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TAŞKIN DENIZ YILDIZ[1]

Will the resource potential of critical raw materials used in electric cars in Turkey be sufficient for the domestic automobile factory? – A review

Abbreviation list

C	–	Graphite,
CAGR	–	Compound Annual Growth Rate,
Co	–	Cobalt,
CRIRSCO	–	Committee for Mineral Reserves International Reporting Standards,
CRM	–	Critical raw material,
Cu	–	Copper,
DRC	–	Democratic Republic of Congo,
EV	–	Electric vehicle and automobile,
Fe	–	Iron,

✉ Corresponding Author: Taşkın Deniz Yıldız; e-mail: tdyildiz@atu.edu.tr
[1] Adana Alparslan Türkeş Science and Technology University, Department of Mining Engineering, Turkey; ORCID iD: 0000-0003-4043-2257; Scopus ID: 57216370111; Researcher ID: ABH-8072-2020; e-mail: tdyildiz@atu.edu.tr

IEA	–	International Energy Agency,
IRR	–	Internal rate of return,
Li	–	Lithium,
Mn	–	Manganese,
MTA	–	General Directorate of Mineral Research and Exploration in Turkey,
Ni	–	Nickel,
REE	–	OSD: Automotive Manufacturers Association in Turkey,
RE	–	Rare earth,
REE	–	Rare earth element,
RM	–	Raw material,
SDS	–	Sustainable Development Scenario,
TOGG	–	"Turkey's Automobile Initiative Group" or Turkish electric car brand,
TREO	–	Total rare earth oxide,
UMREK	–	National Resource and Reserves Reporting Committee in Turkey.

Introduction

Countries must align their use of natural resources with energy consumption in transportation and sustainable development goals (Rentizelas et al. 2022; Gebhardt et al. 2022; Satrovic et al. 2023). Today, ~76% of anthropogenic greenhouse gas emissions on a global scale (37.2 billion tons/year CO_2 equivalent emissions in 2018) are emitted from the energy sector. According to the most recent statistics announced by the World Resources Institute in the Climate Watch Platform, greenhouse gas emissions from transportation constitute ~17% of anthropogenic greenhouse gas emissions (8.3 billion tons/year CO_2 equivalent emissions in 2018) (WRI 2021). At this rate, ~7.5% of CO_2 emissions are emitted from cars, motorcycles, and buses, and the rest from heavy land, sea, air, and railway vehicles (Ritchie et al. 2020). At this point, the prevalence of EVs in the world is gaining importance (İçli 2020; Będowska-Sójka and Górka 2022; Guo et al. 2022; 2023). With the development of EV technology (Kerem 2014) and its costs falling to competitive levels with diesel and gasoline vehicles, it is aimed to reduce greenhouse gas emissions from transportation to a certain extent (Ari 2020; IEA 2023). Although customer trends (Ullah et al. 2021) and government policies (Goel et al. 2021) are also effective in EV sales, with the Covid-19 epidemic, supply chains face more uncertainty than ever before (Durmaz et al. 2021). Despite the 16% decrease in global car sales in 2020 compared to the previous year due to the effect of the COVID-19 pandemic, the rapid increase in the number of EVs continued. In 2020, ~3 million EVs were sold. Thus, the share of EVs in total car sales reached 4.6% in 2020 (IEA 2021). EV sales exceeded 10 million units in 2022. The share of EVs in total car sales increased to 14% in 2022 (IEA 2023).

The Green Deal approach, announced by the European Union (EU) following the Paris Agreement signed in 2015, determined a new roadmap for combating climate change.

This approach, which considers energy transformation as one of its priorities, has led to the supply of RMs used in renewable energy resources, energy storage systems, carbon emissions, and EVs, which have an important place in reducing the use of fossil fuels, gaining great importance (Hodgkinson and Smith 2021; Mining Turkey Magazine 2021b; Guzik et al. 2022; Zanbak et al. 2023). However, the high demand for mineral resources necessary for the transition to a carbon-neutral and circular economy contrasts with the increasing difficulties of discovering new mineral deposits and the existence of several risks such as price increases (Kasmaeeyazdi et al. 2021; Jiang and Jiang 2023). Due to increasing demands, an upward trend in critical mineral prices (Kahraman and Akay 2022; Islam et al. 2022) as well as mining and supply-related risky situations arise (Hou et al. 2023; Islam et al. 2023; Gałaś et al. 2024). Considering these risks, countries determine some trade policies to guarantee the RMs they need (Tian et al. 2021). There will be a transformation with changing technologies and the Green Deal. As a result of this transformation, the importance of minerals such as Li and Co for clean energy and EVs will increase even more (Kavanagh et al. 2018; Poyraz 2022; Kustra et al. 2023).

Especially the battery sector and the technological developments of batteries come to the fore. The storage of electricity produced by renewable energy and the energy required for EVs increases the importance of batteries day by day. In parallel with this, many countries in the world allocate huge budgets to battery development studies (Okyay 2020b). In this direction, the search for the RM resources required to obtain the metals used in advanced technologies becomes more and more important with each passing day. The future of the world needs to determine where these RMs are economically in the earth's crust, whether it is possible to replace them economically when they are used, and to conduct studies for their supply in the future (Aydın and Kılıç 2012). In particular, the increase in the demands of developed countries for RMs reveals the expectation of ensuring supply security of natural resources needed for low carbon emission technologies and products. As a result of all these, developing countries are also faced with a great change. The most concrete example of this change is frequently encountered in our daily lives as EVs. The increase in the economic importance of natural resources that will enable these new technologies and transformation, and the addition of high supply risks, reveals the importance of CRMs. The subject that almost all countries agree on is REEs (Table 1). Apart from this, at least 70% of the 18 different minerals in Table 1 such as Li, Co, Mn, and C are accepted as critical minerals by the country or international organization where they are listed.

Some of these minerals are used within the scope of conversion to green technologies (Całus-Moszko and Białecka 2013; EC 2020). Production growth of minerals required for the automobile sector is projected to increase at a very small CAGR of 2–5% over the next five years. This could lead to higher prices for these minerals if demand exceeds supply (Gülmez 2020; Tabelin et al. 2021). These demand increases reveal the need for an evaluation in terms of the safety of the RM supply chain required for EVs, which constitutes the general scope of this study (Uysal 2021c). Communities of countries such as the EU and other developed countries have started studies to create a roadmap and produce a common strategy for providing uninterrupted and safe access to mineral resources for their future needs. In this framework, the EU lists the minerals it needs according to the criticality level and updates them periodically (Aydın and Kılıç 2012; Galos et al. 2018; EC 2020; Zanbak et al. 2023). Apart from CRMs, Fe-steel, Cu, lead, zinc, rubber-plastic, glass, aluminum, and other RMs are used in an EV. When Li, Ni, Co, Mn, C, and REEs, which are declared as CRMs in the EU CRMs list and used in EVs, are added to this list, a high level of mineral resource potential is required for EV production and mining investments (Okyay 2018). Indeed, Li, Ni, Co, Mn, C, and REEs are considered critical in the production of environmentally friendly clean technology and green industrial products, especially in the manufacture of EV batteries (EC 2020; İçli 2020). A sustainable supply of resources to provide electrical energy is as strategic as the production of EVs and batteries, which are an important part of them (İçli 2020). Thus, the increasing growth of EV targets by countries around the world has started to cause concern in the world about the safety of RM supply in energy storage (Bradsher 2010; Golev et al. 2014; Wellington and Mason 2014; Glöser et al. 2015; YMGV 2018; Liu et al. 2021). To guarantee the future supply of RMs for producing new batteries for EVs, it is important to forecast the future demand for battery metals. (Maisel et al. 2023) focused on the future demand for EV battery cathode RMs Li, Co, Ni, and Mn, considering different technology and growth scenarios. The results show that the future material demand for Li, Co, and Ni for LIB in EVs in 2040 will exceed today's RM production. The recycling potential of Li and Ni will account for more than half of the RM demand for LIBs in 2040. Considering this, (Maisel et al. 2023) recommend increasing resource production and focusing on recycling LIB metals in the future to meet the increasing consumption of electromobility. However, there are assessments that metal and REE recycling from e-waste is not yet feasible and has technical challenges. This situation further increases the importance of production from mineral resources compared to recycling from e-waste (Yazıcı and Deveci 2011; Massari and Ruberti 2013; Andersson et al. 2019; Gidarakos and Akcil 2020; Yıldız 2024a; 2024b; Yıldız et al. 2024). As mentioned above, there is a huge shortage of RM in the world, despite the rapid increase in the number and capacity of battery production facilities. It is foreseen that there will not be enough RMs for battery supply by 2030 if the need for all RMs continues to increase at the current rate and the existing production facilities continue to expand at the same pace. According to this projection, it is estimated that there will be a deficit of ~500 thousand tons in Li supply, ~400 thousand tons in Ni sulfate supply, ~75 thousand tons in Co supply, and ~2 million tons in flake C supply by 2030. Due to the rapidly increasing vehicle demand, it is estimated that there will be problems, especially in the supply of Li and Co in the medium term, and the supply problems for these RMs will prevent world battery production from exceeding 1 TWhs until 2025. It is estimated that the problems to be experienced in the supply of RMs will be caused by the lack of capital investments to be made in these mines rather than the geological factors (Mining Turkey Magazine 2022d; Tuomela et al. 2021; Çendi 2023). This shows the necessity of making new investments in these RMs, the need of which is expected to increase, and that those who will invest will gain an advantage.

As a matter of fact, according to the data of the IEA, the number of EVs, which exceeded 5.1 million in 2018, is expected to maintain its regular increase, even if it loses its momentum. For, it is estimated that the global Ni demand will increase ~19 times with the full capacity of the Li-ion battery facilities expected to start production (İmgel 2020). In terms of Li, Ni, Co, Mn, C, and REE resources, which are among the essential components for advanced battery production and energy storage technologies, they continue to gain importance day by day due to the increasing demand for EVs (Mining Turkey Magazine 2021a) Turkey's position is a matter of curiosity. 49.3 kg of Li, 36.6 kg of Ni, 6.4 kg of Co, 19.8 kg of Mn, and 47.6 kg of C raw ore must be extracted for each Li-ion battery in the production of TOGG (Figure 1). Considering this need, able to solve the RM problems that TOGG will encounter in the future, Turkey, which has many minerals in its lands thanks to its rich geological structure, needs to make a breakthrough in the explore for CRM. In this direction, with good planning, RM production and supply opportunities should be developed for both domestic automobiles and other areas of the industry in Turkey (Aydın 2023). The idea of establishing a domestic automobile factory in Turkey, which was tried in the 1960s but could not be successful in those years, was not achieved until 2022, which is close to the present day. The successful realization of this vision project, its gaining market share not only in the domestic market but also in the world markets, will make significant contributions to the Turkish economy. It may even be instrumental in increasing Turkey's reputation in the world economically. EVs such as TOGG have 3 fundamental differences from traditional vehicles:

1. Electric motor instead of an internal combustion engine,
2. Use of electricity instead of fuel and the battery in which this electricity is stored,
3. Special software that enables the control and management of these batteries and the system.

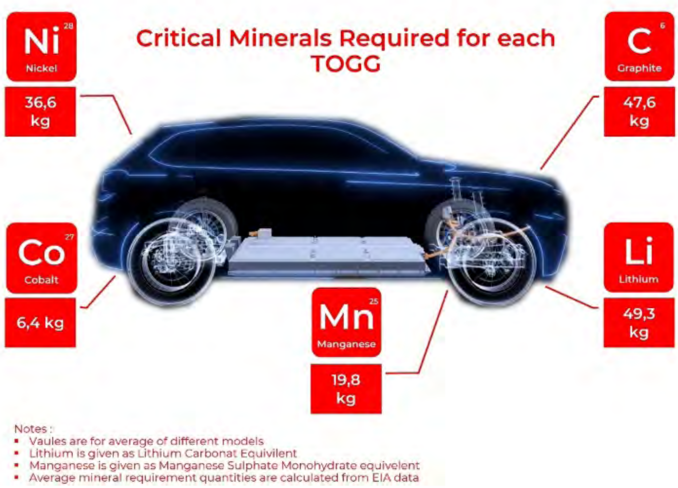

Fig. 1. Critical minerals required for each TOGG

Rys. 1. Minerały krytyczne wymagane dla każdego TOGGa

Apart from software, technology RMs, many of which are also called critical or strategic, are used in the production of electric motors and batteries. At this stage, mining activities are required to explore and extract these technology RMs. For TOGG to achieve worldwide success, the mining industry can play an important role by providing the necessary technology RMs from domestic resources. The development of domestic mineral resources is of great importance in two aspects. The most important of these is ensuring the security of the mineral supply (Uysal 2020a, 2021c). The IEA announced that Germany, in particular, France, England, and Norway, and large countries such as China and India are in preparation

Table 1. Critical mineral lists and common critical minerals

Tabela 1. Wykazy minerałów krytycznych i powszechnie spotykane minerały krytyczne

Mineral		Canada 2021	European Union2023	South Korea 2020	USA 2022	Japan 2019	Australia 2022	South Africa 2022	India 2016	UK 2021	World Bank 2020	Listed in
1	REEs	+	+	+	+	+	+	+	+	+	+	10/10
2	Cobalt	+	+	+	+	+	+	+	–	+	+	
3	Lithium	+	+	+	+	+	+	+	–	+	+	9/10
4	Vanadium	+	+	+	+	+	+	+	–	+	+	
5	Niobium	+	+	+	+	+	+	–	+	+	–	
6	PGM	+	+	+	+	+	+	+	–	+	–	
7	Tantalum	+	+	+	+	+	+	–	+	+	–	
8	Chromium	+	–	+	+	+	+	+	+	–	+	8/10
9	Graphite	+	+	–	+	+	+	–	+	+	+	
10	Indium	+	+	+	+	+	+	–	–	+	+	
11	Manganese	+	+	+	+	+	+	+	–	–	+	
12	Antimony	+	+	+	+	+	+	–	–	+	–	
13	Bismuth	+	+	+	+	+	+	–	–	+	–	
14	Gallium	+	+	+	+	+	+	–	–	+	–	
15	Germanium	+	+	+	+	+	+	–	+	–	–	7/10
16	Magnesium	+	+	+	+	+	+	–	–	+	–	
17	Tungsten	+	+	+	+	+	+	–	–	+	–	
18	Titanium	+	+	+	+	+	+	+	+	+	+	

Source: MNR of Canada 2022; Grohol and Veeh 2023; Hund et al. 2020.

for investments in clean energy. The fact that two countries with the world's most populous populations, India and China, are in this transformation are two very important examples in terms of predicting the limits of the need for RMs in the coming period. This will enable an increase in production and the opening of new operations in the mining sector in response to the demand that will occur in the next few years (Okyay 2018). The fact that mineral exploration activities and feasibility will last for 4–9 years will result in the mining countries speeding up their plans to prepare mining operations and product recovery facilities by completing the mineral exploration and investment phases much faster to meet the required demand in the face of the said RM demand. Under these circumstances, it is a matter of curiosity whether the CRMs required for the TOGG factory established by Turkey can be ensured in the medium and long term. The production of mineral resources from domestic resources can be a strategic orientation in a world where RM supply is risky.

1. Scope and method

Considering the deficiencies in the literature (Section 3), in this study, the contributions of these CRMs, which have been discovered in Turkey and have resource potential, to the TOGG EV factory if the deposits are exploited have been determined. The estimation of Turkey's future demands for these CRMs, and the current and future reserve potential and projects that can be produced in proportion to these demands have been evaluated. By making a comparison with similar ore reserves and deposits in the world in terms of the raw materials in question, preliminary determinations have been made as to whether the reserve potential in Turkey will be feasible. Considering the TOGG factory operating life and the capacity of the Li-battery factory, an evaluation was made on how many EVs the current apparent reserve potential of the raw materials in question would be enough to produce in total. Thus, the study serves as a key strategic guide for investors and policymakers of countries that produce or aim to produce domestic EVs. In the study, the Li-ion batteries needed for EV production, etc. The production factories of the materials, their capacities, and feasible projects are also mentioned. Thus, the study also serves as a guide for investment projects of raw materials and materials needed directly or indirectly in EV production in Turkey. This article, which offers suggestions for solving CRM problems throughout TOGG's operational life, will also increase the number of mineral exploration projects in Turkey. The scope of the article is as follows:

- In Section 2, after the decision to establish a domestic automobile factory, Turkey's electric automobile production targets and the Li-battery investments that support it are explained.
- In Section 3, possible CRM requirements for Turkey's EV target are analyzed. In the last sub-title of the section, the reserve/resource potentials in Turkey are presented as a general summary. To determine Turkey's potential position, the reserve potential required by the EV in Turkey was compared with the rest of the world (with USGS

data). Considering the world's reserve potential of Li, Ni, Co, Mn, C, and REEs, which are the RMs examined for this purpose, it has been discussed whether the reserve potentials in Turkey are sufficient for the future TOGG production target and capacity.

- In Section 4, the literature on CRMs and in particular the supply risks of the raw materials on the EU CRM list that TOGG needs in the world and the automotive sector are reviewed and discussed together with the findings of the study. In the last part of the Section, it is stated which gap in the literature the study fills.

2. Possible CRMs requirement for Turkey's EV target

2.1. Turkey's domestic EV targets and investments

The automobile sector is one of the sectors that has the most important share of the Turkish economy. As of the end of February 2023, Turkey's exports exceeded 32 billion dollars (URL-5) in Turkey's exports of automobiles and related sub-industry in one year. In the same period (March 2022–February 2023), the annual export total in Turkey was ~255 billion dollars (Ministry of Trade and TurkStat 2023). This constitutes 12.5% of total exports. In addition, according to the Automotive Manufacturers Association (OSD) (URL-2), it is stated that the automotive industry production constitutes 5.5% of Turkey's GDP. It is stated by OSD that the direct employment of the automobile industry constitutes 11% of the total industrial employment and 7.3% of the total tax revenues of Turkey. As stated in the Introduction, the transition to EV includes significant opportunities at this stage. In countries such as Turkey, where the traditional automotive industry has such an important place, adapting to this change can be seen as a struggle for the survival of the automotive industry. Because the cost of not keeping up with this process can have devastating consequences for the economy and employment. Therefore, Turkey's participation in the transformation process from conventional internal combustion vehicles to EVs is of critical economic importance. Of course, some steps are being taken in this regard. Various projects have been developed for EVs and Li-ion batteries intended to be used in EVs, not only in the developed countries mentioned in the Introduction but also in Turkey. These are briefly as follows:

- Aspilsan Energy NMC (Ni, Mn, and Co) type 220 MWh facility (URL-3; URL-12) where Li-ion battery production started. The production capacity of this facility is planned to be increased to 30 GWh in 2030 (Doğankaya 2020; URL-4). "ETİ Maden" enterprise cooperates with ASPİLSAN and ASELSAN to use the Li carbonate it produces in the production of Li-ion batteries. Within the scope of this cooperation, Li carbonate, which Eti Maden started trial production at Kırka Boron Operations Directorate, will be used in Li-ion batteries to be produced by ASPİLSAN. Batteries with trial production will also be tested in field applications by ASELSAN. This cooperation will develop the technology for the process from RM to the final product with the knowledge and experience of three big companies in Turkey.

- Along with the TOGG production project, it is planned to build a Li-ion battery factory with a capacity of 20 GWh (Gökkoyun 2021) and type NMC 811 (Durdak 2020), which will be established in partnership with TOGG and Farasis, most of which will be used in TOGG EV.
- Ford, LG Energy Solution, and Koç Holding have a Li-ion battery investment in Ankara that they plan to start production in 2026 (Koç 2023). Its initial capacity is planned to be 25 GWh and to be increased to 45 GWh.
- An LFP-type Li-ion battery investment (Varank 2022; KAP 2022) with a first phase of 250 MWh and a total capacity of 1 GWh is planned in Ankara by Kontrolmatik (Table 2). As it should be noted, if the Li-ion battery investments announced to the public so far are realized, a production capacity of 45.5 GWh will be reached in the short term and 96 GWh if the long-term targets are realized.

Table 2. Li-battery investments in Turkey

Tabela 2. Inwestycje w baterie litowe w Turcji

Company	Short-term, 2030 (GWh)	Long-term, 2040 (GWh)
Aspilsan	0.22	30
TOGG	20	20
Ford/LG/Koç	25	45
Kontrolmatik	0.25	1
Total	45.47	96

As an electric vehicle investment, considering that TOGG (URL-5) is a domestic brand, opened on 29/10/2022 and started production in 2023, and planned production capacity, it can be considered the most important investment in recent years for Turkey (Uysal 2021c). It can be said that the most important features that distinguish an EV from a conventional internal combustion vehicle are its battery and engine (Figure 2) (Samsung SDI 2018). It will also be important to be able to produce these two important parts, especially the Li-ion battery, which will be the main energy resource, from domestic resources.

2.2. Possible CRM requirement for TOGG target

TOGG factory offered models with a battery capacity of 52.4 kWh and a range of 314 km, as well as models with a battery capacity of 88.5 kWh and a range of 523 km (URL-5).

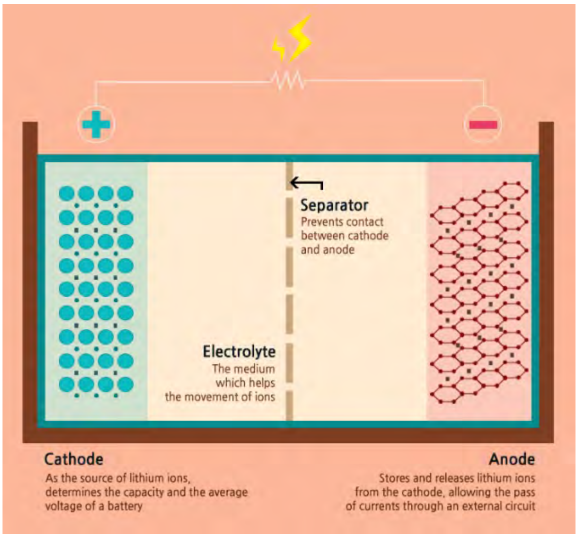

Fig. 2. General structure of the Li-battery and its 4 main components (Samsung SDI 2018)

Rys. 2. Ogólna budowa akumulatora Li i jego 4 głównych elementów

To be used in TOGG EV, a 20 GWh Li-ion battery investment of the NMC 811 type and Farasis partnership is envisaged, as stated above. The fact that this product is made with domestic resources will both increase TOGG's domestic material usage rate and ensure that the country gets a larger share of the value to be produced. At this point, creating employment, more importantly, being competitive in domestic and international markets, and ensuring supply security should be the priority. First of all, it is important to create a mineral requirement list for the TOGG factory, especially to answer the question of which domestic resources will be needed to ensure the planned continuous production of TOGG. The mineral demand forecasts created by the IEA by preparing different scenarios such as comprehensive studies, determined policies (STEPS), SDSs, and the inferences that can be obtained from these forecasts form the basis of the analysis in this paper. The total mineral demand of EVs is presented in Table 3. Based on Table 3, an estimation can be made about Turkey's probable RM requirement. By focusing on Li, Ni, Co, Mn, C, and REEs required in the manufacture of Li-ion batteries and electric motors, the required amount of RMs per GWh can be calculated. In this case, the results in Table 3 appear. Since the data in Table 3 show some differences, it would be more appropriate to use the average of all three data to make a general estimation. Especially for Li, it would be more accurate to evaluate it as the equivalent of Li carbonate to make it easier to understand. With the help of the periodic table, it is possible to calculate the Li and Li carbonate cycle: According to the Periodic Table, the atomic weights are Li =6.94, O = 15.999, and C = 12.011. $Li_2CO_3 / Li_2 = ((6.94 \cdot 2) + 12.011 + (15.999 \cdot 3))/ /(6.94 \cdot 2) = 5.32$ coefficient is calculated. In summary, when the element Li content is multiplied by the coefficient of 5.32, its Li carbonate content is obtained. (Thus, in Table 3,

Table 3. a) Total mineral demand of EVs (IEA 2022), b) RMs requirement per GWh, c) RMs needs for EVs in Turkey

Tabela 3. a) Całkowite zapotrzebowanie na minerały pojazdów EV (IEA 2022), b) Zapotrzebowanie RM na GWh, c) Zapotrzebowanie RM na pojazdy EV w Turcji

Minerals/ years and tons	Total mineral demand of EVs (tons) and minerals required per GWh (tons)/GWh)										EV RM need of Türkiye		
	for 160 GWh in 2020		for 1800 GWh in 2030 STEPS		for 1800 GWh in 2040, STEPS		for 1800 GWh in 2030, SDS		for 6200 GWh in 2040, SDS		20 GWh	45.5 GWh	96 GWh
	tons	tons/GWh	tons	tons/GWh	tons	tons/GWh	tons	tons/GWh	tons	tons/GWh	tons	tons	tons
Li	20,000	125	152,000	N/A	248,000	138	358,000	N/A	859,000	139	14,234	32,360	68,322
Ni	80,000	500	647,000	N/A	950,000	528	1,567,000	N/A	3,287,000	530	10,386	23,613	49,854
Co	21,000	131	106,000	N/A	127,000	71	257,000	N/A	441,000	71	1,820	4,137	8,734
Mn	25,000	156	102,000	N/A	117,000	65	246,000	N/A	404,000	65	1,909	4,341	9,165
C	141,000	881	1,065,000	N/A	1,027,000	571	2,499,000	N/A	3,569,000	576	13,516	30,729	64,878
Si	0	N/A	8,000	N/A	26,000	N/A	20,000	N/A	90,000	N/A	N/A	N/A	N/A
REEs	2	13	11,000	N/A	14,000	8	23,000	N/A	35,000	6	173	393	830

the three columns under "EV RM need in Turkey" are given as Li carbonate equivalents, and the other columns except for these columns are given as elementary Li). In light of all these calculations, the RM needs can be estimated for the 20 GWh capacity to be established in partnership with TOGG and Farasis, and for the total 96 GWh capacity planned to be established in Turkey in the long term (Table 3c). As can be seen from Table 3c, a high level of RM resources will be needed even for the planned capacity for TOGG production.

As can be seen, the RMs that will be needed the most from 2025 are graphite of the quality required for the annual production of ~16 thousand tons of batteries and ~11 thousand tons of Li carbonate per year. In the next 10 years, these productions will need to be increased by ~5 times. Of course, it is not enough to produce these RMs only as ore. The processes necessary to bring them to high purity will also need to be developed. Value-added products will be key here (Uysal 2021c). The primary question to be answered here is what is the potential of Turkey in these RMs.

UMREK was established in Turkey on 07/09/2016 to make reports by CRIRSCO (Demirkan 2018; URL-1). In 2018, the first CRIRSCO-approved resource and reserve reporting code was published in Turkey (URL-6). Before this, it would be more accurate to call the data that do not comply with the reporting codes as potential, since the terms "resource" and "reserve" did not have a definition in international standards in the past years in Turkey. Therefore, in the following headings, instead of naming data as "resource" or "reserve", the data are called "potential" (reserve or resource) not to cause conceptual confusion. The resource potentials of Li, Ni, Co, Mn, C, and REE, which are among the main RMs to be used in TOGG production, are presented in the following sub-headings, respectively.

3. Determined resource/reserve potentials of Turkey and the World

3.1. Lithium

3.1.1. Lithium in the World

Although the existence of more than 150 Li-containing minerals is known, very few of them are of commercial importance. Li minerals of commercial importance are spodumene, lepidolite, petalite and ambligonite (İnci and Aydın 2010). As the most abundant Li ore, spodumene can be considered the most important of these. Although Li is a relatively abundant element in nature, few of the resource-containing sites have sufficient concentration and generally acceptable mining conditions. Salt deposits containing Li, constituting ~60% of the identified reserves, are the primary resource of Li. ~78% of these resources are found in salt lakes or salt flats (dried salt lakes) with Li densities ranging from 0.2 to 6.0 gr/liter. A low level of Li recovery is possible from salt lakes, mineralized water from geothermal resources, concentrates from oil reservoirs, as well as from desalination effluents, and sea salt. Other important primary resources of Li are Li-containing ores and Li clays. In ores, the highest concentrations of Li are found in granitic pegmatites. Typical grades of, e.g. spodumene and petalite are in the 1–2% Li_2O range. Often these low grades may require a beneficiation step before metallurgical processing of the ore and Li leaching (Akgök and Şahiner 2017; Çelebi and Dönmez 2018; Şengüler 2021; Işık and Özkan 2023).

As mentioned above, geologically, Li resources are known to be rich. However, the issue of concern is the concentration of resources in certain geographical areas and the control of reserves. More than 60% of worldwide Li reserves are located in Latin America (Chile and Argentina), while other resources are in China (22%) and Australia (17%) (Aydin 2020). Australia realized 43% of global Li production in 2017 and has become the leader in the world (Metso 2020). Another concern is the inability of worldwide production to meet the needs Szlugaj and Radwanek-Bąk 2022; Kustra et al. 2023; Mining Turkey Magazine 2023). When the mining sector is examined, the supply of RMs seems to be able to adapt to the need, but short-term supply interruptions may cause problems in the battery and EV sectors (Kavanagh et al. 2018; Aydın 2020). Countries that have an important place in Li production are Argentina, Chile, Bolivia, Brazil, Australia, China, Zimbabwe, and Portugal. Li carbonate production was 228,000 tons in 2017, and it was ~690,000 tons in 2022 (USGS 2023). However, the biggest question mark in this regard is that Li is widely available in nature and that increasing production only in South Africa and Australia will meet the demand. Considering the increase in the amount of resources identified due to the ongoing exploration works, it has been stated by the USGS that the Li resource in the world is over 53 million tons (Çelebi and Dönmez 2018).

3.1.2. Lithium in Turkey

According to the Li reports of (Akgök and Şahiner 2017), it was determined that "no significant Li resource was found" in the studies conducted between 1936 and 2016 within the body of MTA. However, the use of Li resources in Turkey is not sufficient for the current domestic needs. It is predicted that a potential increase in Li prices worldwide will be observed together with the increase in demand (Szlugaj and Radwanek-Bąk 2022). This potential shows the necessity of giving importance to Li exploration and enrichment studies, considering Turkey's use of technology, and potential technological and economic development (Çelebi and Dönmez 2018).

The most comprehensive studies on the presence of Li in Turkey are those conducted by (Mordoğan and Helvacı 1994). In the results of this study, it was determined that there is a large amount of Li in the clays, especially in the boron deposits. For comparison, these data were converted to Li carbonate and calculated the arithmetic averages for each zone (Table 4). It has been determined that Turkey has more than 70% of the world's boron assets with a boron potential of 3.3 billion tons (Eti Maden 2022). The distribution of this reserve/ /resource potential is presented in Table 5. Li is found in all boron deposits, with the highest rate in Kırka. When a general arithmetic average is taken, it is possible to reach an average of 0.60% LCE (Li carbonate equivalent). Considering the boron reserve in question, this is an important finding. In light of these data, the results obtained when a Li carbonate resource potential calculation due to boron deposits is made are presented in Table 5. As can be seen, it is possible to talk about the existence of a large Li resource potential depending on the boron deposits. Eti Maden Inc. started a study on this subject and commissioned a pilot plant in 2020. In this facility, 3 tons of ore from 12 tons of RM and 1 ton of refined products from 3 tons of ore are produced (Uysal 2021b). Assuming that there is a production of 4 tons of waste per ton of ore and that these wastes probably contain Li, it can be estimated that the resource potential can reach much larger dimensions.

In recent years, the need for Li and its compounds of 1,000–1,200 tons per year in Turkey has been met through imports. There is currently no known resource of Li with economic value in Turkey (Maraşlıoğlu 2021). After TOGG starts production, e.g. in 2035, the annual need for Li carbonate in Turkey will be ~64 thousand tons (Uysal 2021b). Considering these data, existing Li projects in the country will gain importance.

Projects for the production of Li carbonate and salable boron products by recovering the boron and Li contained in the weak solution released in the production facilities during the boron production process were conducted by Eti Maden. Eti Maden conducted Li recovery studies from factory waste solutions. (E.g., Eti Maden Inc. has developed a project in Bandırma, Balıkesir, where it is planned to produce 120 tons of Li annually through the recovery of boron wastes). The production method in question differs from traditional methods. To protect the method, a patent process has been initiated on behalf of Eti Maden (Dönmez 2020b; Mining Turkey Magazine 2022c; Eti Maden 2022). For comparison, Li, Ni, and Co recovery from LIB, see (Tabelin et al. 2021; Celep et al. 2023). Here, it is understood that the Li dissolved in the liquid wastes of the facility is recovered. There is no mention of a study on other wastes. Within the scope of this study, Li carbonate production has started at the Eti Maden Facilities, which was established in the Kırka District of the Seyitgazi District of Eskişehir. The first Li carbonate was produced at the pilot Li production facility within the Technology Development Center. It is aimed to increase the capacity of the facility, where 10 tons of Li carbonate will be produced annually, to 600 tons with new investments. In this way, it is aimed to meet ~50% of Turkey's industry-oriented Li carbonate need, which is met through imports (Açık 2020; Dönmez 2020a, 2020b, 2022; YMGV 2021a, 2021b). 600 tons of Li carbonate production – before TOGG started production in Turkey – could only meet half of the domestic need in 2021. However, this amount of production is still at a very micro scale in terms of evaluating the identified potential. In light of these data, the amount of Li carbonate that only TOGG will need in its batteries will be over 11 thousand tons. Only 5% of this can be met with 600 tons of production. When the production target of 1 million units is reached in 2035, even 1% of the annual 64 thousand tons of Li carbonate needed for TOGG will probably not be met (Uysal 2021b). In return, hundreds of millions of USD will have to be spent each year to meet this demand. Of course, the question to be asked here is whether there are sufficient mineral resources in Turkey to meet this Li need.

Table 4. Li presence in clays in boron deposits

Tabela 4. Obecność Li w iłach w złożach boru

Region	Sample locations	Li%	Li Carbonate (%)	Mean LCE (%)
Bigadiç	Acep open-pit above the boron zone	0.21	1.12	0.69
	Clay 15m above the ore	0.02	0.11	
	Tuffy level within the carbonate unit	0.04	0.21	
	Tailing Dam – 1	0.18	0.96	
	Tailing Dam – 2	0.21	1.12	
	Tülü open-pit is the uppermost nodular ore	0.07	0.37	
	Günevi open-pit	0.18	0.96	
	Simav open-pit	0.13	0.69	
Sultançayırı	Open-pit – Medium	0.08	0.43	0.29
	Clay – 1	0.05	0.27	
	Clay – 2	0.04	0.21	
	Clay – 3	0.05	0.27	
Kestelek	Opposite the open-pit mine	0.07	0.37	0.39
	The upper zone of open-pit	0.08	0.43	
	The lower zone of the open-pit	0.07	0.37	
Emet	Clay stone	0.12	0.64	0.42
	Example of weathered tuffite	0.07	0.37	
	Espey open-pit 2nd ore zone	0.07	0.37	
	Espey open-pit 2/3 ore zone	0.05	0.27	
	Espey open-pit 3rd ore zone	0.08	0.43	
	Espey open-pit concentrated slam pool	0.08	0.43	
Kırka	Dolomitic clay in a large borax crystal	0.30	1.60	0.98
	Dolomitic clay at the eastern fault contact	0.08	0.43	
	Unweathered tuff at the eastern fault contact	0.04	0.21	
	Intermediate green clay in ore	0.26	1.38	
	Ulexite top clay	0.16	0.85	
	Ulexite zone clay	0.26	1.38	

Revised from: Mordoğan and Helvacı 1994.

Table 5. Eti Maden's resource potential amounts

Tabela 5. Wielkość potencjału zasobów Eti Maden

Basin Name	Quantity (ton)	Share (%)	Mean LCE (%)	LCE Content (tons)
Emet	1,803,491,939	55.8	0.42	7,574,666
Kırka	811,468,299	25.1	0.98	7,952,389
Bigadiç	614,649,966	19.0	0.69	4,241,085
Kestelek	5,254,923	0.2	0.39	20,494
Total	3,234,865,127	100	0.61	19,788,634

As explained above, Li production is mainly made from spodumene in hard rocks and salts called "Brine" (Latham ve Kilbey 2019). Apart from that, Li in clay deposits also came to be seen as a source on a large scale. In this context, Li, which is thought to be bound to clays in boron deposits, can also be seen as a remarkable resource. Eti Maden was able to partially recover a certain part of the Li in the boron deposits with its pilot study (Uysal 2021b). When all these studies and the data in the explanations are considered correct, if only the boron ore production and the annual 37 thousand tons (~500 million USD worth) wastes are also evaluated, a Li carbonate production of close to 150 thousand tons (~2 billion USD) can theoretically be possible. Considering the ~3.3 billion tons of boron reserve in Turkey, and probably ~4 times the amount of ore and waste, it can be thought that the value of Li reserves can reach hundreds of billions of USD or even trillions of dollars. Of course, it cannot be claimed that these calculations and data are 100% correct. However, it needs to consider what dimensions the Li resource potential in Turkey can reach within the framework of the available information. These data also create a positive impression on the transfer of high-level resources to R&D projects to be conducted on a subject that can generate billions of USD of income every year. It is to show that if these studies are successful and this potential can be evaluated, e.g., a ~100 million dollar search and R&D budget to be allocated as a monetary resource can create an added value of hundreds of billions of USD. It cannot be claimed that this could be easy to achieve. However, it would be beneficial for Turkey to value a potential asset at this level at least as much as the value given to oil and natural gas. Because, there are various projects and studies on this subject in the world (Uysal 2021b). For, there is the Clayton Valley Lithium Project developed in the Nevada region for the production of Li from the aforementioned clays (URL-16). As can be seen from this project, in the pre-feasibility studies conducted by allocating large monetary resources, it has been determined that even a Li presence of around 1,100 ppm in clays can be operated economically (This data is equal to the 0.6% content it was calculated above as Li carbonate).

Li is present in geothermal resources at low but potentially significant concentrations. It is estimated that ~14 million tons of Li can be recovered from rocks and salt waters worldwide. Seawater also contains high levels of Li, but its concentration is very low

(0.1–0.2 ppm) (Şengüler 2021). Li concentrations of geothermal brines are reported as 13 ppm in the Berlin geothermal field (Monterrosa 2003), 300 ppm in the Salton Sea region of California (Hoffman 1975), and 970 ppm in Lake Zabuye in China (Sailer 2000). It is reported as 30 ppm (Karaca et al. 2003) in wells in Tuzla-Çanakkale Region in Turkey. In Turkey, the Li concentration in Tuz Gölü is given as 325 ppm, but it is not considered a geothermal brine (Helvaci et al. 2004). Li can be extracted from geothermal fluids as Li salts by direct precipitation. The advantage of this method is its high quantitative efficiency. However, if the geothermal resource is rich in various metal components, it may be possible to obtain metal salts as a result of processes such as precipitation and purification. For Li concentrations of some geothermal fluids in Turkey, see (Çetiner et al. 2015).

It is known that Li found in boron deposits is generally associated with clays. In an article published on this subject (Treleaven 2023), it is stated that the interest in obtaining Li from clays as a third option is increasing, in addition to Li obtained from salt mines and ores such as spodumene by traditional methods. It is known that Li found in boron deposits is generally associated with clays. In this article, it is stated that Li-containing clay, which can be called cation exchange, is mixed with a cation resource such as salt (NaCl) and subjected to a high-energy grinding process. Afterward, an uncomplicated method of obtaining a Li-rich solution by liquid leaching is mentioned in this article (Treleaven 2023). Tesla's automotive company is considering implementing this method (Jin ve Scheyder 2023). Of course, the successful application of this method would be feasible in terms of Li production. Thus, this method can be applied for Li recovery from boron wastes.

Similar to boron and Li mineralization, extensive feasibility studies of the Rhyolite Ridge Boron and Li project developed by Ioneer Company in the Nevada Region of the USA can be counted. As a result of these studies (URL-7), a total of 146.5 million tons of 1,600 ppm Li-containing (LCE = 0.9%) resource estimation and a total 60 million-ton average 1,800 ppm Li (LCE = 1%) reserve estimation were made. In the comprehensive feasibility study, it was determined that primarily the production of Li carbonate and the process to convert this Li carbonate to battery quality Li hydroxide can be done with an expenditure of 2,510 USD/ton on an average product basis. If similar parameters can be applied to Turkish boron wastes, it can be thought that the cost of 2510 USD/ton against the current Li hydroxide price of 59,900 USD/ton (LME 2023) can make operations with much lower grades economical. As a result, if the Li in the boron deposits can be recovered economically, it can be accepted that there is a Li resource potential where the long-term Li need for TOGG can be met from Turkey for many years.

A comparison can be made about the claim that Turkey may have the world's largest Li reserves. Among the world Li reserves, Chile is the first with 9.2 million tons, Australia is the second with 4.7 million tons, and Argentina is the third with 1.9 million tons (Table 12). Considering that 3.3 billion tons of boron reserves in Turkey may have 3.7 million tons of Li metal content, Turkey will rank 3rd. It can be thought that it would be theoretically possible for this amount to exceed 10 million tons if the existing stored tailings are evaluated. In this case, it turns out that Turkey can take first place (Uysal 2021b).

3.2. Nickel

3.2.1. Nickel in the World

In nature; Ni, found in the form of oxides, sulfides, and silicates, is generally produced from two types of ore deposits, lateritic and sulfide. It is estimated that ~60% of the Ni ore known in the world is located in laterites and 40% in sulfide deposits. On the other hand, ~45% of the world's Ni production is realized from lateritic ore deposits. Another type of deposit is considered a hydrothermal deposit, which, despite its relatively high grades, has small reserves and is less important (Okyay 2020b; Mining Turkey Magazine 2021b). Ni resources with a grade of 0.5% or higher in the world are estimated to have a Ni metal content of at least ~300 million tons. According to the USGS data, the known Ni reserves in the world are 94 billion tons. Indonesia ranks first among the countries producing the most Ni in the world with 760 million tons. The Philippines is in the 2nd rank with 320 million tons and Russia is in the 3rd rank with 280 million tons. Canada and Australia are the countries that produce the most Ni in the world. There are also high levels of Ni production in South America. When world Ni reserves are examined, it is known that Brazil, Indonesia, the Republic of South Africa, and Cuba have significant Ni reserves as well as Canada, New Caledonia, Australia, China, and Russia (Table 12). Especially with the acceleration of the battery sector, the demand for Ni is expected to increase much faster. Industrially developed countries such as China, Japan, the USA, Germany, and South Korea are among the countries with the highest Ni demand (Okyay 2020b; Mining Turkey Magazine 2021b). It is estimated that the number of EVs will increase ~10 times in the next ~10 years. In this direction, Ni consumption is expected to increase ~5 times until 2025 (Yüngül 2018). The authorities state that the need for Ni (especially from 2025 onwards) may lead to a demand that is even higher than anticipated (Okyay 2020b). There are increasing opinions that the Ni supply will be less compared to the rapidly growing demand for the EV industry (Mining Turkey Magazine 2022b). Among the batteries to be used in EVs are NiMH (Ni metal hydride) and Ni-Cd batteries. The usage amount of Ni element in NiMH batteries is ~23% of the total mass. With the increase in the number of EVs, it is estimated that the worldwide demand for Ni will increase by 3-4% annually to meet the demand of the NiMH-based battery industry (Yılmaz 2018). In addition, there is a transition towards intensive Ni use in areas such as rechargeable battery technology, Li-ion batteries, and energy storage of EVs (Özdemir et al. 2022). Considering ~50,000 tons of Ni consumed so far, it is predicted that Ni consumption in these applications will vary between 150,000–250,000 tons annually until 2025 (Yılmaz 2018). Considering this expectation, the operation of Ni deposits in Turkey will provide significant gains for the sectors that use Ni, especially the TOGG factory.

3.2.2. Nickel in Turkey

In the reports made by MTA, it is stated that the largest Ni deposits in Turkey are located in Manisa-Turgutlu-Çaldağ, Manisa-Gördes, and Eskişehir-Mihalıççık-Yunus Emre regions. In addition, Ni deposits have been identified in Uşak-Banaz, Bitlis-Pancarlı, Bursa-Orhaneli--Yapköydere, Sivas-Divriği-Gümüş, Bolu-Mudurnu-Akçaalan, and Hatay-Payas-Dörtyol. Detailed information is given about the resource potentials of the deposits (Eroğlu and Akgök 2018):

1. In the Çaldağ region, which has the largest Ni reserve in Turkey, the total metal Ni potential of the 29.7 million ton mining site, where 1.16% Ni, 0.07% Co and 21.66% iron raw ore is available, is ~400 thousand tons.
2. It has been stated that there are ~300 thousand tons of metal Ni potential in the lateritic type Ni-containing area in the Gördes region with an average grade of ~1%. Metal Ni production started in the enrichment facilities (high-pressure leaching facility) established on the site, using hydrometallurgical methods. Thanks to this facility, commercial production has been started since 2016 and exports have been realized.
3. The Ni grade average is ~1% in the mining site located within the boundaries of Eskişehir-Mihalıççık-Yunus Emre District. It has been stated that the Ni and Fe produced in the operated field are exported abroad as raw ore.

It was mentioned that Gördes Region (URL-8) contains 68.5 million tons, 1.1% Ni and 0.08% Co, and Eskişehir Mihalıççık deposit also has 0.2–0.3% Co content (IMMIB 2022). Except for nickel deposits, copper deposits (Gümüşsoy et al. 2020) and iron deposits (Sirkeci et al. 2006) are also known to contain cobalt. It is stated that the copper mine in the Küre district of Kastamonu, which is currently being operated, contains 13 million tons of 0.3% Co (Çağatay et al. 1982). It is thought that some Mn deposits in Turkey may also contain Ni and Co (This subject has been mentioned in sub-title 3.4). With a cautious approach in the amounts given above, assuming that ~300,000 tons of metal of Gördes corresponds to ~30 million tons of ore with 1.1% Ni content, all data are presented in Table 6 as a summary.

Table 6. Reserve potentials and grades of large Ni and Co deposits in Turkey

Tabela 6. Potencjał rezerwowy i stan dużych złóż Ni i Co w Turcji

Ni and Co Deposit	Quantity (tons)	Ni (%)	Co (%)	Ni Content (tons)	Co Content (tons)
Çaldağ	29,700,000	1.14–1.16	0.05–0.07	344,520	20,790
Gördes	30,000,000	1.1–1.3	0.07–0.08	300,000	24,000
Mihalıççık	N/A	–	0.2–0.3	N/A	N/A
Küre	13,000,000	N/A	0.3	N/A	39,000
Total	59,700,000	N/A	N/A	644,520	83,790

In addition, in the reports published by MTA, it is stated that there is a determined Ni and Co metal content of 1,186,000 tons (Şahiner et al. 2021). By inference, it can be said that Ni deposits have a minimum of 1% Ni and 0.07% Co content. When these grades and MAPEG mineral production amounts (MAPEG 2022) are considered, the data on Ni and Co RM/metal production in Turkey are presented in Table 7. Turkey's first and largest Ni processing facility in Gördes district has an annual capacity of ~1.75 million tons of ore feeding and 10 thousand tons of Ni production. In the last 5 years, the enterprise has produced ~24,000 tons of Ni-equivalent concentrated products and exported all of them. Apart from this, calcine, which is the product of the sulfuric acid facility where the pyrite concentrates in the Kastamonu Küre mining facility is used as an input, is also used as the RM of the metal recovery facility in Mazıdağı Phosphate facilities in Turkey to produce 2,000 tons of cathode Cu, 2,530 tons of zinc carbonate, and 6740 tons of Co carbonate (URL-9). Thanks to the annual production of 2,500 tons of Co from the residual pyrite concentrate after the Cu concentrate is separated at the Mardin Mazıdağı Metal Recovery and Integrated Fertilizer Facilities, ~2% of the world's Co-production is realized (Mining Turkey Magazine 2022a). According to MAPEG data, 1.787 million tons of run-of-the-mill Ni ore were produced in Turkey in 2020 (Okyay 2020b). When the world's annual Ni demand and Turkey's current reserve amounts are compared, it is seen that Turkey's current reserves are very small against this demand. While the Ni reserve is estimated to be ~1 million tons in Turkey, it is stated that there is a total of 178 million tons of reserves in the world. Turkey's annual nickel consumption is ~3,800 tons (Meta Nickel Cobalt Inc. 2018). It is seen that even Turkey's largest known Ni reserves cannot meet the annual Ni demand of China. Despite these current data, the geological structure of Turkey is suitable for Ni mineralization (Mining Turkey Magazine 2021b). It is seen that 10 thousand tons of Ni metal, which is the annual need of 20 GWh TOGG production capacity, and 1,800 tons of Co metal equivalent product are currently produced in various forms such as different run-of-the-mill ore, MHP (Mixed Hydroxide Precipitation) or carbonate. It can be thought that this reserve can significantly meet the long-term capacity of 96 GWh.

3.3. Cobalt

3.3.1. Cobalt in the World

Ni and Co have similar geochemical properties and can be found together in nature. Co is usually found scattered in the earth's crust. The number of economically mineralized regions is limited. According to the calculations, the Co/Ni ratio was determined as ~4/10. In Ni and Co deposits, Ni is generally recovered as the main element and Co as a by--product. The most well-known minerals of Co are smaltine and cobaltite. (For important Co-containing ore minerals and their average grades, see (Aydın and Kılıç 2012)). Apart from this, it is found in small amounts in Co, Ni, and Cu ores (0.02–0.5%). However, it is difficult to obtain in pure form due to the difficulty of separating it from other elements. The most important Co deposits are those of magmatic origin and those of alteration type. The formation of economically exploitable Co deposits in igneous deposits is related to mesothermal Co-Ni-Ag-bismuth-uranium veins. Alteration deposits are a type of deposit where Ni and Co are separated and recovered as asbolane. Co occurs in laterite in the form of bluish-black nodules or clouds called asbolane. Asbolan is a mixture of Co, Fe, and Mn oxides, silica, and aluminum rather than a mineral. Examples of this type are the deposits formed by superficial alteration in New Calendonia and the Manisa-Çaldağ deposit. Here, there are Co enrichments formed by the lateralization of a serpentinized ultrabasic rock. Self-exploitable deposits of Co are deposits containing ~3% Co (Aydın and Kılıç 2012; Okyay 2020a). Apart from this, the most important deposits for world Co production are the Cu-Co deposits of Katanga (Zaire). Co (Linneite) is also found alongside Cu sulfides in the Cu veins of Katanga and Zimbabwe. Hydrothermal Ni deposits, on the other hand, are not mostly Ni deposits. Rather, they can be considered important for Co. Rather, they may be considered important to Co. There are Co enrichments in ferrous laterites formed as a result of the laterization of peridotite and gabbros. The most important Co deposits are located in the Shaba Copper Mines in Zaire, in central Africa. Co is found with silver in Ontario, Canada, with lead and zinc in the central US states, and with Cu in Zambia. Co is produced in 17 countries around the world. Co alone is obtained from arsenic ores found only in Morocco and Canada (Aydın and Kılıç 2012). The majority of Co metal used in the world is produced in Zambia and the DRC (Gulley 2022). According to 2018 data, DRC ranks 1st with 90,000 tons of production, Russia is 2nd with 5,900 tons of production, and Cuba is 3rd with 4,900 tons of production in the list of countries with the highest Co production. There is no alternative to Co in battery manufacturing yet. According to Bloomberg, the interest in EVs will rapidly increase the demand for Co, and the need for Co will increase from 100,000 tons in 2016 to ~450,000 tons by 2030 (Ergünalp and Yalçın 2019; Okyay 2020a).

3.3.2. Cobalt in Turkey

In sub-section 2.2.2, Co deposits and production projects were mentioned along with Ni. As a result of the research conducted to date in Turkey, there is no Co deposit on its own. However, in some Cu and Ni deposits, Co can be found in amounts that can be produced as a by-product. In new studies conducted in 2010, it was determined that Co was found in the historical slags found in the mineral deposit in Kastamonu-Küre, one of the important Cu fields of Turkey, and in the tailings dam of the mine. In a study conducted in 1981, it was stated that Co minerals were found in an economical amount in Küre deposits and that these deposits contain an average of 0.3% Co. In the same study, Linneite is shown as an important Co mineral in Küre deposits. In 2010, it was announced that the mining operation in Küre would evaluate the detected Co with appropriate technologies and that studies were continuing for this purpose. It is also known that various R&D studies were conducted by another private company to produce Co-containing compounds (Co acetate and Co hydroxide) from waste slag in the past, but the studies were terminated when sufficient efficiency could not be achieved. It is known that the Manisa-Çaldağ lateritic Ni deposit also contains Co. The ore content of ~38 million tons was determined in 1.14% Ni and 0.05% Co grade of the ore deposit. Concentrated products containing Ni and Co as semi-finished products will be obtained from this low-grade deposit. Another project belonging to the private sector in Manisa-Gördes is planned to produce 10,000 tons of Ni and 800 tons of Co salt per year. Investments were made in the mining site and the production of Ni and Co end products was started. The total reserve within the project area is 31.3 million tons, and the annual amount of ore to be mined is 1.3 million tons. The deposits contain 1.28% Ni and 0.07% Co. At the end of the operation period, it is aimed to produce 250,000 tons of Ni and 20,000 tons of Co salt. The operation process in this field consists of two separate stages. In the first stage, an intermediate product containing ~35% Ni and ~3% Co will be obtained from the ore leached under high temperature and pressure. In the second step, metallic Ni and Co salts will be obtained from this intermediate product. R&D studies continue within the scope of a Fe-Ni-Co production project in Sivas Kangal. During the enrichment of the run-of-the--mill Ni ore to be extracted from the mine site, if the Co/Ni ratio is 1/30, Co-production can also be conducted in the same ore deposit. Within the scope of the activity subject to the project, firstly open-pit operating will be conducted and Ni ore will be produced as RM, then flotation process will be applied in the ore enrichment facility and Ni-Co concentrate with a grade of ~40–45% will be produced and presented to the market (Aydın and Kılıç 2012).

3.4. Manganese

3.4.1. Manganese in the World

According to the data of USGS in 2022, 20 million tons of Mn was produced. Australia, Gabon, and South Africa realized 75.5% of the total production (Schnebele 2023).

3.4.2. Manganese in Turkey

In MTA reports, it is stated that a total of 4,744,163 tons of reserve potential containing ~35% Mn has been detected in Turkey. It is stated that this determined potential contains 1,792,500 tons of metal Mn (Şahiner et al. 2021). Only this data alone can be seen as a very low level of Mn potential. However, the sum of reserve/resource potentials reported by Mn operations in Turkey in their 2018 annual reports is ~62 million tons. As it is known, there are Mn mines in many parts of Turkey, some of which have large reserve potentials. It has been determined that an annual average of ~100 thousand tons of Mn ore has been produced in Turkey in the last 10 years (MAPEG 2022) (Table 7). Assuming that the average grade of this total production contains 35% Mn, it can be estimated that the run-of-the-mill ore with an average annual Mn metal content of 35 thousand tons is produced. Euro Manganese,

Table 7. Mn, C, Ni and Co productions in Turkey

Tabela 7. Produkcja Mn, C, Ni i Co w Turcji

Year	Mn (raw) Production (tons)	C Production (tons)	Ni (raw) Production (tons)	Co production (as metal) (tons)
2022	64,203	27,715	1,286,313	900
2021	86,654	28,336	1,030,670	721
2020	101,766	15,205	1,787,714	1,251
2019	114,037	9,990	419,659	294
2018	85,334	16,752	1,199,943	840
2017	77,895	0	1,306,800	915
2016	46,867	0	826,285	578
2015	142,809	0	764,346	535
2014	24,583	3,850	268,545	188
2013	321,785	28,740	95,187	67
2012	192,756	31,500	337,530	24

Li and REE productions are not yet realized in Turkey. Co production was not reported as production in the MAPEG data. In "META Nickel", which produces, Ni and Co, called MHP, are sold as concentrated Ni in mixed form.

which developed the Chvaletice Mn project in the Czech Republic, aims to produce high-purity Mn sulfate monohydrate that can be used in Li-ion batteries by processing the wastes containing Mn within the scope of the project. This firm claims this project has a net present value of USD 1.3 billion with an IRR of 22%. The resource and reserve status of the project are presented in Table 8. Apart from this, South32 company, which can be considered one of the largest mining companies in the world, plans to produce Mn chemicals for use in EVs in the USA. For this purpose, it is estimated that there are 55 million tons of reserves with 9% Mn grade developed by Clark Deposit (Fernyhough 2022). Compared with these data, it can be concluded that Turkey's reserve potential of over 4 million tons with 35% Mn content can be exploited for EVs. It can be said that ~2 thousand tons of Mn are needed for 20 GWh TOGG production and ~9 thousand tons of Mn in the long run can already be produced as ore and that sufficient Mn reserve potential exists in Turkey.

Especially in recent years, it has been mentioned about the recovery of Mn ores within the scope of deep seabed mining. It is evaluated that deep seabed mining can play an important role in the clean energy transformation. It is thought that Mn nodules in areas up to 5,000 meters of the sea may constitute an important reserve resource thanks to the Ni, Co, and Cu they contain (Kenza and Harry 2023). In this context, the geological evolution of Turkey is an E-W trending component of the Alpine-Himalayan Orogenic Belt, which is observed as a border between Lavrasia in the north and Gondwana in the south. The Alpine Orogenic system is formed by the closure of different branches of the Tethys Ocean. During the closure of the Tethys Ocean, different continental fragments of the Gondwana and Lavrasya continents collided. Turkey is in the form of an orogenic mosaic with these continental fragments and the residual oceanic materials between these fragments. Mn mineralizations observed in radiolarite cherts, which are located within the borders of Çorum and Yozgat provinces and developed depending on Alpine ophiolites, were investigated. Mn up to 60% and Co contents up to 1432 ppm were found in these mineralizations (Öksüz and Karakuş 2010). Therefore, the fact that this region is located on land increases its importance compared to mining to be carried out from thousands of meters of the sea. In addition, it can be thought that this region may have great resource potential in terms of both Mn and Co since it was a sea floor millions of years ago (Nizamoğlu 2014; Ehsani and Kesimal 2015; Ehsani and Sivrikaya 2018).

Table 8. Comparisons for Mn, C, and REEs and grades

Tabela 8. Porównania dla Mn, C i REE oraz ich klas

EuroManganes Company Mn tonnages and grades			
Resource and Reserve	Amount (tons)	Mn grades (%)	Mn content (tons)
Total Reserve	26,644,000	7.4	1,974,320
Total Resource	26,960,000	7.3	1,976,168
Detailed studies on graphite			
In Turkey	Potential (tons)	C grades (%)	C content (tons)
Karabacak-Oysu	7,200,000	5.8	417,600
Kastamonu Doğanyur	4,500,000	6.1	272,700
Kahramanmaraş-Fındıklıkoyak	2,300,000	5.6	128,800
Total	14,000,000	5.9	819,100
Eskişehir-Beylikova REE potential			
	Potential (tons)	TREO grades (%)	RE Oxide content (tons)
	694,000,000	1.75	12,145,000
Lynas Mount Weld Project			
	Amount (tons)	TREO grades (%)	RE Oxide content (tons)
Total Reserve	19,500,000	8.5	1,648,000
Total Resource	55,200,000	5.4	2,980,000

Euro Manganese Company resources and reserves are quoted from (Euro Manganese 2023).

3.5. Graphite

3.5.1. Graphite in the World

C can first be divided into two main classes. These are synthetic C and natural graphite. Since synthetic graphite is an industrial product rather than a natural resource, the focus can be on natural C, which is the basis for mining (Uysal 2021a). It is possible to divide natural C into 3 main classes (URL-13): Amorphous C (also known as microcrystalline or cryptocrystalline C), flake C, and crystalline C. This classification is directly related to the structure of the element carbon in graphite (Uysal 2012, 2020b). The grade of crystal C is the highest (Devrim 2015). C used in batteries can be 6-15 times the amount of Li (Ergünalp 2014).

In 2018, the world's total C supply was ~2.52 million tons. Of this, 62%, 1.57 million tons, is synthetic, and 38%, 0.95 million tons, is natural C. Natural C consists of 71% flake C, less than 1% Sri Lankan C and the remaining 28% amorphous C. China alone accounts for 50% of the total synthetic C supply and 60% of the natural C supply. Other major producers are North Korea, Brazil, Mexico, Canada, Norway, Madagascar, and Sri Lanka (Moores 2012; Roberts 2012; Devrim 2015; Uysal 2020). Worldwide consumption of C has been increasing steadily since 2011. Natural C production is ~1 million tons per year. Amorphous C constitutes ~60% of the total production. C demand is expected to increase by ~4% in the coming years (Jara et al. 2019). Between 2011 and 2019, China produced ~6.8 million tons of C, which corresponds to ~10% of the country's reserves and ~5% of the world's C reserves. Brazil is followed by China and Madagascar (Table 12). Amorphous C is mostly used in the steel and refractory industries. The increase in steel demand will also increase the demand for C. However, it is very difficult to find amorphous C in sufficient and desired grades to support this demand. China, Turkey, India, and Brazil, which are the countries where global amorphous C reserves are concentrated, will play an important role in this demand chain in the future (İlhan et al. 2020). The main producing and exporting countries are China, North Korea, and Brazil. Among the importing countries are the USA, China, the EU, and Turkey. Due to the shortage of available high-grade flake or vein-type C resources, supply-demand mismatch, will be a global problem in the future. Developing compatible purification methods for both new mineral deposit discoveries in natural C exploration sites and for impurities in C is critical for countries with C production potential (Jara et al. 2019).

3.5.2. Graphite in Turkey

A small number of C deposits with economic value have been identified in more than 22 regions by MTA (MTA 2018). According to these determinations, almost all of the formations in Turkey are amorphous C. There are no very detailed studies on C in Turkey, except for a few fields. However, in the studies conducted, information is given about the potential regions. This information consists of the reserves of the parts that can be seen and determined as a result of the surface studies (Uysal 2012). The only known active graphite operation in Turkey is located in Kütahya Oysu. The mining operation came into operation in the early 1990s. However, between 1993 and 2004, production was suspended for economic and technological reasons. The increase in C demand after 2004 enabled the re-establishment of the graphite flotation process in the Oysu deposit (Urcun 2008; Uysal 2012). It is known that this company produced graphite concentrate in the Kütahya-Oysu graphite project and had a resource report made in the JORC code related to this project. The deposit contains 7.2 million tons of graphite ore with 5.8% organic carbon content and potentially 125 million tons of C ore. It is mentioned that there is C mineralization in the region at deeper depths (more than 225 m) and that there is a mine life of 15 years. (Karabacakmaden 2012; Tufan and Batar 2015; Nardera 2018). The facility in Kütahya-Altıntaş is designed to produce 22,000 tons of raw C and 8,000 tons of enriched C per year if it operates at full capacity (Ergin 2014). In addition, when the MTA data are examined, a resource study has been conducted by the UMREK code related to two C fields in recent years (MTA 2018). As a result of the enrichment tests of MTA's C field in Kastamonu-Doğanyurt, 4.5 million tons of C resource with 6.06% carbon content was estimated (Pehlevan 2019). In the graphite field of MTA located in Kahramanmaraş-Göksun-Fındıklıkoyak Village, 2.3 million tons of C resource with 5.6% carbon content was estimated according to the drilling results made by MTA in 2017 in the license area (Yığmatepe 2019). Apart from this, graphite studies of different companies continue. It is expected that deposits of similar size will be discovered, especially in the Kastamonu region (URL-10). The fact that the above-mentioned three examples have resource estimation reports in JORC and UMREK standards and the studies conducted are quite detailed necessitates the acceptance of the high reliability of these data. The three examples are summarized in Table 8. To get an idea about whether these results have an economic significance or not, it is necessary to present different data to compare these data. Especially in recent years, it is seen that there is a concentration on the African continent in terms of C projects. In this region, there are projects whose feasibility has been completed, have passed the construction and production stages, and therefore have been decided to be economically viable. These projects, which mainly target the Li-ion battery market, are presented in Table 9. In these graphite fields, projects with a grade lower than the average grade of 5.9% were also evaluated. Therefore, it is noteworthy that over 800 thousand tons of C with an average grade of 5.9% were detected in the 3 C fields in Turkey where detailed studies were conducted. It can be said that this resource potential will be sufficient to meet the annual C demand of 13 thousand tons for 20 GWh Li-ion batteries to be used in TOGG EVs and the annual C demand of 64 thousand tons that may be needed in the long term for a reasonable period. It can be estimated that even the values in the USGS reserve scale can be approached thanks to the determination of the resource potentials in other C fields with the studies to be conducted.

As stated above, global C production is ~1 million tons. China produces ~70% of this. There is only one C operation in Turkey. This operation produces ~2,000 tons per year. However, the C import is ~11,000 tons (Ergünalp 2021). Turkey is not competitive in the

Table 9. Some graphite projects that have completed the feasibility stage in the African continent

Tabela 9. Wybrane projekty grafitowe, które zakończyły fazę wykonalności na kontynencie afrykańskim

Project	Company	Country	TGC grade (%)	C content (million tons/year)	Planned capacity (thousand tons/year)
Balama	Syrah Resources Ltd.	Mozambique	15.7	16.8	313.0
Montepuez Centre	Battery Minerals Ltd.	Mozambique	9.3	3.9	100.0
Epanko	EcoGraf	Tanzania	8.3	1.0	60.0
Mahenge	Black Rock Mining Ltd	Tanzania	8.5	6.0	340.0
Nachu	Magnis Energy Ltd.	Tanzania	4.8	3.6	235.0
Chilalo	Evolution Energy Mineral Ltd.	Tanzania	9.9	0.6	50.0
Bunyu	Volt Resources Ltd.	Tanzania	4.3	5.5	23.7
Lindi Jumbo	Walkabout Resources Ltd.	Tanzania	17.9	1.0	40.0
Molo	NextSource Ltd.	Madagascar	7.0	1.6	45.2
Maniry	Evion Group NL	Madagascar	6.6	1.1	39.0
Lola	SRG Mining INC	Guinea	4.2	1.7	100.0

Source: Taylor 2022.

world market in terms of graphite production. However, domestic C needs are generally met by importing from other countries (İlhan et al. 2020). For each TOGG production, 47.6 kg of flake C will be needed. In an MTA report, it was stated that the potential of 6,886,736 tons of 2–17% C, unreachable C potential was determined in Turkey (Şahiner et al. 2021). On the other hand, according to USGS data, with a reserve of 90 million tons, Turkey alone has 27% of the world's total C reserves and is the country with the largest C potential (USGS 2023). According to the production data, C is also produced in Turkey (Table 8). Provided that it has the right crystal structure, the need for C used in TOGG production can be met in the future, thanks to the development of the process, considering the C deposits determined by MTA and achieving 99% purity of the C.

14% (133,000 tons) of natural C produced in the world is used in battery production, mainly in Li-ion batteries (Uysal 2021a). In addition, it is known that major automobile manufacturers have invested over 300 billion USD in EV and Li-ion battery production, and over 100 billion USD of this is for Li-ion batteries (URL-14). With all these investments, it is estimated that the Li-ion battery production capacity will exceed 2000 GWh/year in 2028 and the C demand will be 2.4 million tons if all this capacity can be used (Benchmark Mineral Intelligence 2019). Of course, this is the situation that will emerge as a result of the positive scenario. Even if half of this built capacity is used in the next 10 years, the C required for batteries will be ~10 times the current usage. This creates a demand more than the total natural C production (Uysal 2020). As can be seen, C, which has an increasing use in Li-ion batteries in Turkey, will emerge as a need of 650 million USD and 93 thousand tons of anode in 2035, only as TOGG's need. Moreover, according to USGS data, while there are 1.1 million tons of (URL-15) world C ore production in 2019, only Turkey will have a demand of nearly 250 thousand tons. If this production is not increased in proportion to the demand, a high level of supply security problem will arise in the market. For this reason, the development of domestic resources is important not only economically, but also in terms of ensuring the supply security of the sectors using RMs and continuing production.

As stated above, almost all C in Turkey falls under the amorphous C classification in the world, and most of them are microcrystalline formations that are disseminated in the rock. Regarding C, a situation that is not very positive at first glance, it is generally accepted that C in Turkey is of low quality and cannot be used in high technologies such as Li-ion batteries (Devrim 2015; İlhan et al. 2020). However, as mentioned above, the high Rmax of Susurluk, İnebolu, Yozgat, and Adıyaman C, which are stated to have a high degree of graphitization, may enable their use in Li-ion batteries, even if they have microcrystalline structure. E.g., MTA data mention the presence of C with Rmax between 9–11 and 4.67% carbon content in the Kastamonu Central Imam District area (URL-14). If it is possible to operate these Cs with high Rmax, it may be possible to use them in different technological products, including Li-ion batteries. In addition, although the carbon content of 4.67% seems low, it has been demonstrated by feasibility studies that much lower carbon grades can be operated economically in many projects carried out around the world. The Bissett Creek project of Northern Graphite Company in Canada can be given as an example. It has been demonstrated that the C deposit with 2% carbon content can be operated economically.

C production in Turkey has been conducted for more than 30 years as stated above. The average grade of the existing reserves in Turkey is quite high and production is quite low-cost. Even with price drops, costs in Turkey could still allow for a profitable mining operation. If the existing outcrops are examined in more detail and necessary R&D studies are conducted on high-grade and high-value-added products, Turkey will be able to reach an important position in the world in terms of C mining and products. Turkey may not have a mineral potential with very large-scale C production like Australia or South Africa. However, thanks to the right strategies, right investments, and R&D, profit, and income equivalent to large projects can be obtained (Uysal 2012).

3.6. REEs

3.6.1. REEs on Earth

Mining projects such as the Nechalacho Project (Northwest Territories, Canada), Zandkopsdrift Project (Northern Cape, South Africa), Bear Lodge Project (Wyoming, USA), Kvanefjeld Project (South Greenland), and Dubbo Zirconia Project (New South Wales, Australia) It is expected to meet ~1/3 of the total REE consumption (García et al. 2017). Various REE projects/deposits and specifications in China and other countries are presented in Table 10.

3.6.2. REEs in Turkey

Regarding REEs, an MTA report states that a reserve potential of 1,348,898 tons with 99.5% RE oxide content has been determined in Turkey (Şahiner et al. 2021). REE deposits have been identified in Eskişehir-Beylikova, Malatya-Kuluncak, Sivas, and Burdur as a result of the searches conducted by MTA in Turkey in the past years. A reserve potential of ~52 million tons with an average REE grade of 3.14% containing barite-fluorite and bastnasite in Eskişehir-Beylikova has been identified (General Directorate of Industry 2020). In the statements made in 2022, it was stated that 694 million tons of REE reserve potential were determined in the Beylikova district of Eskişehir with the studies started in 2011. It has been stated that this potential is the world's second-largest REE deposit after China's 800 million-ton reserve. It is stated that it will start with a pilot plant first and then larger capacities will be established. In this way, it has been stated that 570 thousand tons of ore will be processed annually in these facilities, and 10 thousand tons of RE oxide will be obtained from this processed ore (URL-11). Since all the details of these studies are not published openly, it is not clear what exactly the grades and other information are. If a simple calculation is made, it can be considered to obtain 10 thousand tons of RE oxide by processing 570 thousand tons of ore: As 10,000/570,000 = 1.75%, the RE oxide content of the ore can be calculated. In addition, other factors, such as efficiency, need to be considered. But at this stage, they can be ignored.

Eskişehir-Beylikova REE deposit will have a large share in the production of Li-ion batteries and batteries to be used in TOGG (Çekiç 2023). There are some question marks, especially about the operability of REEs. The Mount Weld project of Lynas Resources, which is actively producing REE, can be considered (Lynas 2019). As can be seen in Table 8, the average TREO grade of the operating reserve is ~8.5%. This project has ~5 times higher grades than the Beylikova site. However, price increases as a result of increasing demand and the development of new process technologies give hope that lower grades can also be operated.

The same assumptions can be used for REE projects under development. In comprehensive comparison studies with the economic models prepared in this way, an economically

Table 10. Various REE projects/deposits and features available in China and other countries

Tabela 10. Różne projekty/złoża i funkcje REE dostępne w Chinach i innych krajach

Project	Country	Company	Grades of TREO (%)	Annual processing capacity (million tons/year)	Mine life (year)	NPV@ 10% (million USD)	IRR (%)
Steenkampskraal	South Africa	Great Western Minerals Group Ltd.	4.7	2.0	13.0	161	25.8
Mount Weld Phase-1	Australia	Lynas Corporation Ltd.	9.7	11.0	25.0	−249	9.9
Mountain Pass	USA	Molycorp Inc.	6.6	20.0	N/A	−1,257	N/A
Ngualla	Tanzania	Peak Resources Ltd.	4.2	10.0	58.0	161	14.2
Bear Lodge	USA	Rare Element Resources Ltd.	2.7	7.5	45.0	−175	2.5
Nolans	Australia	Arafura Resources Ltd.	2.6	20.0	23.0	250	12.8
Zandkopsdrift (JV)	South Africa	Frontier Rare Earths Ltd.	2.2	20.0	20.0	103	11.3
Nechalacho Basal	Canada	Avalon Rare MetalsInc.	1.4	7.0	20.0	−698	−1.3
StrangeLake	Canada	Quest Rare Minerals Ltd.	1.4	10.0	30.0	53	10.5
Brwons Range	Australia	Northern Minerals Limited	0.7	3.0	11.0	125	18.3
Lofdal	Namibia	Namibia Rare Earths Inc.	0.6	1.5	7.25	−34	3.8
Bokan	USA	Ucore Rare Metals Inc.	0.6	1.8	11.0	−308	N/A
Norra Kärr	Sweden	Tasman Metals Ltd.	0.6	4.8	20.0	−155	3.7
Kipawa	Canada	Matamec Explorations Inc.	0.4	3.6	15.25	15	10.8

Project	Country	Company	Grades of TREO (%)	Annual processing capacity (million tons/year)	Mine life (year)	NPV@ 10% (million USD)	IRR (%)
N/A	China	Mineral deposit	Grades of TREO (%)	REO content (million tons)			
N/A	China	The Bayan Obo Ree–Nb–Fe Deposıt	6.0	35.0	N/A	N/A	N/A
N/A	China	The Sichuan Mianning Rare Earth Deposit	3.7	1.0	N/A	N/A	N/A
N/A	China	Shandong Weishan Rare Earth Deposit	3.13	2.55	N/A	N/A	N/A
N/A	China	Mianning and Weishan Ion Adsorption Reo Deposit	3.7	1.0	N/A	N/A	N/A

Data for China is quoted from: Li and Yang 2016.

attractive investment can be decided. It has been revealed that many factors such as the places where REE projects are located and what types of REEs these projects contain, the market price, and mining methods are effective. A summary of this study is presented in Table 10 (Jaroni et al. 2019). Considering the above comparisons, it can be said that Eskişehir Beylikova reserve potential has the potential to be operated economically with a possible TREO content of 1.75%. Of course, knowing all the details of this project and making a decision about the project depends on the final result to be revealed by the studies to be conducted.

The fact that a few countries, especially China, have a high share of processed REE production and their efforts to secure REE supplies for technologies in which REE is used in their countries, set an example for Turkey's REE policies. The need for REE will increase proportionally with domestic production and product development in Turkey. The amount of REE that will be needed for the factory opened for the production of TOGG in Turkey and its monetary equivalent will play an important role in the follow-up of the REE RM and product production strategy for Turkey. As stated in the 3.1 sub-section, the electric power of the batteries in TOGG is planned to be 52.4 and 88.5 kWh. It is planned to produce 175 thousand EVs every year starting from 2023. For the NdFeB magnet, a total of ~18.25 million USD will be needed for the production of the 175,000 EVs, and ~107.43 million USD worth of REEs will be needed for the battery. There has been an increase in these prices, which are foreseen for November 2020. The value of REEs, which are needed only for the NdFeB magnet, increased by ~50% and reached ~27.5 million USD in 1 year. Feasibility studies are conducted for TOGG based on the production of NdFeB magnet with domestic facilities (Çimen 2021). REE compounds are needed in metallurgy, machinery-chemistry, electricity-optics-magnetic, and ceramic-glass sectors operating in Turkey. In addition, the need for REE will increase proportionally in line with the domestic product development target of the Ministry of Industry and Trade. REE supply poses a risk for both existing and planned industry activities. Due to the supply risk of REEs in these sectors, the Turkish government is expected to take some steps.

3.7. Comparison of resource potentials with the World and general analysis of the potential in Turkey

The reserve/resource potentials of Turkey identified above are presented as a general summary (Table 11). To determine its potential position in Turkey, it will also be useful to compare these data with the world. For this purpose, USGS data can be taken as a basis. According to the reports of the (USGS 2023), the comparison of the three countries with the largest reserves in the world among the reserves of the six minerals we examined in our study, and the potential of Turkey, which is presented in summary above, is presented in Table 12. In the USGS data, it was stated that there are 90 million tons of reserves in Turkey, and the world's C reserves were stated to be 330 million tons in total. Since there is

Table 11. Reserve/resource potentials determined in Turkey and The adequacy of these for TOGG

Tabela 11. Potencjały rezerw/zasobów określone w Turcji oraz ich adekwatność dla TOGG

Minerals	Determined potential in Turkey					The capacity that the determined potential in Turkey can meet			Number of TOGGs that can be produced		
	total potential (tons)	grades (%)	contents (tons)	annual requirement for 20 GWh (tons)	sufficiency (years)	requirement per GWh (tons)	the total capacity that can be produced (GWh)	capacity during 10 years of operation (GWh)	per kWh Requirement (kg)	52.4 kWh TOGG number that can be produced	88.5 kWh TOGG number that can be produced
Li (as Li carbonate)	3,234,865,127	0.61	19,788,634	14,234	1,390	134	147,924	14,792	0.134	2,822,983,362	1,671,461,335
Ni	59,700,000	1.10	644,520	10,386	62	519	1,241	124	0.519	2,3685,137	14,023,742
Co	59,700,000	0.14	83,790	1,820	46	91	921	92	0.091	17,576,143	10,406,666
Mn	4,744,163	37.78	1,792,500	1,909	939	95	18,775	1,878	0.095	358,310,057	212,151,943
C	14,000,000	5.85	819,100	13,516	61	676	1,212	121	0.676	23,130,051	13,695,081
REE (as TREO)	694,000,000	1.75	12,145,000	173	70,276	9	1,405,512	140,551	0.009	26,822,746,667	15,881,490,682

Table 12. USGS world reserves and Turkey's reserve/resource potential

Tabela 12. Rezerwy światowe USGS i potencjał rezerwowo-zasobowy Turcji

Comparison of USGS data with Turkey				
Minerals	Top 3 Countries	Reserve (ton)	Total Reserve (ton)	Shares of Countries (%)
Li (as Li carbonate)			138,320,000	
	Chile	49,476,000		35.77
	Australia	32,984,000		23.85
	Argentina	14,364,000		10.38
	Turkey	19,788,634		14.31
Nichel			300,000,000	
	Australia	21,000,000		7.00
	Indonesia	21,000,000		7.00
	Brazil	16,000,000		5.33
	Turkey	44,790		0.01
Cobalt			8,300,000	
	DRC	4,000,000		48.19
	Australia	1,500,000		18.07
	Indonesia	600,000		7.23
	Turkey	83,790		1.01
Manganese			1,700,000,000	
	South Africa	640,000,000		37.65
	China	280,000,000		16.47
	Australia	270,000,000		15.88
	Turkey	1,792,500		0.11
Graphite (USGS excluding Turkey)			240,000,000	
	Brazil	74,000,000		30.83
	China	52,000,000		21.67
	Madagascar	26,000,000		10.83
	Turkey	819,100		0.34
REE (as TREO)			130,000,000	
	China	44,000,000		33.85
	Vietnamese	22,000,000		16.92
	Russia	21,000,000		16.15
	Turkey	12,145,000		9.34

no information to confirm this data, Turkey's data has been excluded from the total and the world reserve has been considered. The most important conclusion that can be drawn from Table 12 is that Turkey's Li reserve potential may rank among the top three in the world and that Turkey may have a very important potential in the world in terms of REEs.

The need to better understand how it sources and consumes the RMs required for decarbonization is driving demand for data on mineral resources. One of the main applications of these data is to understand resource potentials by evaluating known geological stocks of RMs based on estimates of mineral resources and reserves (Bide et al. 2022). The interesting detail about resource and reserve data is the varying values. Undoubtedly, it is natural that the newly discovered mineral deposits, which were previously described as a resource, turned into reserves with the findings that emerged later and changed due to reasons such as continued production (Yılmaz 2018). This change can be considered in a general reserve/resource potential and needs assessment for TOGG. However, by partially ignoring this change, whose calculation is uncertain, an assessment can be made about the general resource potential that is tried to be determined and whether it will meet Turkey's targeted capacities for TOGG production (Table 11). As can be seen, considering the Co potential, which constitutes the most bottleneck among the RMs examined in the study, it can be mentioned that there is a ~46-year resource potential that will be sufficient for the 20 GWh battery facility to be established for TOGG. It was stated in sub-section 2.2 that TOGG's models with a battery capacity of 52.4 kWh and a range of 314 km and models with a range of 523 km with a battery capacity of 88.5 kWh were offered for sale. In this context, an evaluation can be made about how many EVs the current potential will be enough to produce. The known potential of Turkey is enough to produce more than 10 million EVs, even when considering the bottleneck Co. If this evaluation is carried to a different dimension and a 10-year TOGG factory operational life is assumed, the answer to the question of how many GWh Li-ion battery capacity can be installed and the capacity that Turkey's known reserve/ /resource potential can meet are presented in Table 11. Considering the Co potential, there is a sufficient reserve/resource potential to operate a battery facility to be established in Turkey with a capacity of 92 GWh, which mainly uses the NMC type, for ~10 years. Apart from this, e.g., the C reserve potential can be sufficient for a battery facility with a total capacity of 121 GWh for ~10 years. Of course, most importantly, considering only batteries, the Li potential may be sufficient for TWh capacities beyond GWh. Another important result is that even the RM need for the total battery capacity of 96 GWh, which is planned to be established in Turkey in the long term, can be met for ~9.6 years in the presence of the known reserve/resource potentials.

4. The World supply status of RMs needed by TOGG in the EU CRMs list – discussion of the literature

4.1. CRMs supply risks

Li-ion batteries are gaining a crucial role in the projected energy transition of the 21st century. This development leads to an increased interest in battery RMs such as Li, Ni, Co and natural C. Innovations in battery cathode technology are one of the factors that diversify RM requirements (Weimer et al. 2019; Tang et al. 2021; Mu et al. 2023). (Weimer et al. 2019) conducted a joint analysis of Li-ion technology and RMs, and conducted criticality studies, presenting an integrated description of the value chain stages from the deposit to the production of battery cell components.

Growth in the production and consumption levels of emerging economies such as China and India has led to growing concerns about the supplies of certain minerals RMs (Campbell 2014; Yun 2020). These resources are limited and are rapidly depleting. Simultaneously, the demand continues to increase. This causes an overall increase in the value of mineral RMs, or the subsequent dramatic price increases and fluctuations. Therefore, resource security has become a priority, especially for developed countries. The concept of "criticality" is based on the combination of economic importance and supply risk for mineral RMs (Careddu et al. 2018; Nwaila et al. 2024). E.g., the importance of a secure RM supply for the European economy is obvious. However, securing the supply of RMs based on an appropriate EU mineral policy was rarely addressed by decision-makers until 2010. The impact of price development in international commodity markets has led to a rethinking of this subject (Tiess 2010). It is also important to determine economic indicators (such as the average annual RM price) to better predict the future demand for CRMs or to better encourage the extraction of such RMs. (Černý et al. 2021) found that their findings are consistent with economic theory, which states that mineral prices are not a determinant of demand, but affect quantity demanded. It is important to emphasize that no one can predict the future of RM prices. However, these markets may lead to supply shortages in the future. Therefore, it can be aimed at better understanding the weaknesses that may affect the price. Considering this (Rosenau-Tornow et al. 2009), a method has been developed to identify and assess long-term supply risks for mineral RMs. Moreover, the strong increase in demand for some commodities in recent years will have a major impact on the future supply situation. For this reason (Stepanek et al. 2013) evaluated the criticality of goods, especially the supply risk, with appropriate indicators. An important issue for ensuring the economic security of a country includes the assessment of the supply risk of strategic mineral resources. In this direction (Yu et al. 2021) suggested the evaluation of the supply risk indicators of strategic metallic minerals. Considering the impact of China's strategic mines on supply risk for emerging strategic industries, the study establishes an indicator system to assess such risks.

4.2. Relationship between mineral criticality and resource research

According to the results of this study, the level of supply risk for Li increased and for Ni, it decreased (Edahbi et al. 2019; Yu et al. 2021; Deng et al. 2021; Espinoza 2021; Li et al. 2022; Zhou et al. 2022; Szamałek et al. 2023; Liu et al. 2023). For REEs, it fluctuated irregularly. The supply risk of Li and REEs was affected by the potentially higher risk factors caused by poor substitutability and low recycling rate. An important first step in improving mineral supply security in the face of these risks is locating a country's mineral resources and estimating the quantities that may be available. Although the presence of resources does not mean that they will be mined, knowing which minerals can be found within a region can facilitate the development of strategies for sustainable management (Bide et al. 2020). Securing a long-term stable supply of RMs is vital for industrialized countries (Armstrong et al. 2016; Lewicka and Burkowicz 2017; Galos et al. 2018). The discourse on mineral criticality helps identify minerals that are subject to supply disruptions and are of high economic importance within an industrial system. Multiple research efforts have generated different critical mineral lists and proposed strategies to alleviate various concerns in this regard (Lapko and Trucco 2018; Zanbak et al. 2023). Organizations of all sizes are vulnerable to critical mineral supply disruptions. While there is substantial literature examining how countries can assess and reduce criticality, there is little study that addresses firm-level criticality in an actionable way for companies (Griffin et al. 2019). Future research on strategic mineral resources security should focus on assessing the availability of these resources, sustainable strategic mineral supply from the perspective of the entire industry chain, and the construction of these resource trade networks based on new global trade models (Zuo et al. 2021). With the increasing demand for resources, the opening and stability of the key mining industry chain have become a key area of national security (Kang et al. 2022). Therefore, various methods have been developed to assess resource availability constraints concerning their vulnerability (criticality) within countries and/or sectors (Bach et al. 2017).

4.3. Critical minerals and supply risks in the automotive industry

In Turkey, a developing country, the supply and security of CRMs to the automotive industry is a matter of concern (Uysal 2021c). Automotive production is material-intensive and relies on a wide variety of mineral products. In addition, automotive manufacturing industries depend on complex and sometimes opaque multi-layered global supply chains. Supply disruptions in, e.g. gallium, tellurium, and indium (which are semiconductor elements used in power electronics, display coatings, and other parts) have the potential to significantly impact the electronics and computer industries (Manley et al. 2022). EV manufacturers are aware of the complexity of the supply chain of EVs and the role of consumers in influencing the management of this chain (Liu et al. 2022). In addition, the global Li-ion battery supply chain network of EVs is vulnerable to disruptions as the activities of related companies become increasingly international, complex, and interdependent (Mu et al. 2023). In recent years, the RM markets have shown a great deal of volatility and significant price increases, which in many cases indicate an increasing economic scarcity. This scarcity makes the supply of RMs a critical issue for national economies, industrial sectors, and manufacturing companies (Gleich et al. 2013). (Tilton et al. 2018), considers costs and prices to be better measures of supply than physical quantities of mineral availability. It also considers that strong government interventions to reduce future mineral shortages are unnecessary. In contrast, the widespread view of the availability of minerals requires strong government initiatives to ensure adequate supply in the future (Tilton et al. 2018). Indeed, a short-term shortage, such as the failure of an EV factory to supply the required minerals, may result in the closure of that factory.

(Jasiński et al. 2018) proposed a new approach that includes risk classes to assess the supply risk of thirty-one RMs used in automobile manufacturing. Criticality evaluations of RMs are based on a large number of criteria. Accordingly, 8 supply risk assessment criteria have been defined to evaluate the supply security of these RMs used in automotive manufacturing (Jasiński et al. 2018). (Ericsson et al. 2023) evaluated cobalt supply risks in Congo and China. Similarly, (Campbell 2014) examined issues involving REE availability, usage, China's participation, and REE market and pricing in China. (Campbell 2020) determined whether the Co-market and supply are growing at the rate necessary to meet the projected increase in EV production.

4.4. Mineral criticality and mineral prices

Companies, economies, and technologies in general are vulnerable to supply disruptions or price peaks for certain RMs. Numerous research groups around the world have proposed methodologies for determining the criticality of RMs, including assessments of vulnerability to supply constraints (Helbig et al. 2016). There are interdependencies between manufacturers using the same CRM for different applications. The European Commission has identified a group of minerals/materials that are claimed to be critical due to their high economic importance and high supply constraints, which could become a bottleneck for the implementation of emerging technologies and ensuring sustainable production. (Lapko et al. 2016) examined how five EU manufacturing companies operating in different sectors and supply chains view material criticality and strategies to reduce such criticality. The findings point to the existence of interdependencies within supply chains and between companies that should be included in the material criticality assessment to develop workable implications for industrial systems. Disruptions in the mineral supply chain directly affect future mineral stocks (Castillo et al. 2023) and therefore mineral prices. Changes in mineral prices also directly affect the feasible operation of enterprises and factories that extract and use raw materials (Yıldız 2022). At this point, mineral exploration activities (Yıldız 2013;

Castillo et al. 2023), and geological stock management (Simoni et al. 2024) gain importance in terms of industry-government data integration and resource management and strategy development.

4.5. Supply risks increase the criticality of minerals

The rapid development of innovative technologies, population growth, changing resource management, and decarbonization challenges are expected to increase the demand for CRMs in the coming years (Göçmen-Polat et al. 2023). The growing imbalance between the growing demand for minerals and their increasingly growing supply has raised concerns about their criticality (Careddu et al. 2018). This encouraged both resource-rich and resource-poor countries to take an active role in implementing their mining strategies (Barteková and Kemp 2016). Increasing concerns have led to the evaluation of CRMs with high economic importance and high supply risk. In this direction, a detailed evaluation of RM criticality will provide an adequate database for future studies (Radwanek-Bąk 2011; Humphreys 2013; Zhou et al. 2016 Gałaś et al. 2024). In this context (Göçmen-Polat et al. 2023) aimed to develop a conceptual methodology to identify CRMs in Turkey. With some modifications, the EU criticality methodology, industry practices, and a method for measuring the added value and supply disruptions of the RM for each material were used. RMs in Turkey characterize many sectors (Göçmen-Polat et al. 2023). However, -as given above- there has not been a study in the literature discussing whether the resource potential of minerals in the EU's CRM list, especially among RMs used in EVs, can provide a safe supply to EVs in a country. Additionally, it is noteworthy that no study has been published in the literature on the supply of mineral reserves required for an EV factory. Such a study will not only be concerned with the supply of reserve/resource potential in a country for EV production but also with other countries producing EVs. Considering this shortcoming in the literature, this study discusses whether Turkey has sufficient domestic mineral resources for its EVs and Li-ion battery production targets. However, in this study, the feasibility of the TOGG factory against the volatility of RM prices was not discussed. Instead, in this study, it has been discussed whether the RMs required for the TOGG factory can be met from the resources in Turkey. In addition, it has been discussed whether the resources in Turkey alone will be able to supply RMs to this factory if the possibility of supply from abroad disappears in case of extraordinary circumstances. Other than the CRMs used in EVs, other minerals/ /materials also cover the issue of RM supply concerning other sectors. In addition, since these other minerals are not on the EU list of CRMs, only Li, Ni, Co, Mn, C, and REEs, which are considered to be more critical to supply to the factories producing vehicles in the automobile industry, are examined in this article. Published studies on this subject were used in the analysis. In this respect, the article has the characteristics of a review article. Evaluations have been made about the rates or conditions under which the existing reserve potential in Turkey can meet TOGG's needs in these minerals. These evaluations may also encourage mineral exploration activities in a country whose proved reserves have not yet been identified and may enable the mining administrations in the country to pay more attention to the issue and encourage mineral exploration or process development activities in these raw materials.

The findings in this study are compatible with the results of (Gleich et al. 2013; Lapko et al. 2016; Tilton et al. 2018; Jasiński et al. 2018; Griffin et al. 2019; Campbell 2020; Zuo et al. 2021; Kang et al. 2022; Liu et al. 2022; Manley et al. 2022; Mu et al. 2023; Maisel et al. 2023) studies that analyze the supply risks of critical minerals, especially on a sectoral basis or on an electric vehicle basis. On the other hand, this study contains differences in terms of subject scope and method from other references (mentioned in the study) that only examine the critical raw materials of countries in terms of criticality factors and supply risks on a country basis.

Conclusion and suggestions

It can be concluded that there are satisfactory studies and evidence that the existence of reserve/resource potentials of RMs required for possible EV production in Turkey may be sufficient. In addition, if attention is paid to the comparison of these potentials with similar-purpose projects developed around the world, a positive opinion is formed about the economic operability of these reserve/resource potentials. In particular, studies on RMs such as Ni, Co, and C are very detailed and currently operating reserve/resource potentials. Using different exploration and resource/reserve studies, the certainty of their reliability level and their economy can be decided. Additionally, with the exploration of new mineral deposits, resource potentials can be further clarified and made reliable, and increases in new reserve discoveries can be possible.

Only if Turkey can use the reserve potentials specified in this study, it can operate the 20 GWh NMC battery factory that it will establish for TOGG for ~46 years without experiencing any RM supply problems. In this way, more than ~10 million (TOGGs) EVs can be produced in Turkey. Even if the other 96 GWh project, which is planned to be established in the long term, works at full capacity, RM problems may not occur for ~10 years. With the new domestic resources to be discovered, this period can be increased much more. Even in the cathode mixtures that do not require Co, which constitute the biggest bottleneck among the RMs examined in the study, much larger capacities can be established.

In Turkey, REE potential and especially Li potential rather than REEs are among the largest resource potentials in the world. It may even be revealed in the future that the Li resource potential in Turkey is the largest in the world. Therefore, it would not be correct to say that Turkey has a mineral resource problem in terms of TOGG. Of course, the existence of mineral resources alone makes no sense. There is a large gap in the value chain between the mineral resource and the end product, the Li-ion battery, and the EV. It should eliminate this gap. For this, it is necessary to develop R&D and process projects, and the infrastructure and human resources needed. E.g., C is produced in Turkey. However, production takes place only in concentrated form. Unfortunately, it is not possible to convert C into a high-purity product at present. Similarly, the problem in Turkey is not the resource problem for the minerals in question, but the problem of processing these resources and converting them into suitable end products. If the transformation into end products can be achieved, self-sufficiency and non-dependence on foreign sources will be achieved, especially in CRMs, in the field of Li-ion batteries and EVs.

Developed countries, considering the RM problems they will experience in the future, are conducting various studies to meet the increasing RM needs in the face of developing technology. Technology and emerging industrial RM needs will play an important role in determining the power and position of countries soon. In Turkey, it is necessary to conduct more studies on underground resources and RM production to maintain and increase the economic power in the country's geography. It is possible to overcome the current account deficit problem in Turkey to some extent by evaluating the existing mineral resources. In this context, increasing mineral exploration activities will increase the reliability level of resource potentials and the apparent reserves. At this point, the research to be conducted and the resources that can be discovered (Aydın and Kılıç 2012) will provide benefits in the feasibility of TOGG production and the planning of capacity increases. In this study, it has been discussed whether the RM supply required for the TOGG EV factory to meet the planned production capacity can be met from the reserve/resource potentials in Turkey, considering the mineral deposits abroad. In other words, it has been discussed whether there are mineral reserves/potential that can only be met by domestic resources. In the article, it is preferred not to consider the expectations in the mineral markets, and new technologies//investments. Changes in mineral markets undoubtedly affect the feasibility of EV production and operating profitability. However, these changes are not the only and most important criterion in supply security. In this study, by examining the existence of reserves/potentials in a country, which is the most dominant criterion that reduces the supply risk, it is determined whether the supply of EV production can be ensured safely or not. Li-battery, etc. used in EV production in the future. Studies that will analyze price changes and new investment expectations in the material/RM sector will be able to fill the gap in this study.

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WILL THE RESOURCE POTENTIAL OF CRITICAL RAW MATERIALS USED IN ELECTRIC CARS IN TURKEY BE SUFFICIENT FOR THE DOMESTIC AUTOMOBILE FACTORY? – A REVIEW

Keywords

critical minerals, electric car, rare earth elements, supply risks, supply security

Abstract

Considering the security problem experienced in the world in the supply of critical raw materials within the scope of energy transformation, it would be extremely strategic for countries to operate electric car (EV) factories from their domestic resources. A factory was opened in Bursa on 29/10/2022 for the production of "TOGG", an electrically powered domestic automobile in Turkey, established by "Turkey's Automobile Initiative Group" (TOGG). It is curious whether this electric car factory can meet the raw materials it needs in the presence of raw material supply risks worldwide. At this point, it can be considered that the supply from domestic sources gives a raw material supply assurance compared to the foreign supply. In this study, the supply risks of the minerals used in producing electric cars in Turkey were determined, and suggestions were presented to policymakers in this regard. Many metals and minerals are used in EV production. In this study, only lithium, nickel, cobalt, manganese, graphite, and REEs, declared critical in the EU critical raw materials list, have been analyzed in Turkey, considering their potential in the world. In the analysis, without examining the market of the mentioned minerals, the safety of the raw material supply of the TOGG electric car production factory, which is the only one in Turkey with the potential to supply the world, is discussed from domestic sources in Turkey. Considering the TOGG factory operating life and the capacity of the Li-battery factory, an evaluation was made on how many EVs the current apparent reserve potential of the raw materials in question would be enough to produce in total.

CZY POTENCJAŁ ZASOBÓW SUROWCÓW KRYTYCZNYCH STOSOWANYCH W SAMOCHODACH ELEKTRYCZNYCH W TURCJI BĘDZIE WYSTARCZAJĄCY KRAJOWA FABRYKA SAMOCHODÓW? – RECENZJA

Słowa kluczowe

minerały krytyczne, samochód elektryczny, pierwiastki ziem rzadkich, ryzyko dostaw, bezpieczeństwo dostaw

Streszczenie

Biorąc pod uwagę występujący na świecie problem bezpieczeństwa w zakresie dostaw surowców krytycznych w zakresie transformacji energetycznej, niezwykle strategiczne dla krajów byłoby prowadzenie fabryk samochodów elektrycznych (EV) z własnych zasobów. 29.10.2022 r. w Bursie otwarto fabrykę produkującą w Turcji „TOGG", samochód domowy zasilany elektrycznie, założoną

przez „Turkey's Automobile Initiative Group" (TOGG). Zastanawiające, czy ta fabryka samochodów elektrycznych będzie w stanie zaspokoić zapotrzebowanie na surowce w obliczu zagrożeń związanych z dostawami surowców na całym świecie. W tym miejscu można uznać, że zaopatrzenie ze źródeł krajowych daje pewność dostaw surowca w porównaniu z podażą zagraniczną. W badaniu określono ryzyko związane z dostawami minerałów wykorzystywanych do produkcji samochodów elektrycznych w Turcji i przedstawiono decydentom sugestie w tym zakresie. Do produkcji pojazdów elektrycznych wykorzystuje się wiele metali i minerałów. W niniejszym badaniu przeanalizowano jedynie lit, nikiel, kobalt, mangan, grafit i REE, uznane za krytyczne na unijnej liście surowców krytycznych, pod kątem ich potencjału na świecie. W analizie, bez badania rynku wymienionych minerałów, omówiono bezpieczeństwo dostaw surowca do fabryki samochodów elektrycznych TOGG, która jako jedyna w Turcji ma potencjał zaopatrywania świata, ze źródeł krajowych w Turcji. Biorąc pod uwagę żywotność fabryki TOGG i wydajność fabryki akumulatorów Li, oszacowano, ile pojazdów elektrycznych można w sumie wyprodukować przy obecnym pozornym potencjale rezerw omawianych surowców.