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Overview of Indonesians sustainable nickel mining and processing

Introduction

In December 2015, 196 countries adopted the Paris Agreement, which set out a goal to hold the global average temperature to well below 2°C above pre-industrial levels (United Nations 2024). To achieve it, the world needs a rapid transition towards a low-carbon economy, and greenhouse gas emissions must peak before 2025 at the latest and show a 43 percent decline by 2030. Indonesia signed the Paris Agreement on April 22, 2016, and ratified it on October 31, 2016 (United Nations 2024). The country submitted its enhanced Nationally Determined Contributions (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) on September 23, 2022. According to the strategy LTS-LCCR 2050

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(low carbon and climate resilience scenario), Indonesia will reach 540 mtCO₂e by 2050 with a possible net-zero emission goal in 2060 (Analytics & Institute 2023). But in the long-term strategy, the country has not yet communicated explicit information on the target's emissions coverage, but only explored scenarios on how to deal with the targets. Indonesia was rated as “critically insufficient” by The Climate Action Tracker. It reflects minimal to no action, and that all climate policies and commitments are not sufficient to the Paris Agreement (Analytics & Institute 2024). The increasing number of newly operating coal plants in Indonesia increased the emissions by 21 percent in 2022. In addition, they are off-grid coal plants that supply energy to the domestic metal industry and large infrastructure projects. Especially, the nickel mining industry plays a critical role not only in the domestic but also in the global energy transition. And sustainable mining has a huge impact on how the transport electrification works.

In the process of the vehicle industry's electrification, a substantial issue is the development of new technological solutions in EVs compared to their traditional vehicles. EVs are equipped and powered by batteries, and lithium-ion batteries appear to be one of the most suitable types of batteries due to their high energy density, long cycle life, modularity, low maintenance, and eco-friendly features (Bhattacharjee 2020). From the raw material part, nickel is a key material. EVs overall are believed to be a promising solution to achieve climate goals and reduce environmental pollution (Ghosh 2020).

Global EV sales have been increasing in recent years. A total of 14.2 million new EVs were delivered during 2023, an increase of 35 percent compared to 2022 (EV-Volumes 2023). 10 million were battery electric vehicles (BEV) and 4.2 million were Plug-in-Hybrids (PHEV). EV shares still continued to increase in most markets. BEVs (11.1 percent) and PHEVs (4.7 percent) stood for 15.8 percent in total sales. These types of vehicles seem to be dominant in the future transportation by 2050, with a 56 percent share of all vehicles to be sold that year (International Energy Agency 2023). At the end of 2023, the total number of EVs amounted to 40 million, and taking into consideration the development of sales, the number of EVs could reach 950 million by 2050 (Prachi Mehta 2021). Indonesia, with immense resources of nickel, has a great opportunity to play an important role in the global battery value chain.

The EVs sales growth has a huge impact on increasing demand for critical metals like lithium, cobalt, and nickel. In 2023, lithium used for batteries was around 140 kt (more than 30 percent compared to 2022); cobalt was at 150 kt (a growth of 15 percent), and nickel stood at almost 370 kt (nearly 30 percent more than in 2022) (International Energy Agency 2024).

Indonesia has a good landscape for becoming an important regional player. In 2023, the country was the largest vehicle market with one million passenger and commercial vehicles sold and with a production of 1.4 million passenger and commercial vehicles among the ASEAN countries (ASEAN Automotive Federation 2024). The Indonesian authorities prepared the ground for that development. In August 2019, a decree to support the electric vehicle industry was signed by the Indonesian President (The Business Times 2019),

grounding EV production conditions in 2022, with a goal to reach a 20 percent share of total car production by EVs until 2025 (The Bangkok Post 2019). In order to attract some foreign investors, in January 2020, the government introduced a ban on exports of unprocessed nickel ore, aiming to improve the value-added opportunities for nickel products (NikkeiAsia 2021). They came especially from China, the country that holds the leadership in the upstream EV battery industry. Large Chinese companies have already started to invest in the Indonesian mineral industry, and in parallel, obtain supplies needed for their own battery production.

The key purposes of the review paper are threefold: firstly, to investigate the increasing role of Indonesia in the global battery value chain; secondly, to identify the environmental concerns related to the adopted nickel mining technology, and thirdly, to identify the actions to make future Indonesian mining more sustainable. Based on that, three research questions have been formulated:

- ◆ RQ1: How is Indonesia increasing its role in the global battery value chain?
- ◆ RQ2: What are the environmental concerns related to the adopted nickel mining technology?
- ◆ RQ3: What actions should be applied to make future Indonesian mining more sustainable?

The article uses the method of analysis of secondary research and the observational method. The method of analysis and logical construction allowed the division of the research challenge into smaller factors.

1. Sustainability in the mining industry

A successful low-carbon transition will depend on access to cheaper materials. Taking into consideration that the production of these materials (from mining to manufacturing) incurs environmental costs linked to the methodology of mining, extraction, purity of product, and manufacturing infrastructure. In order to ensure a healthy and sustainable energy future, it is vital that clean energy technologies be developed to reduce carbon footprint and ensure the security of the clean energy supply. Several processes can be used for the extraction of energy-critical materials, which include different processes, e.g., pyro-, hydro-, and electrometallurgical ways (Lívia Salles Martins 2021). One of the future environmental processes could be bioleaching, which is a process of using microbes to break down minerals that contain rare earth and energy-critical elements. It could be more environmentally friendly and generate less material waste and energy (Debnath 2018). A potential method is also to use ionic liquids without implementing harsh chemicals or high temperatures, which can reduce the impact of the extraction process on the environment. The method has been proposed as a replacement for organic solvents in the solvent extraction of metal ions (Quijada-Maldonado and Romero 2021).

The mining industry consists of five phases: exploration, extraction, exploitation, processing, and refining. Integration of sustainability and efficiency in all the above stages

aims to minimize the environmental and societal impacts of related activities. Mining is regarded as one of the most energy-demanding industries, and taking into consideration the increasing demand for metals, the energy consumption by the mining industry will increase. In addition, the following three factors will likely increase the mining industry's energy demand: falling mineral ore grade, the grind size of the extracted ores, determining the size of mineral particles that must be ground to separate valuable minerals from the gangue (Aramendia et al. 2023), and the mine depth. A decline in the ore's average grade requires the extraction of increasing quantities of raw mineral materials from the depths of the ground (Lezak et al. 2019).

The mining industry accounts for approximately 38 percent of the energy used in all industries, 15 percent of the global electricity consumption, and it uses about 19 percent of coal and coal products worldwide (Pouresmaieli et al. 2023). Energy is one of the key drivers of the most significant expenses for the mining industry. It could account for 15–40 percent of total operating costs (Igogo et al. 2021). The situation where a big part of energy is sourced from fossil fuels makes the mining industry highly exposed to volatility. Especially when energy demand is forecasted to grow by 36 percent by 2035 (Maennling and Toledano 2018).

Energy usage is of two main types: off-grid and grid-connected. The first type is mostly dependent on fossil fuel for on-site generation and haulage (Igogo et al. 2020). To some extent, grid-connected mining operations are also reliant on fossil fuels. The cost of energy is dependent on the mining sites where the energy is supplied. In many countries where the grid supply is unreliable, most grid-connected operations have to add an energy supply backup, which is mostly sourced from fossil fuels. It would be an additional cost of production.

Mining is often associated with environmental and social challenges conducive to health risks, air, water, and soil pollution, and human rights abuses. Mining raises ecological concerns due to the use of mechanical equipment and systems for mining operations, which produce greenhouse gases. Immense waste is collected in waste accumulation sites, which impacts agricultural lands (Shi 1979). Furthermore, the mining operations like mineral washing, processing, and treatment contribute to soil contamination (Ebrahimabadi et al. 2018). Moreover, mining activities, e.g., blasting and processing, enhance noise pollution and produce dust and waste containing chemicals. They present a negative impact on soil erosion, land-use change (LUC), soil, water, and air pollution, and eventually pose significant risks to human health and living (Ekrami et al. 2022).

With the increasing attention on sustainable processes, the mining manufactures are under pressure to implement environmental efficiencies in the production process to eliminate waste and emissions. Depending on how strong the mining industry is, this approach will impact the potential demands of the battery supply chain.

2. Nickel ore processing outlook and its applications

Nickel resources have been globally estimated to be more than 350 million tons, located in laterites (54 percent) and in magmatic sulfide deposits (35 percent) (UN Comtrade 2020). Identified land-based resources (with 0.5 percent nickel or greater) contain no less than 300 million tons of nickel, 60 percent of which are in laterites and 40 percent in sulfide deposits (IVL Swedish Environmental Research Institute 2017). Nickel sulfide deposits form through the precipitation of nickel minerals by hydrothermal fluids (Ahead of The Herd 2021), and nickel laterite deposits are created by the intense chemical and mechanical weathering of ultramafic parent rocks (UN Comtrade 2020). Laterite deposits involve higher capital costs to be viable when compared to sulfide operations (Ahead of The Herd 2021). Laterite ores are traditionally separated into two main types: limonites and saprolites. Limonites contain lower nickel and high iron and typically have cobalt as an additional value component. Saprolites contain higher nickel and lower iron (Nickel Institute 2024).

In the past, the majority of nickel was produced from sulfide ores, such as the deposits in Canada, Russia, and South Africa, which are becoming depleted. Currently, the lower-quality nickel laterites, including those in the Philippines, Indonesia, and New Caledonia, are starting to be explored (Ahead of The Herd 2021). Not every type of nickel can be used in the manufacturing of EV batteries, and only 5 percent of the nickel supply is consumed by the battery industry (McKinsey & Company 2020). Nickel is recognized as Class 1 or Class 2. The main concern is its quality. The EV battery industry requires mainly high-purity Class 1 products. In theory, it is possible to use all Class 1 nickel to produce nickel sulfate; it is most frequently used in the form of powder or briquettes (McKinsey & Company 2024). At best, only 46 percent can be used in batteries (McKinsey & Company 2020). The other producers, e.g., from the stainless-steel industry, use both Class 1 (high-purity) products in pure nickel metal form and lower-purity Class 2 products, including various forms of nickel alloys and chemicals. It is also possible to use Class 2 nickel to make nickel sulfate, but this purity potentially creates too high manufacturing costs. Today, the production of nickel sulfate vastly depends on Class 1 nickel.

Depending on the type of process carried out in nickel extraction, nickel can be used in various applications. Today, two main ways of processing nickel laterite are used: pyro- and hydrometallurgy (Bahfie et al. 2022). The pyrometallurgical process uses high heat and produces nickel pig iron and ferronickel. These products are used by stainless steel and steel alloy manufacturers (Bunjaku et al. 2012). The other process uses chemical solutions and low heat, and it can produce nickel sulfate and nickel oxide with a purity of 99 percent by weight (Bunjaku et al. 2012).

The hydrometallurgical process (mainly leaching) is used to extract limonite ores, where the ore is reacted with sulfuric acid, and the dissolved nickel and cobalt are covered as nickel-cobalt intermediate products. They can be refined to nickel metals or used as raw materials for sensors, magnets, or batteries by the hydrometallurgical process. Saprolite ores are treated by the pyrometallurgical process. Taking into consideration the growing

demand for batteries, it is vital to convert the alloy into a higher-grade material (nickel matte) for refining (Nickel Magazine 2024). From nickel matte, the high-grade nickel of 99.8 percent purity (Class 1) is required to produce the battery cathode. For producing battery-grade nickel in a viable and cost-effective way, it is compulsory to process the limonite to the nickel intermediate mixed hydroxide precipitate (MHP) as nickel sulfate raw material (Fastmarkets 2022). The advantage of producing battery material from lateritic ores is to use the hydrometallurgical processing through a HPAL, in which the ore is beneficiated to improve the nickel and cobalt concentration. However, it requires high-temperature and high-pressure autoclaves, which translates into higher capital and maintenance costs (Norgate and Jahanshahi 2011). It could bring some disadvantages to this type of process.

3. The Indonesia's nickel strategy

3.1. Production and exports

Considering global transport electrification requirements, Indonesia started to develop and construct EV battery production facilities and encouraged international producers to invest in extracting chemicals from nickel ore and construct the production sites that produce batteries for EVs (Konewka et al. 2021).

In order to support the EV industry, the Indonesian President signed a decree in August 2019 (The Business Times 2019). The goal of the Indonesian government is to become one of the world's top three producers of EV batteries by 2027. The country develops the EV supply chain to achieve a total capacity of 140 GWh per year by 2030. This will allow Indonesia to cover between 4 and 9 percent of global demand (ASEAN Briefing 2024).

Indonesia produced an estimated 1,800,000 tons of nickel in 2023 (14 percent more compared to 2022), with another 21 million tons in reserves (UN Comtrade 2020). This means that the country accounts for around 50 percent of the world's nickel production and about 16 percent of global reserves (Table 1). In value terms, in 2022, Indonesia exported nickel for USD 20 bn worldwide (compared to USD 9 bn in 2021) (UN Comtrade 2020). It accounted for around 28 percent of the world's nickel trade exports. In 2023, mining contributed to 1.9 percent of Indonesia's gross domestic product (Center for Strategic & International Studies 2024).

The rapid increase in Indonesian nickel production has driven a global surplus and has contributed to a collapse in prices (S&P Global 2024).

The price collapse led to the closure of mine operations in Australia (First Quantum Minerals is closing Ravensthorpe operations) (ABC News 2024) and New Caledonia (Glencore is closing Koniambo Nickel operation) (Mighty Earth 2024). This situation will secure Indonesia a larger global share of production in the future, but at a time when prices have been collapsing, it can suggest the Indonesian mining operations are making a loss.

Table 1. Indonesia’s nickel production and export in 2019-2023 (tons)

Tabela 1. Produkcja i eksport niklu w Indonezji w latach 2019–2023 (tony)

	2019	2020	2021	2022	2023
World production	2,610,000	2,510,000	2,730,000	3,270,000	3,600,000
Indonesia’s production	853,000	771,000	1,040,000	1,580,000	1,800,000
Indonesia’s export	91,000	93,000	166,000	775,000	1,260,000

Source: U.S. Department of the Interior 2021, 2024.

An export ban on nickel ore was imposed by Indonesia in 2014, and it was relaxed in 2017 due to a sharp decline in nickel production and budget deficit. In January 2020, the government reintroduced the ban on the exports of unprocessed nickel ore to improve value-added opportunities for nickel products and to strengthen the local industry (NikkeiAsia 2021) and to tax exports of nickel pig iron and ferronickel, which would boost production of battery-grade nickel (Castillo et al. 2022). As a result, many NPI smelters and two stainless steel plants started operation in the country within only a few years, which will use mainly high-grade saprolite ore (Szurlies and Vasters 2024).

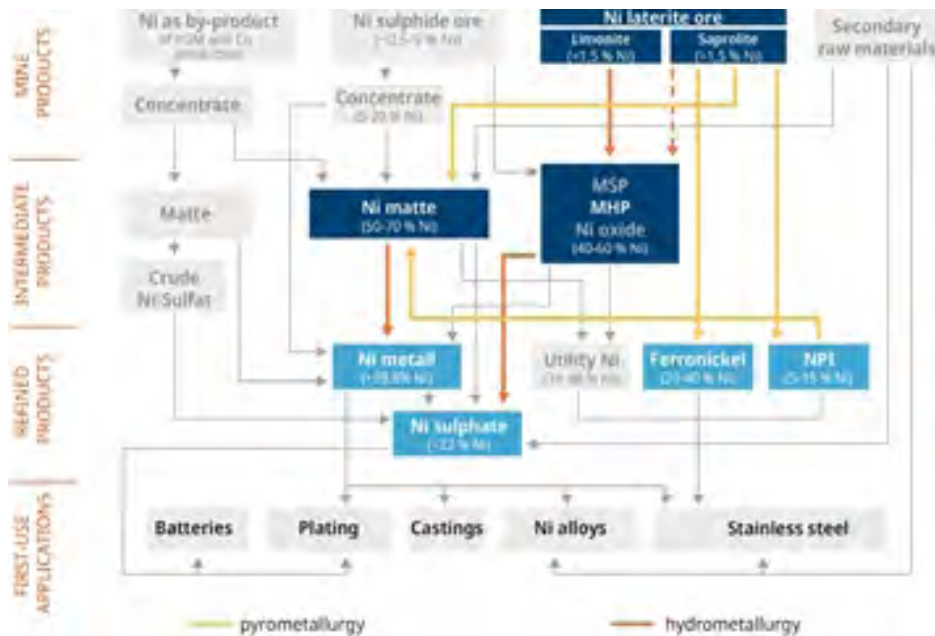


Fig. 1. Simplified nickel value chain by product category
Source: Szurlies and Vasters 2024

Rys. 1. Uproszczony łańcuch wartości niklu według kategorii produktów

Indonesia's experience with the mining and production of nickel dates back to the time of the Dutch East Indies. During the 1960s, nickel production expanded rapidly (Averay 2020). Today, most nickel mining activities are only spread across 4 provinces, which contain 90 percent of all nickel reserves in Indonesia. Three provinces are in Central and South Sulawesi, and one province in North Maluku (Naryono 2023).

In Indonesia, there are two smelting methods. One method uses a pyrometallurgical treatment for Class 2 nickel to produce nickel pig iron, and the other treatment for Class 1 nickel to produce mixed hydroxide precipitate (MHP) (Figure 1).

3.2. Legal framework and Mining Transformation

Mining-related processes in Indonesia are regulated under Law No. 4/2009. The Law provides the procedure and criteria for setting mining areas, state reserve areas, requirements and procedures for obtaining mining business permits, rights and obligations of permit holders, suspension or expiry of permits, the use of land for mining business activities, etc. (Food and Agricultural Organization of the United Nations 2009). The Law was imposed in order to improve mining governance and develop mineral and coal downstream programs (Federal Ministry for Economic 2022).

Since 2009, many problems have occurred regarding the implementation of this Law, such as restrictions on foreign ownership of shares and the obligation to process mining products in the country (Setyadi et al. 2021). In 2020, the Minerba Amendment Act No. 3/2020 was issued (Hukumonline.com 2020) to simplify regulatory procedures. According to that, the companies must hold shares in an Indonesia-incorporated mining company as the license holder. In addition, the Job Creation Law, known as the Omnibus Law, was enacted, containing regulations related to licensing clusters. The mining cluster Omnibus Law contains the authority to control minerals and coal by the state, which is held by the Central Government (licensing authority in the Central Government) and can be delegated to local governments (Setyadi et al. 2021). Indonesia's nickel mining strategy was fully integrated into the country's goal to set up a hub for the EV supply chain (from nickel mining to EV production).

3.3. Domestic nickel mining / HPAL nickel capacity development

Rich mineral deposits are not the only reason behind the country's objective to build its growing position in the EV supply chain; another significant factor is its geographical position, with direct marine shipping routes to Japan and China. These two countries are global leaders in developing new technologies, including power cell manufacturing. Large Chinese companies are investing in the Indonesian mineral industry and introducing new technologies into nickel mining. After one year, the ban on nickel ore export was introduced,

and Indonesia received downstream investments and commitments from Chinese companies totaling some USD 30 billion (East Asia Forum 2024). Chinese investment and know-how have developed HPAL operations, and today most smelting plants are producing Class 1 high-grade nickel NCM battery cathodes. About 80–82 percent of Indonesia's battery-grade nickel output is expected to come from majority Chinese-owned producers in 2024 (Financial Times 2024). Indonesia is taking a significant opportunity to build a competitive advantage in the upstream EV industry. As of July 2023, there were already 43 nickel smelters operating, 28 under construction, and 24 in the planning stage (The Diplomat 2024).

As of 2020, Indonesia issued 292 permits for nickel mining (The Republic of Indonesia 2020). In the Central Sulawesi Province, Indonesia, the Indonesia Morowali Industrial Park (IMIP) is an integrated nickel hub for steel production. At least two HPAL projects: PT Huayue NiCo and PT QMB New Energy Materials, were constructed at IMIP. The QMB plant was developed by Chinese materials producer GEM, Chinese battery producer CATL, IMIP, Hanwa, and other smaller stakeholders. The plant was commissioned with an initial capacity of 30ktpy Ni, reaching the total capacity of 100ktpy by 2024 (Project Blue 2023). Another nickel hub, Indonesia Weda Bay Industrial Park, on Halmahera Island in North Maluku Province, started to operate in 2020, which was the first operating with HPAL (Strategic and Studies 2021). In 2023, the five largest nickel mines by production in Indonesia were: Weda Bay Project (517k tons), PT Halmahera Persada Lygend Project (95k tons), Sorowako Mine (64k tons), PT Huayue Nickel Cobalt Project (42k tons), Pakal Island Mine (36k tons) (Mining Technology 2024).

The three HPAL operations will provide a significant volume of nickel units in the form of MHP and sulphate to the Li-ion battery supply chain. Before Indonesia had developed a capacity for its own domestic battery production, the first MHPs were shipped to China (Reuters 2021). Now, the domestic raw materials will be used for the local production. Indonesia, together with Hyundai Motor Group, has recently launched the first EV battery plant located in the province of West Java. The plant will have an estimated annual capacity of 10 gigawatt hours (GWh) of battery cells, sufficient to power 150,000 EVs (ASEAN Briefing 2024). The final capacity of the plant aims at 20 GWh.

Another global supplier of EV battery materials, like the French mining group Eramet or BASF, has also shown interest in establishing nickel processing plants in the country (Jakarta Globe 2024), and is investing to develop a vehicle battery plant in North Maluku province. The facilities would supply an annual 42,000 tons of nickel and 5,000 tons of cobalt, for use in cathode materials (NikkeiAsia 2021). This year, following several agreements, a Chinese EV producer BYD plans to build a production facility in 2024. The company also launched three EV models on the Indonesian market to reach a yearly production of 150,000 units. Vale Indonesia and China's Zhejiang Huayou Cobalt signed an agreement to build an MHP plant together with Ford Motor with a capacity of 120,000 tons, and another one with a 60,000 tons capacity of hydroxide precipitate (ASEAN Briefing 2024).

4. Environmental concerns of Indonesia's nickel mining industry

Mining has a big influence on the richness or poverty of people living close to the extraction locations, and it is one of the major drivers of land-cover change, having significant implications on biodiversity and ecosystem functioning (Sonter et al. 2017). The process management of the mineral extraction can lead to negative impacts on greenhouse emissions, biodiversity loss, and social disruption due to land use change, water depletion and pollution, waste-related contamination, and air pollution (International Energy Agency 2022).

4.1. Greenhouse emissions

A part of the energy transition is the electrification of the vehicle industry. It provides an exceptional opportunity, but in this case, the lifecycle of low-carbon technologies begins with the mining of minerals. In a 100 percent renewable energy future, demand for nickel could reach 136 percent of the documented nickel deposits that are currently economically feasible to extract (International Energy Agency 2022). The threat of mining nickel from lower-grade laterite deposits is that the process can produce as much as twice the carbon emissions of the industry average (Earthworks 2021).

The nickel supply will continue to expand from Indonesia. The country accounts for 60 percent of the global nickel mined output and 40 percent of the refined output by 2030. To produce nickel from laterite ores in Indonesia, a HPAL process has been adopted in more laterite projects there. The process is highly toxic, polluting, and energy intensive. Producing Class 1 nickel releases two to six times more carbon dioxide emissions than producing Class 1 nickel sulfide deposits: (10 tCO₂-eq per tonne of nickel from sulfide deposits, compared to 19 tCO₂-eq per tonne of nickel from laterite – HPAL process, and 59 tCO₂-eq per tonne of nickel from laterite – matte via NPI process) (Lead the Charge 2024). Compared with other countries, nickel production in Indonesia and China (78 tCO₂-eq per tonne of nickel) has the highest CO₂ intensity worldwide (International Energy Agency 2021). The Weda Bay industrial park, along with its eleven blocks installed to date, has a rated capacity of more than 3,000 MW. At full capacity use, that would be equivalent to an annual consumption of about 10 million tons of coal (Federal Ministry for Economic Cooperation and Development 2022).

Despite the advantage of HPAL being to process low-grade nickel laterite ores and to recover nickel and cobalt, it has high maintenance costs (average 260–400 kg/t at existing operations) and is unable to process high-magnesium or saprolite ores (Federal Ministry for Economic Cooperation and Development 2022).

Moreover, Indonesia is highly reliant on coal-sourced energy. In 2023, 27.5 percent of the coal-fired power plants operating were captive (ten times more compared to 2013). Of 6.3 GW of new coal capacity that began to operate. 3.7 GW was captive capacity, and 2.6 GW was on-grid capacity (Mining 2024). The captive power for operating nickel

and aluminum parks accounted for 15 percent of the country's coal power output. When all the recorded projects are completed, it will grow to 24 percent (Global Energy Monitor 2024). The newly captured power plants are affiliated with China. These projects have found ways of extracting nickel with significantly lower capital costs than previous projects set up by Chinese companies in other countries. For example, the HPAL project in Obi Islands (PT Halmahera Persada Lygend), which has recently been opened, uses a very similar size to the currently operating Ramu plant. Both are owned by the same Chinese company. Another example is the companies setting up HPAL projects within Industrial Parks in Morowali and Weda Bay. They have been able to lower capital costs by leveraging existing infrastructure (Dialogue Earth 2024).

However, it is necessary to implement in the captive coal plants such activities that are in line with a net zero-emission path and move towards a green classification according to the Paris Agreement. Today, captive coal plants are classified as “facilitating emission reduction” by the Financial Services Authority, Indonesia's financial sector regulatory body, and they fall into the “transition” category (Bhuwarka and Olivetti 2024).

4.2. HPAL and RKEF waste management concerns

With the increase in nickel production, the Indonesian authorities must tackle the problem of tailings disposal management, which remains a key challenge. The key issue is the HPAL method, which brings a large amount of waste generation, with an estimated 1.4–1.6 tons of waste generated for every ton of nickel produced (Global Energy Monitor 2024). As a solution for waste management, many mining companies originally proposed deep-sea tailings placement (DSTP) based on solutions used in Ramu in Papua New Guinea. It has already been adopted by PT Trimegah Bangun Persada in Obi Island in North Maluku and PT Hua Pioneer Indonesia in the IMIP. However, this method of utilizing the waste causes big environmental impacts on local communities, and they have to control the activities of mining companies around. For example, after protests of the local community in Obi Island, PT Trimegah Bangun Persada decided to withdraw from the previously planned yearly disposal of 6 million tons of tailings waste into the ocean. (WoodMackenzie 2024).

Especially in a country like Indonesia, waste management may potentially impact marine ecosystems. Indonesia has a limited amount of space on its islands for large dams to store the waste tailings. The storage on land is difficult but necessary in order to avoid local groundwater contamination. On the other hand, the disposal process requires extensive tailings treatment, elaborate storage, and seepage control (Mongabay 2024). If this approach is not adopted by mining companies, it can lead to a situation where the environment will suffer more (like marine life in the Coral Triangle) than profits from the global clean-energy transition (Tritto 2023). Currently, in both countries, Indonesia and Papua New Guinea, four of the sixteen mines worldwide that practice DSTP operate. They account for 91 percent of 227 million tons of tailings dumped so far into the ocean (S&Global 2023).

The activity of mining companies in Indonesia that allows submarine tailings disposal is based on Government Regulation No. 22 of 2021 on the Implementation of Protection and Management of the Environment. It allows submarine tailing disposal, with a minimum depth of 100 meters in the area if a thermocline does not exist (Reuters 2024).

Another method for managing HPAL tailings is dry stacking. Before compacting the tailings and storing them in a stable, dry place, they should be filtered and dried. Sometimes, tailings are used to backfill old open pits (Earthworks 2024). The companies operating in Indonesia, like Vale SA and Lygend Resources & Technology Co. Ltd., intend to utilize this method for their HPAL projects despite dry stacking being challenging and costly in rainy areas, where waste poses a danger of contaminating groundwater and nearby areas (Bhuwalka and Olivetti 2024). This method has already been tested in other tropical regions of the world, but some environmental organizations are still worried about the viability of using it in the Indonesian environment.

The saprolite ores, containing higher Si and Mg and lower Fe, are suitable for pyrometallurgical processes, including mainly the ferronickel process and the nickel matte process. The ferronickel process includes rotary kiln-electric furnace (RKEF), originally developed in New Caledonia in the 1950s and currently widely used to process saprolites with nickel content greater than 1.8 percent Fe/Ni, Ni/Co, and to produce nickel pig iron containing 8–12 percent nickel, with a nickel recovery rate of more than 90 percent.

Using the RKEF method, there are similar environmental concerns as in the case of the HPAL method: the high operation costs (with the electricity costs accounting for about 50 percent of them) resulting from carbon emissions and high energy consumption. However, the atmosphere reduction during the ore-reduction and smelting process can lower the smelting temperature by 50–90°C, which effectively decreases the electricity consumption and operation costs by 5–10 percent.

The RKEF method proves to be suitable mainly for processing serpentine and saprolites to obtain high-nickel-content ferronickel (Zhang et al. 2025). Approximately 80 percent of laterite nickel ore is currently produced using RKEF, primarily for the stainless-steel sector. The HPAL, in contrast, is designed for the clean energy power battery sector. The overall cost differences between the aforementioned processes are not high. With the increasing demand for nickel sulfate in power batteries, the economic viability of the HPAL process is expected to improve. The economic viability takes place when the price difference between nickel sulfate and ferronickel exceeds USD 17,000 per ton.

4.3. Land use change, deforestation, biodiversity

Land use change (LUC) is a critical source of visible environmental effects that can compound climate change and climate vulnerability. The nickel mining growth will result in an increase in LUC in regions with high biodiversity. Research shows that emissions could increase 6 times by 2050 in a 1.5 degree C scenario (S&P Global 2023), and the land

footprint of laterite mining in Indonesia is particularly high, corresponding to $\sim 40 \text{ m}^2/\text{tNi}$ (International Finance Corporation 2023). In the case of Indonesia, it is particularly important. If all Indonesian under-development mining projects are opened, the land area occupied by the nickel mining industry in Indonesia would grow from 360 km^2 in 2020 to 800 km^2 by 2026 (International Finance Corporation 2023).

Over the last few decades, Indonesia faced a deforestation process coming from the palm oil and forest industry. The demands from consumers and other stakeholders, e.g., environmental organizations, influenced those industries to adopt policies which resulted in a reduction of deforestation by 90 percent (Heijlen and Duhayon 2024). And now, nickel mining has started to be a significant driver of deforestation again. Analyzing 329 nickel mining concessions in Indonesia, it was found that associated operations have driven up to 378,970 acres of deforestation since 2000 (Heijlen and Duhayon 2024), and over 1.2 million acres of forest are at risk inside nickel concessions (Heijlen and Duhayon 2024). Sulawesi has lost more than half a million hectares of forest since 2011 (Heijlen and Duhayon 2024). The neighboring islands of the Maluku region, which are rich in nickel, are also under threat. In 2018, construction began on the Indonesia Weda Bay Industrial Park, resulting in at least 5,331 hectares of tropical forests being cut, totaling a loss of approximately 2.04 million metric tons of greenhouse gases (CO_2e) previously stored as carbon in those forests (Heijlen and Duhayon 2024).

Apart from the impact on biodiversity and carbon emissions, land-use changes can significantly hurt local communities. According to a report by Climate Rights International (Heijlen and Duhayon 2024), the mining companies, in coordination with Indonesian police and military personnel, have engaged in land grabbing, coercion, and intimidation of Indigenous Peoples and other communities, who are experiencing serious and potentially existential threats to their traditional ways of life.

Conclusions

Indonesia is one of the countries with the largest nickel mineral reserves. By imposing a ban on nickel ores in 2020, Indonesia has become a key player in the nickel-rich batteries market. In 2023, Indonesia produced an estimated 1,800,000 tons of nickel. The country provides around 50 percent of the world's nickel production and about 16 percent of global reserves. In value terms, in 2022, Indonesia exported nickel for USD 20 bn worldwide, so it accounted for around 28 percent of the world's nickel trade exports. The green transition requires a substantial supply of energy and critical materials, including nickel. Nickel is a key ingredient in the ion-lithium battery, which is used for EVs. EVs are a key part of the transition of the automotive industry, and the number of EVs has been significantly rising in major markets worldwide. Increasing EV sales are driving up global battery demand, and to keep up with that demand, nickel production will need to expand. However, the nickel extraction processes from laterite ores using pyro- and hydrometallurgical processes bring

environmental concerns due to energy consumption, carbon emissions, environmental impacts, and economic viability. The most commonly used pyrometallurgical method is the RKEF, which faces high energy consumption and operation costs. In contrast, HPAL is the hydrometallurgical process and is primarily used for processing low-grade nickel ore. The concerns of HPAL remain regarding high investment intensity, water waste, and process complexity.

Special attention should be given to the sustainable aspects of the mining process. The mining process is associated with environmental challenges, and innovative low-carbon technologies should be implemented to minimize environmental concerns (RQ2). The carbon footprint of the technology required to complete the processing route is potentially a big question for an exploration into green EVs. The current process raises environmental concerns due to fossil energy used in the mining operations, contributing to health risks, air, water, and soil pollution, and also to human rights abuses. For Indonesia, coal is a problem. To meet the goals of the Paris Agreement, Indonesia must phase out coal-fired power plants by the end of the next decade. Today, the country has not set up a coal phaseout target yet, and having analyzed the current and future investment in smelting plants, the coal power capacity will continue to increase.

Moreover, environmentally risky practices concern the HPAL technology used in the nickel extraction in connection with waste management. The important concern is potential influence on marine ecosystems, especially in environments like Indonesia, with high rainfall, seismic activity, and a limited island's space for large dams. Disposing of these tailings in a wet climate makes drying them for storage difficult. In order to avoid local groundwater contamination, other methods of waste management should be used.

The forecasted growth in nickel mining may cause an increase in LUC in high biodiversity regions of Indonesia, like the island of Halmahera, destroying tropical forests. Extracting nickel from laterites through open-cast mining takes up a big part of the land. The area of land occupied by the nickel mining industry will grow as the number of new mining sites increases. Over the last few decades, Indonesia faced a deforestation process coming from the palm oil and forest industry, and today, nickel mining is a significant driver of deforestation and biodiversity loss.

Therefore, it is essential to analyze the advantages of each nickel extraction process and room for improvement, focusing on saving energy, reducing emissions, operational costs, and clarifying the economic viability.

Indonesia is developing an integrated EV supply chain and becoming one of the world's top producers of Class 1 nickel for EV batteries (RQ1). The country is receiving strong support from foreign investments, mainly from China. Today, the dependence on Chinese investors seems to be too big, which impacts the global EV value chain. China holds a strong position in all stages of the EV battery process, and for China, the cooperation means cheaper access to resources and labor in the country with less strict environmental regulations. The tightened ties between both countries give China a bigger competition advantage against other stakeholders and for Indonesia a strong material manufacturing place in the developing

EV growth. The mutual cooperation influences the relations with other countries, mainly the European Union and the United States. In the future, a big challenge for Indonesia would be working on cutting carbon emissions in the nickel supply chain and reducing the Chinese ownership in the nickel mining projects. The new EU Batteries Regulation, coming into force from 2027, will require the disclosure of the carbon footprint of all EV batteries sold in Europe. In the U.S., from 2025, the tax incentives under the Inflation Reduction Act will exclude from the incentive program batteries containing raw materials, like nickel, sourced from the “countries or companies of concern”.

The transition to EVs seems to be a part of solving the climate crisis, but without transparency around many mineral operations and attention on sustainable processes in the nickel mining, all sides of the fossil fuel economy could be repeated. The paradox is that the developed countries or regions, like Europe and the U.S., are under a renewable energy transformation process in order to keep the goal of reducing greenhouse emissions according to the Paris Agreement. To achieve it, they would need a large amount of nickel, which is not sustainable and not produced in a transparent way. In fact, the transformation is aiming to reduce greenhouse emissions for final consumers, but not using EVs would be powered by batteries, which were produced with a coal-induced heavy CO₂ footprint. Therefore, the extraction of nickel for a clean energy transformation and all stages of the mining process in Indonesia must be done in a sustainable way (RQ3). The transition to EVs is a key part of the renewable energy and green transportation change, but this process will only be green when all stakeholders of the EV value chain are involved in the process. Battery and EV manufacturers should demand that the nickel used in their products is sourced responsibly. EV companies such as Tesla, Ford, and Volkswagen that have contracts to source nickel from Indonesia should push suppliers by addressing environmental and social concerns. They should even consider stopping sourcing nickel from manufacturers that do not respect a responsible way of mining. The regulations to be adopted in Europe and the U.S. should help to increase transparency about critical minerals supply chains by providing public information about all suppliers. In addition, they should assist in implementing the transparent rules so that independent audits of mines and facilities can be conducted. On the other hand, consumers should demand products made in a sustainable way with respect for the environment and taking into consideration social aspects.

The nickel mining industry in Indonesia must improve the environmental approach both to mineral and energy efficiencies during processing and eliminate waste and emissions into nature. Increased extraction should not affect people and the environment in extractive locations. The nature of mining makes it challenging to be 100 percent clean. Therefore, the companies would not likely do so by themselves if they still see the demand for nickel. At this stage, the Indonesian government, probably together with other governments and financial institutions, should take a step to implement policies to ensure nickel production becomes cleaner. These include cleaner, low-emission nickel refining and processing ways defined by the Financial Services Authority, Indonesia’s financial sector regulatory body. It would stimulate investments in more sustainable technologies for mining, waste management, and

biodiversity conservation. By integrating all those aspects, Indonesia could become one of the countries that have successfully implemented sustainable practices.

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REFERENCES

- ABC News, First Quantum Minerals to close Ravensthorpe nickel project with lose of 330 jobs. [Online:] <https://www.abc.net.au/news/2024-04-29/ravensthorpe-nickel-mine-to-close/103781186> [Accessed: 2024-07-22].
- Ahead of The Herd. The Future of Canada's Nickel Supply is NOT Indonesia. 2 June 2021. [Online:] <https://aheadoftheherd.com/the-future-of-canadas-nickel-supply-is-not-indonesia/> [Accessed: 2024-07-18].
- Aramendia et al. 2023 – Aramendia, E., Brockway, P.E., Taylor, P.G. and Norman, J. 2023. Global energy consumption of the mineral mining industry: Exploring the historical perspective and future pathways to 2060, *Global Environmental Change* 83, <https://doi.org/10.1016/j.gloenvcha.2023.102745>.
- ASEAN Automotive Federation. Statistics. [Online:] http://www.asean-autofed.com/files/AAF_Statistics_2023.pdf [Accessed: 2024-07-07].
- ASEAN Briefing, Indonesian's Electric Battery Industrial Strategy. [Online:] <https://www.aseanbriefing.com/news/southeast-asias-first-ev-battery-plant-begins-operations-in-indonesia/> [Accessed: 2024-07-21].
- ASEAN Briefing, Southeast Asia's First EV Battery Plant Begins Operations in Indonesia. [Online:] <https://www.aseanbriefing.com/news/southeast-asias-first-ev-battery-plant-begins-operations-in-indonesia/> [Accessed: 2024-07-21].
- Averay, M. 2020. The Future of Nickel Mining in Indonesia. 15 June 2020. [Online:] <https://medium.com/enegra/the-futureof-nickel-mining-in-indonesia-af6cf206c08a> [Accessed: 2024-07-20].
- Bahfie et al. 2022 – Bahfie, F., Manaf, A., Astuti, W., Nurjaman, F., Prastyo, E. and Herlina, U. 2022. Development of laterite ore processing and its applications. *Indonesian Mining Journal* 25(2), <https://doi.org/10.30556/imj.Vol25.No2.2022.1261>.
- Bhattacharjee et al. 2024 – Bhattacharjee, A., Mohanty, R.K., Ghosh, A. 2020. Design of an Optimized Thermal Management System for Li-Ion Batteries under Different Discharging Conditions. *Energies* 13(21), <https://doi.org/10.3390/en13215695>.
- Bhuwarka, K. and Olivetti, E. 2024. *Nickel Market Dynamics and the Security of the Battery Supply Chain*, University of Texas. [Online:] https://sites.utexas.edu/mineralstransition/files/2024/06/Nickel_Memo_Bhuwarka_Olivetti-Google-Docs.pdf [Accessed: 2024-07-31].
- Bunjaku et al. 2012 – Bunjaku, A., Kekkonen, M., Pietilä, K. and Taskinen, P. 2012. Effect of mineralogy and reducing agent on reduction of saprolitic nickel ores. *Mineral Processing and Extractive Metallurgy* 121(3), pp. 156–165, <https://doi.org/10.1179/1743285512Y.000000001>.
- Castillo et al. 2022 – Castillo, R., Blumenthal, L. and Purdy, C. 2022. *Indonesian's electric vehicle batteries dream has a dirty nickel problem*. Brookings, 2022. [Online:] <https://www.brookings.edu/articles/indonesias-electric-vehicle-batteries-dream-has-a-dirty-nickel-problem/#top1> [Accessed: 2024-07-20].
- Center for Strategic & International Studies, Diversifying Investments in Indonesia's Mining Sector, 2024. [Online:] <https://www.csis.org/analysis/diversifying-investment-indonesias-mining-sector> [Accessed: 2024-07-22].
- Center for Strategic & International Studies, Indonesia's Nickel Industrial Strategy, 2021. [Online:] <https://www.csis.org/analysis/indonesias-nickel-industrial-strategy> [Accessed: 2024-07-21].
- Climate Analytics and New Climate Institute, Climate Action Tracker, 4 December 2023. [Online:] <https://climateactiontracker.org/countries/indonesia/> [Accessed: 2024-07-06].
- Climate Analytics and New Climate Institute, Climate Action Tracker, CAT Rating Methodology. [Online:] <https://climateactiontracker.org/methodology/cat-rating-methodology/> [Accessed: 2024-07-06].
- Climate Rights International, CRI Indonesia Report, Nickel Unearthed, The Human and Climate Costs of Indonesia's Nickel Industry. [Online:] <https://cri.org/reports/nickel-unearthed/> [Accessed: 2024-08-07].

- Climate Rights International, Indonesia: Huge Nickel Project Driving Climate, Rights, Environmental Harms. [Online:] <https://cri.org/indonesia-huge-nickel-project-driving-climate-rights-environmental-harms/> [Accessed: 2024-08-07].
- Debnath et al. 2018 – Debnath, B., Chowdhury, R. and Ghosh, S.K. 2018. Sustainability of metal recovery from E-waste. *Frontiers of Environmental Science & Engineering* 12(2), <https://doi.org/10.1007/s11783-018-1044-9>.
- Dialogue Earth, Coal-powered industrial parks test Indonesia's climate pledges – and China's too. [Online:] <https://dialogue.earth/en/energy/coal-powered-industrial-parks-test-indonesias-climate-pledges-and-chinas-too/> [Accessed: 2024-07-30].
- Earthworks, Indonesians Demand Government Match Words with Action and Ditch Ocean Dumping. [Online:] <https://earthworks.org/blog/indonesians-demand-government-match-words-with-action-and-ditch-ocean-dumping/> [Accessed: 2024-08-06].
- Earthworks, Recharge Responsibly, The Environmental and Social Footprint of Mining Cobalt, Lithium, and Nickel for Electric Vehicle Batteries, 2021. [Online:] <https://earthworks.org/wp-content/uploads/2021/09/Recharge-Responsibly-Final.pdf> [Accessed: 2024-07-29].
- East Asia Forum, Reassessing Indonesia's nickeldownstreaming policy. [Online:] <https://eastasiaforum.org/2023/10/14/reassessing-indonesias-nickel-downstreaming-policy/> [Accessed: 2024-07-22].
- Ebrahimabadi et al. 2018 – Ebrahimabadi, A., Pouresmaeili, M. and Afradi, A. 2018. Esmaeil Pouresmaeili, Sahand Nouri, Comparing two methods of PROMETHEE and Fuzzy TOPSIS in selecting the best plant species for the reclamation of Sarcheshmeh copper mine. *Asian Journal of Water, Environment and Pollution* 15(2), pp. 141–152, <https://doi.org/10.3233/AJW-180026>.
- Ekrami et al. 2022 – Ekrami, E., Pouresmaeili, M., Hashemiyooun, E., Noorbakhsh, N., Mahmoudifard, M. 2022. Nanotechnology: A sustainable solution for heavy metals remediation, *Environmental Nanotechnology, Monitoring & Management* 18, <https://doi.org/10.1016/j.enmm.2022.100718>.
- EV-Volumes, Global EV Sales for 2023. [Online:] <https://ev-volumes.com/news/ev/global-ev-sales-for-2023/> [Accessed: 2024-07-07].
- Fastmarkets, MHP emerges as preferred route to sulfate for international nickel market, 9 August 2022. [Online:] <https://www.fastmarkets.com/insights/mhp-emerges-as-preferred-route-to-sulfate-for-international-nickel-market/> [Accessed: 2024-07-19].
- Fastmarkets, Oversupply sets tone for China's nickel market/2024 preview, 2024. [Online:] <https://www.fastmarkets.com/insights/oversupply-sets-tone-for-chinas-nickel-market-2024-preview/> [Accessed: 2024-07-22].
- Federal Ministry for Economic Cooperation and Development, The Nickel for the Energy Transition, Deutsche Gesellschaft fuer Internationale Zusammenarbeit GmbH, 2022. [Online:] <https://rue.bmz.de/resource/blob/152990/giz-nickelstudie.pdf> [Accessed: 2024-07-26].
- Financial Times, Indonesia moves to reduce Chinese ownership of nickel projects. [Online:] <https://www.ft.com/content/0f8e2fe8-c7cb-4d6a-9436-1cb1806af4e0?countryCode=POL&multistepRegForm=multistep> [Accessed: 2024-08-08].
- Fonseca et al. 2013 – Fonseca, A., McAllister, M.L. and Fitzpatrick, P. 2013. Measuring what? A comparative anatomy of five mining sustainability frameworks. *Minerals Engineering* 46–47, <https://doi.org/10.1016/j.mineng.2013.04.008>.
- Food and Agricultural Organization of the United Nations, FAOLEX Database, Indonesia, Law No. 4/2009 on Mineral and Coal Mining. [Online:] <https://www.fao.org/faolex/results/details/en/c/LEX-FAOC085947/> [Accessed: 2024-07-26].
- Ghosh, A. 2020. Possibilities and Challenges for the Inclusion of the Electric Vehicle (EV) to Reduce the Carbon Footprint in the Transport Sector: A Review. *Energies* 13, <https://doi.org/10.3390/en13102602>.
- Global Energy Monitor, Global Coal Plant Tracker, July 2024. [Online:] <https://globalenergymonitor.org/projects/global-coal-plant-tracker/> [Accessed: 2024-07-30].
- Gorman, M.R. and Dzombak, D.A. 2018. A review of sustainable mining and resource management: Transitioning from the life cycle of the mine to the life cycle of the mineral. *Resources, Conservation and Recycling* 137, pp. 281–291, <https://doi.org/10.1016/j.resconrec.2018.06.001>.
- Heijlen, W. and Duhayon, C. 2024. An empirical estimate of the land footprint of nickel from laterite mining in Indonesia. *The Extractive Industries and Society* 17, <https://doi.org/10.1016/j.exis.2024.101421>.

- Hukumonline.com, Law of The Republic of Indonesia, Number 3 of 2020 on Amendment to Law Number 4 of 2009 on Mineral and Coal Mining. [Online:] <https://www.delvedatabase.org/uploads/resources/Amendment-to-Law-Number-4-of-2009.pdf> [Accessed: 2024-07-28].
- Igogo et al. 2020 – Igogo, T., Awuah-Offei, K., Newman, A., Lowder, T. and Engel-Cox, J. 2020. The Joint Institute for Strategic Energy Analysis, Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches. Technical Report NREL/TP-6A50-76156. [Online:] <https://www.nrel.gov/docs/fy20osti/76156.pdf> [Accessed: 2024-07-17].
- Igogo et al. 2021 – Igogo, T., Awuah-Offei, K., Newman, A., Lowder, T. and Engel-Cox, J. 2021. Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches. *Applied Energy* 300, <https://doi.org/10.1016/j.apenergy.2021.117375>.
- International Council on Mining and Metals. [Online:] <https://www.icmm.com/en-gb/our-principles> [Accessed: 2024-07-11].
- International Energy Agency, Electric car sales break new records with momentum expected to continue through 2023. [Online:] <https://www.iea.org/energy-system/transport/electric-vehicles> [Accessed: 2024-07-07].
- International Energy Agency, GHG emissions intensity for class 1 nickel by resource type and processing route, 2021. [Online:] <https://www.iea.org/data-and-statistics/charts/ghg-emissions-intensity-for-class-1-nickel-by-resource-type-and-processing-route> [Accessed: 2024-07-20].
- International Energy Agency, *Global EV outlook 2024*. [Online:] <https://iea.blob.core.windows.net/assets/a9e3544b-0b12-4e15-b407-65f5c8ce1b5f/GlobalEVOutlook2024.pdf> [Accessed: 2024-07-07].
- International Energy Agency, The Role of Critical Minerals in Clean Energy Transitions, 2022. [Online:] <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/sustainable-and-responsible-development-of-minerals> [Accessed: 2024-07-29].
- International Finance Corporation, Net Zero Roadmap for Copper and Nickel, Technical Report, 2023. [Online:] <https://ccsi.columbia.edu/sites/default/files/content/docs/publications/ccsi-net-zero-roadmap-copper-nickel.pdf> [Accessed: 2024-07-31].
- IVL Swedish Environmental Research Institute. The Life Cycle Energy Consumption and CO2 Emissions from Lithium-Ion Batteries, A Study with Focus on Current Technology and Batteries for Light-Duty Vehicles; IVL Swedish Environmental Research Institute: Stockholm, Sweden, 2017; p. 5.
- Jakarta Globe, Volkswagen, BASF to Invest in Indonesia's EV Battery Sector. [Online:] <https://jakartaglobe.id/business/volkswagen-basf-to-invest-in-indonesias-ev-battery-sector> [Accessed: 2024-07-21].
- Journalist Resorce, Investigating Rainforest Destruction: The Nickel Mines Clearing Indonesian Forests. [Online:] <https://pulitzercenter.org/investigating-rainforest-destruction-nickel-mines-clearing-indonesian-forests> [Accessed: 2024-08-07].
- Khan et al. 2023 – Khan Y., Liu F. and Hassan T. 2023. Natural resources and sustainable development: Evaluating the role of remittances and energy resources efficiency. *Resources Policy* 80, <https://doi.org/10.1016/j.resourpol.2022.103214>.
- Konewka et al. 2021 – Konewka, T., Bednarz, J. and Czuba, T. 2021. Building a Competitive Advantage for Indonesia in the Development of the Regional EV Battery Chain. *Energies* 14(21), <https://doi.org/10.3390/en14217332>.
- Krishna et al. 2023 – Krishna, R., Dhass, A.D., Arya, A., Prasad, R. and Colak, I. 2023. An assessment of the strategies for the energy-critical elements necessary for the development of sustainable energy sources. *Environmental Science and Pollution Research* 30, 90276–90297, <https://doi.org/10.1007/s11356-023-28046-2>.
- Land & Climate Review, Electric vehicles are driving deforestation in Indonesia. But they don't have to. [Online:] <https://www.landclimate.org/electric-vehicles-are-driving-deforestation-in-indonesia-but-they-dont-have-to/> [Accessed: 2024-08-07].
- Lead the Charge, The importance of equitable, sustainable and fossil-free automotive supply chains: a case study on nickel mining and processing in Indonesia. [Online:] <https://leadthecharge.org/resources/the-importance-of-equitable-sustainable-and-fossil-free-automotive-supply-chains-a-case-study-on-nickel-mining-and-processing-in-indonesia/> [Accessed: 2024-07-29].
- Lèbre et al. 2017 – Lèbre, E., Corder, G.D. and Golev, A. 2017. Sustainable practices in the management of mining waste: A focus on the mineral resource. *Minerals Engineering* 107, pp. 34–42, <https://doi.org/10.1016/j.mineng.2016.12.004>.

- Lezak et al. 2019 – Lezak, S., Cannon, C. and Koch Blank, T. 2019. Low-carbon metals for a low-carbon world: a new energy paradigm for mines. *Rock Mountain Institute* 6. [Online:] https://rmi.org/wp-content/uploads/2019/12/Low-Carbon_Metals_for_a_Low-Carbon_World.pdf [Accessed: 16.07.2024].
- Li et al. 2015 – Li, J.H., Li, Y.Y., Zheng, S., Xiong, D.L., Chen, H. and Zhang, Y.F. 2015. Research review of laterite nickel ore metallurgy. *Nonferrous Metals Science and Engineering* 6(1), pp. 35–40 (in Chinese with English abstract), <https://dx.doi.org/10.13264/j.cnki.yjskx.2015.01.007>.
- Li et al. 2017 – Li, G.H., Luo, J., Jiang, T., Peng, Z.W., Rao, M.J. and Zhang, Y.B. 2017. A method for reducing energy consumption in the production of nickel-iron alloy using the RKEF process. CN201711388806.2
- Maennling, N. and Toledano, P. 2018. The Renewable Power of the Mine, Columbia Center on Sustainable Investment, 2018. [Online:] https://scholarship.law.columbia.edu/sustainable_investment_staffpubs/77 [Accessed: 2024-07-17].
- Martins et al. 2021 – Martins, S., Guimarães, L.F., Botelho, A.B., Tenório, J.A.S. and Espinosa, D.C.R. 2021. Electric car battery: An overview on global demand, recycling and future approaches towards sustainability. *Journal of Environmental Management* 295, <https://doi.org/10.1016/j.jenvman.2021.113091>.
- McDonald, R. and Whittington, B. 2019. 2008. Atmospheric acid leaching of nickel laterites review. Part II. Chloride and bio-technologies. *Hydrometallurgy* 91, pp. 56–69, <https://doi.org/10.1016/j.hydromet.2007.11.010>.
- McKinsey&Company. How Clean Can the Nickel Industry Become? September 2020. [Online:] <https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become> [Accessed: 2024-07-18].
- McKinsey&Company. The Future of Nickel: A Class Act. [Online:] <https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-future-of-nickel-a-class-act> [Accessed: 2024-07-18].
- Mehta, P. 2021. *The Global Electric Vehicle Race Is Heating Up*. Who will lead the EV race?, WoodMacKenzie, 2021. [Online:] https://www.woodmac.com/news/opinion/the-global-electric-vehicle-race-is-heating-up/?utm_campaign=energy [Accessed: 2024-07-07].
- Mighty Earth, Destroying Indonesia’s forests to mine nickel. [Online:] https://drive.google.com/file/d/16EBpKEQWy9-d7_NgOfItZ-ETe07BHsGM/view [Accessed: 2024-08-07].
- Mighty Earth, Sourcing responsible nickel for EVs. [Online:] <https://mightyearth.org/article/electric-vehicles-evs-are-vital-to-the-transition-away-f-efficient-than-cars-that-run-on-gasoline-even-better-th/> [Accessed: 2024-08-07].
- Mining Technology, The five largest nickel mines in operation in Indonesia. [Online:] <https://www.mining-technology.com/marketdata/five-largest-nickel-mines-indonesia/?cf-view> [Accessed: 2024-07-21].
- Mining.com, Glencore to sell stake in troubled New Caledonia nickel operation. [Online:] [https://www.mining.com/glencore-to-sell-stake-in-troubled-new-caledonia-nickel-operation/#:~:text=\(Image%20courtesy%20of%20Glencore.\),continues%20to%20hit%20the%20industry](https://www.mining.com/glencore-to-sell-stake-in-troubled-new-caledonia-nickel-operation/#:~:text=(Image%20courtesy%20of%20Glencore.),continues%20to%20hit%20the%20industry) [Accessed: 2024-07-22].
- Mining.com, Indonesia and China killed the nickel market, 2024. [Online:] <https://www.mining.com/web/indonesia-and-china-killed-the-nickel-market/> [Accessed: 2024-07-30].
- Mongabay, Indonesian miners eyeing EV nickel boom seek to dump waste into the sea. [Online:] <https://news.mongabay.com/2020/05/indonesian-miners-eyeing-ev-nickel-boom-seek-to-dump-waste-into-the-sea/> [Accessed: 2024-08-06].
- Mongabay, Red seas and no fish: Nickel mining takes its toll on Indonesia’s spice islands. [Online:] <https://news.mongabay.com/2022/02/red-seas-and-no-fish-nickel-mining-takes-its-toll-on-indonesias-spice-islands/> [Accessed: 2024-08-06].
- Mudd, G. 2010. Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews* 38(1–2), <https://doi.org/10.1016/j.oregeorev.2010.05.003>.
- Naryono, E. 2023. Nickel mine exploitation in indonesia, between a blessing and a disaster of environmental damage, <https://doi.org/10.31219/osf.io/y58qe>.
- Nickel Institute, Nickel Industry – Part 1 – Processing nickel laterites and sulfides, 2024. [Online:] <https://nickelinstitute.org/en/blog/2024/may/nickel-industry-part-1-processing-nickel-laterites-and-sulfides/> [Accessed: 2024-07-18].
- NikkeiAsia, Nickel-Rich Indonesia Draws Global Suppliers of EV Battery Materials. 23 April 2021. [Online:] <https://asia.nikkei.com/Business/Markets/Commodities/Nickel-rich-Indonesia-draws-global-suppliers-of-EV-battery-materials> [Accessed: 2024-07-20].

- Norgate, T. and Jahanshahi, S. 2011a. Assessing the energy and greenhouse gas footprints of nickel laterite processing. *Minerals Engineering* 24(7), pp. 698–707, <https://doi.org/10.1016/j.mineng.2010.10.002> [Accessed: 2024-07-20].
- Norgate, T. and Jahanshahi, S. 2011b. Reducing the greenhouse gas footprint of primary metal production: Where should the focus be? *Minerals Engineering* 24(14) pp. 1563–1570, <https://doi.org/10.1016/j.mineng.2011.08.007>.
- Nurjaman et al. 2020 – Nurjaman, F., Bahfie, F., Herlina, U., Astuti, W. and Suharno, B. 2020. Kajian literatur parameter proses reduksi selektif bijih nikel laterit. *Metal Indonesia* 42(2), <https://doi.org/10.32423/jmi.2020.v42.63-71>.
- OECD 2023 – Purchasing power parities (PPP) (indicator), <https://doi.org/10.1787/1290ee5a-en>.
- Pell et al. 2021 – Pell, R., Tijsseling, L., Goodenough, K., Wall, F., Dehaine, Q., Grant, A., Deak, D., Yan, X. and Whattoff, P. 2021. Towards sustainable extraction of technology materials through integrated approaches. *Nature Reviews Earth & Environment* 2, pp. 665–679, <https://doi.org/10.1038/s43017-021-00211-6>.
- Pouresmaieli et al. 20203 – Pouresmaieli, M., Ataei, M., Qarahasanlou, A.N. and Barabadi, A. 2023. Integration of renewable energy and sustainable development with strategic planning in the mining industry. *Results in Engineering* 20, <https://doi.org/10.1016/j.rineng.2023.101412>.
- Processing nickel. *Nickel Magazine* 39(1), 2024, pp. 6–7. [Online:] <https://nickelinstitute.org/en/nickel-magazine/nickel-magazine-vol39-no1-2024/> [Accessed: 2024-07-18].
- Project Blue, PT QMB New Energy materials ships first MHP, 2023. [Online:] <https://projectblue.com/blue/news-analysis/285/pt-qmb-new-energy-materials-ships-first-mhp> [Accessed: 2024-07-21].
- Qu et al. 2020 – Qu, T., Gu, X.P., Shi, L., Luo, M.Y., Wang, Q., Tian, F.Y. and Dai, Y.N. 2020. Research status of development and utilization of garnierite. *Materials Reports* 34(S1), pp. 261–267
- Quijada-Maldonado, E. and Romero, J. 2021. Solvent extraction of rare-earth elements with ionic liquids: Toward a selective and sustainable extraction of these valuable elements. *Current Opinion in Green and Sustainable Chemistry* 27, <https://doi.org/10.1016/j.cogsc.2020.100428>.
- Reuters 2021 – China’s Lygend starts milestone nickel project in Indonesia, 2021. [Online:] <https://www.reuters.com/article/indonesia-nickel-lygend/update-1-chinas-lygend-starts-milestone-nickel-project-in-indonesia-idUSL2N2N60XR/> [Accessed: 2024-07-21].
- Reuters 2024 – Reuters, Exclusive: facing green pressure, Indonesia halts deep-sea mining disposal. [Online:] <https://www.reuters.com/article/us-indonesia-mining-environment-exclusiv-idUSKBN2A50UV/> [Accessed: 2024-08-06].
- S&P Global 2023 – S&P Global, Indonesia’s nickel processing boom raises questions over tailings disposal, 2023. [Online:] <https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/indonesia-s-nickel-processing-boom-raises-questions-over-tailings-disposal-75180844> [Accessed: 2024-07-31].
- S&P Global 2024 – S&P Global, Indonesian nickel production dominates commodity market, 2024. [Online:] <https://www.spglobal.com/market-intelligence/en/news-insights/articles/2024/2/indonesian-nickel-production-dominates-commodity-market-80242322#:~:text=The%20island%20nation%20is%20reaping,energy%20transition%2C%20are%20cutting%20production> [Accessed: 2024-07-31].
- Setyadi et al. 2021 – Setyadi, A., Pieris, J. and Tehupeiry, A. 2021. Juridical review of nickel governance law in Indonesia, ICHRL, <https://doi.org/10.4108/eai.14-4-2021.2312511>.
- Shi et al. 2019 – Shi, T., Ma, J., Zhang, Y., Liu, C., Hu, Y., Gong, Y., Wu, X., Ju, T., Hou, H. and Zhao, L. 2019. Status of lead accumulation in agricultural soils across China (1979–2016). *Environment International* 129, pp. 35–41, <https://doi.org/10.1016/j.envint.2019.05.025>.
- Sonter et al. 2017 – Sonter, L.J., Herrera, D., Barrett, D.J., Galford, G.I., Moran, C.J. and Soares-Filho, B.S. 2017. Mining drives extensive deforestation in the Brazilian Amazon. *Nature Communications* 8(1), <https://doi.org/10.1038/s41467-017-00557-w>.
- Szurliés, M. and Vasters, J. 2024. The importance of Indonesia for the global nickel market. *BGR commodity TopNews* 71, <https://doi.org/10.25928/c9aj-xx96>.
- The Bangkok Post 2019 – The Bangkok Post, Indonesia Forges Ahead with Electric Car Drive. 9 August 2019. [Online:] <https://www.bangkokpost.com/world/1727439/indonesia-president-signs-new-ev-decree-to-bolster-industry> [Accessed: 2024-07-07].

- The Business Times, Indonesia President Signs New Electric Vehicle Decree to Bolster Industry. 9 August 2019, <https://www.businesstimes.com.sg/transport/indonesia-president-signs-new-electric-vehicle-decree-to-bolster-industry> [Accessed: 2024-07-07].
- The Diplomat, Optimizing Indonesia's Nickel Industry potential and Maximizing its Derivatives. [Online:] <https://thediplomat.com/2023/07/optimizing-indonesias-nickel-industry-potential-and-maximizing-its-derivatives/> [Accessed: 2024-07-21].
- The Korea Times, Hyundai Motor Group chief visits Indonesia for EV, hydrogen partnership. [Online:] https://www.koreatimes.co.kr/www/tech/2024/05/129_375066.html [Accessed: 2024-07-21].
- The Republic of Indonesia, Booklet Tambang Nikel 2020. [Online:] <https://www.esdm.go.id/id/booklet/booklet-tambang-nikel-2020> [Accessed: 2024-07-21].
- Transport&Environment, On paving the way to cleaner nickel, 2023. [Online:] <https://www.transportenvironment.org/articles/paving-the-way-to-cleaner-nickel/> [Accessed: 2024-07-08].
- Tritto, A. 2023. How Indonesia Used Chinese Industrial Investments to Turn Nickel into the New Gold, Carnegie Endowment for International Peace, Washington, 2023. [Online:] https://carnegie-production-assets.s3.amazonaws.com/static/files/files__Tritto_Indonesia_Nickel.pdf [Accessed: 2024-08-06].
- UN Comtrade 2020 – UN Comtrade, Chattam House, The Royal Institute of International Affairs, 2020. [Online:] <https://resourcetrade.earth/?year=2021&category=165&units=value&autozoom=1> [Accessed: 2024-07-18].
- United Nations 2024 – United Nations, Climate Change, The Paris Agreement. [Online:] <https://unfccc.int/process-and-meetings/the-paris-agreement> [Accessed: 2024-07-05].
- United Nations, Department of Economic and Social Affairs, *India overtakes China as the world's most populous country*, Future of the World, Policy Brief No. 153, April 2023. [Online:] https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undes_a_pd_2023_policy-brief-153.pdf [Accessed: 2024-07-03].
- United Nations, Treaty Collection. [Online:] https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-7-d&chapter=27&clang=en&_gl=1*12shnt*_ga*MTQ1MTMyMDY1LjE3MjAyMDk4NTg.*_ga_TK9BQL5X7Z*MTcyMDIwOTg1OC4xLjAuMTcyMDIwOTg1OC4wLjAuMA [Accessed: 2024-07-05].
- U.S. Department of Interior, U.S. Geological, Mineral Commodity Summaries 2024. [Online:] <https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf> [Accessed: 2024-07-05].
- U.S. Department of the Interior. Mineral Commodity Summaries 2021; National Minerals Information Center: Reston, VA, USA, 2024; p. 125. [Online:] <https://www.usgs.gov/publications/mineral-commodity-summaries-2021> [Accessed: 2024-07-18].
- Wang et al. 2020 – Wang, Q.M., Chen, Y.L., Guo, X.Y., Wang, S.S. and Tian, Q.H. 2020. A method for extracting metallic nickel from laterite nickel ore. Chinese patent, CN202010533112.9 (*in Chinese*).
- Weiser et al. 2020 – Weiser, A., Bickel, M.W., Kümmerer, K. and Lang, D.J. 2020. Towards a more sustainable metal use – Lessons learned from national strategy documents. *Resources Policy* 68, <https://doi.org/10.1016/j.resourpol.2020.101770>.
- Whittington, B.I. and Muir, D. 2000. Pressure acid leaching of nickel laterites: a review. *Mineral Processing and Extractive Metallurgy Review* 21(6), <https://doi.org/10.1080/08827500008914177>.
- WoodMackenzie, The rise and rise of Indonesian HPAL – can it continue? [Online:] <https://www.woodmac.com/news/opinion/rise-of-indonesian-hpal/> [Accessed: 2024-07-31].
- Zhang et al. 2022 – Zhang, Z.F., Chen, X.F., Li, Y.C., Gao, A.H., Wang, Y.G., He, X.Z. and Wang, Q.S. 2022. Multipurpose utilization trend of nickel mineral resources under the goal of carbon peaking and carbon neutrality. *Multipurpose Utilization of Mineral Resources* (2), pp. 31–39.
- Zhang et al. 2025 – Zhang, Z., Zhang, W., Zhang, Z. and Chen, X. 2025. Nickel extraction from nickel laterites: Processes, resources, environment and cost. *China Geology* 8, pp. 187–213, <https://doi.org/10.31035/cg2024124>.

OVERVIEW OF INDONESIANS SUSTAINABLE NICKEL MINING AND PROCESSING

Key words

sustainable nickel mining and processing, HPAL, EV battery value chain, Indonesia

Abstract

The green transition will require a substantial supply of energy-critical materials, including nickel, which is emerging as a critical material for that. A part of the transition is the electrification of the vehicle industry. The electric vehicle (EV) has been significantly rising in major markets worldwide. In 2023, 14.2 million electric vehicles were sold, which was 35 percent over the previous year (EV-Volumes 2023). Increasing EV sales are driving up global battery demand. The battery capacity reached 750 GWh in 2023, a 40 percent increase compared to the previous year. (International Energy Agency 2024). To keep up with rising demand, nickel is a critical material, and its production will need to expand. Indonesia is taking part in that growth, reaching around half of the global supply of nickel-containing chemistries by 2030 (Transport & Environment 2023). Since 2019, Indonesia has been accelerating its plans to position the country as a key player in the global EV value chain. Indonesia holds the world's largest nickel reserves with an estimated 55 million tons (United Nations 2024). However, not all types of nickel can be used as a material for EV batteries. The way the nickel is mined from laterite ores leads to an increase in total costs for nickel production (Mudd 2010). Therefore, Indonesia should focus on including more advanced technologies in the mining process that can reduce the environmental impact. The increasing number of newly operating coal plants in Indonesia increased the emissions by 21 percent in 2022. In addition, they are off-grid coal plants that supply energy to the domestic metal industry and large infrastructure projects. The key purposes of this review paper are threefold: firstly, to investigate the increasing role of Indonesia in the global battery value chain; secondly, to identify the social and environmental concerns related to the adopted nickel mining technology, and thirdly, to identify the ways to make future Indonesian mining more sustainable.

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łańcuch wartości akumulatorów do pojazdów elektrycznych, Indonezja

Streszczenie

Przejsie na gospodarkę niskoemisyjną będzie wymagało znacznych dostaw surowców kluczowych dla energetyki, w tym niklu, który staje się w tym kontekście surowcem o kluczowym znaczeniu. Jednym z elementów tej transformacji jest elektryfikacja przemysłu motoryzacyjnego. Sprzedaż

pojazdów elektrycznych (EV) znacznie wzrosła na głównych rynkach na całym świecie. W 2023 roku sprzedano 14,2 mln pojazdów elektrycznych, co stanowiło wzrost o 35% w porównaniu z rokiem poprzednim (EV-Volumes 2023). Rosnąca sprzedaż pojazdów elektrycznych napędza globalny popyt na akumulatory. Pojemność akumulatorów osiągnęła 750 GWh w 2023 r., co stanowi wzrost o 40% w porównaniu z rokiem poprzednim (Międzynarodowa Agencja Energetyczna 2024). Aby nadążyć za rosnącym popytem, nikiel jest materiałem o kluczowym znaczeniu, a jego produkcja będzie musiała wzrosnąć. Indonezja uczestniczy w tym wzroście, osiągając do 2030 r. około połowy światowej podaży związków chemicznych zawierających nikiel (Transport & Environment 2023). Od 2019 r. Indonezja przyspiesza realizację planów pozycjonowania kraju jako kluczowego gracza w globalnym łańcuchu wartości pojazdów elektrycznych. Indonezja posiada największe na świecie zasoby niklu, szacowane na 55 mln ton (United Nations 2024). Jednak nie wszystkie rodzaje niklu nadają się do wykorzystania jako surowiec do produkcji akumulatorów do pojazdów elektrycznych. Sposób wydobywania niklu z rud laterytowych powoduje wzrost całkowitych kosztów produkcji niklu (Mudd 2010). W związku z tym Indonezja powinna skupić się na wdrażaniu bardziej zaawansowanych technologii w procesie wydobywczym, które pozwolą ograniczyć wpływ na środowisko. Rosnąca liczba nowo uruchomionych elektrowni węglowych w Indonezji spowodowała wzrost emisji o 21 procent w 2022 roku. Ponadto są to elektrownie węglowe działające poza siecią, które dostarczają energię do krajowego przemysłu metalowego i dużych projektów infrastrukturalnych. Niniejszy artykuł przeglądowy ma trzy główne cele: po pierwsze, zbadanie rosnącej roli Indonezji w globalnym łańcuchu wartości akumulatorów; po drugie, zidentyfikowanie problemów społecznych i środowiskowych związanych z zastosowaną technologią wydobywania niklu; oraz po trzecie, wskazanie sposobów na zapewnienie większej zrównoważoności przyszłego wydobywania w Indonezji.

