface and underground water, displacement of the local population, cessation of sustainable and profitable agricultural activities, and establishing a scenario of permanent risk to the health of residents of nearby villages and the city of Loznica. Scientists also conclude that the continuation of the uncontrolled realization of similar mining projects would lead to serious ecosystem disturbances, environmental degradation and would be an indicator of the inability of the state, but also of the wider social community, to see the harm of such activities to the public interest. It is crucial that any form of economic development does not endanger the environment, does not lead to displacement of population, and does not deprive future generations of living space, drinking water, healthy food, fertile land and preserved, clean and diverse nature. Scientists have concluded that it is necessary to clean and recultivate the existing 250 landfills. They also stated that all the projects that envisage the construction of tailing dumps, waste landfills and waters discharge should be banned in populated areas, as well as on fertile land, in zones of importance for water supply, and in places of importance for the preservation of wildlife. Activities similar to project Jadar can only be allowed in uninhabited and barren deserts, far from living world, far from people and from strategic water reserves. Given Serbia's strategic interest in joining the European Union, mines with waste dumps, landfills and water discharges should not be permitted. Implementation of the Jadar project and similar projects would leave Serbia outside the European Union. With a very high cost of environmental remediation in Serbia, the inclination and desire of EU member states to take Serbia under their umbrella of responsibility will be significantly lower.

6.6. EU policy so far

The encouragement of Serbia to become a raw material base for the EU is not accompanied by firm and unquestionable guarantees regarding environmental protection and financial gains. On the contrary, EU experts [40], [41] point out that modern technologies that enable the acquisition of minerals with minimal environmental impact are currently too expensive. Thereform, they conclude that mining on EU territory is not profitable and that it takes too long to obtain the relevant permits. Given the circumstances, there is a preference and interest in acquiring minerals from countries where mining with dumps, landfills and water discharges is permitted, and EU regulations do not apply. Responsible EU politicians point out that one should not expect their guarantees for mining operations abroad, and that the sole responsible for the environment in Serbia is the Serbian government. Serbian laws have been changed in the interests of international mining companies and against the interests of citizens. Toxic substances such as boron, whose reduction to permissible levels would be too expensive for investors have been removed from the relevant Serbian regulations [30], [32], [49], [50]. At the same time, despite verbal commitments from some EU politicians that mining outside the EU would not endanger the environment in other parts of the world, Europe continues to source minerals from Africa, where the environment is devastated and workers and the population are exposed to very harsh working and living conditions. The conclusion is that the implementation of the planned lithium mining in Serbia would have devastating effects comparable to those we are witnessing today in Congo and Morocco.

6.7. Adverse impacts on relations between Serbia and the EU

The EU's attempt to solve the mineral supply crisis through cheap, unsustainable mining in Serbia is questionable. Outline of the existing plan is to export the environmental hazards that accompany mining from EU to Serbia, to the detriment of the citizens of Serbia, and to pay for it with political support for questionable local Serbian authorities. Public resistance to projects where narrow interest groups make profits at the expense of the environment in Serbia is gradually growing, and therefore the outlined plan may soon call into question the security of mineral supplies. Experiences from Papua New Guinea and Congo show that public resistance can be suppressed by armed force of an authoritarian government, but only in the short term. On the other hand, public unrest in Serbia and the EU's concern for the supply of minerals, as well as the EU's visible lack of concern for the environment and the health of citizens in Serbia, create the preconditions for the influence of non-European influential states and interest groups. In the long term, the described situation sharply conflicts with the interests of Serbia and the interests of the EU.

7. Discussion and recommendations

Efforts to suppress global warming, to curb the use of fossil fuels, to reach zero net CO_2 emissions and to achieve climate neutrality, has been based on devices such as batteries, electric cars, solar power plants, wind farms and grid energy storage. Manufacturing the above-mentioned devices requires very large quantities of critical minerals, which are scarcely present in the earth's crust. Their extraction requires considerable amounts of energy and fossil fuels. Recycling is often problematic, while cheap mining and processing pose considerable risks to the environment and the living world, particularly in countries sacrificed to become suppliers of raw materials. The current Green Agenda would require quantities of rare earths, graphite, silver and cobalt exceeding their annual production by 38, 61, 40 and times, respectively. The required quantities of silver and cobalt are 1,724 and 1,711 times greater than the corresponding global reserves. The above arguments do not support the sustainability of the plans, primarily because the necessary devices and systems cannot be produced in the required quantities. In the long term, the development and design of mass-produced devices and systems should be directed towards using minerals that are present in the earth's crust at more than 0.1%, including silicon, aluminum, iron, calcium, magnesium, sodium, potassium, titanium, manganese, and phosphorus. Until then, it is important to keep in mind that the devices we currently use are not renewable due to the lack of minerals. They should therefore be designed to facilitate energy-efficient recycling, in order to reduce the extraction and processing of critical minerals.

For the sake of a secure and sustainable supply of minerals from third world countries, it is necessary to end the current practice of cheap mining with tailings dumps, waste landfills and massive environmental destruction. The ability of international mining companies to spot and exploit the corruption capacity of local authorities and to temporarily affect the public opinion through media campaigns provides short-term results, but is not sustainable in the long term. The unrest in Congo and the civil war in Papua New Guinea have brought uncertainty in the supply of minerals, created problems on a global scale, and created a wide space for the Chinese capital and further increase of their domination in the field of critical minerals. In order to achieve long-term sustainability and regain the economic power of our continent on a global scale, it is necessary to offer fair conditions to the population of mining colonies. While traditional, environmentally unacceptable mining generates higher profits, it is not sustainable because it draws mineral suppliers into places where they expose the environment, wildlife and people to large-scale devastation that can be seen in Congo, Morocco and the Serbian town of Bor. For the sake of long-term sustainable mineral supply, the project Jadar and all similar projects involving waste dumps, landfills and water discharge should be forbidden. To achieve such a goal, it is necessary to assist the local population in targeted countries and to protect them from the harmful alliance of autocratic authorities and large companies.

In order to achieve a fair distribution of benefits and coherent environmental protection in line with EU standards, it is necessary to promote transparent and multilaterally controlled agreements between countries supplying raw materials and countries where minerals are used to manufacture final products. In countries aspiring to join the EU, existing dumps, landfills and waters must first be remediated and recultivated. All projects that forsee the construction of waste dumps, tailing landfills and water discharge should be prohibited. Furthermore, all ventures similar to the Jadar project and all preparations for the construction of new mines in non-European countries for the extraction of critical minerals must be suspended until the status of soil, water and air pollution is improved and brought to the levels existing in Austria, Norway and Luxembourg.

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