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NICKEL PERSPECTIVES

Nickel, a transition metal with particular physico-chemical properties, is a key critical element playing an important role in the production of steel, batteries, special alloys, and catalysts. The present article aims at a concise update concerning main current and future uses, production, reserves, and recycling prospects.

Nickel is employed in coin alloys since Hellenistic times and today plays an outstanding role in advanced industrial sectors such as steel, batteries, and catalysts, whose segment specifically represents the major share of the refinery market with a value of US$ 2.9 billion in 2022 [1].

The element is the fifth most common on Earth with an average content approximately 0.007% (70 ppmw). It belongs to group VIIIB of the periodic table and the electronic configuration of the atom ground state is $[Ar]3d^8 4s^2$: the most common oxidation state is +2, but compounds of Ni^0, Ni^+, and Ni^{3+} are well known [2]. The metal is lustrous, silvery-white, moderately hard, very ductile, and can form alloys with many other elements. It has low electrical and thermal conductivities and a high melting point (1453 °C); in the pure state it is ferromagnetic and becomes paramagnetic above 353 °C. The metal is resistant to attack by moist air or water at room temperature and by concentrated alkaline solutions, but dissolves in dilute mineral acids such as hydrochloric acid (HCl) and nitric acid (HNO_3). Finely divided nickel absorbs 17 times its volume of hydrogen and adsorbs other gases such as carbon monoxide, carbon dioxide, and ethylene: this surface adsorption capability makes nickel an important catalytic component [3].

Since the introduction of the nickel contract in 1979, the London Metal Exchange (LME) price has been the industry benchmark although the Shanghai Futures Exchange (SHFE) grew in importance in the last years. Spot trade is the main settlement method adopted in international commerce and price is influenced by the supply-demand balance, speculative activities, currencies, extractive news, and geo-political factors. Nickel under contract at LME and SHFE is primary nickel of minimum 99.8% purity (so-called Class I nickel) from selected producers enclosed in approved lists and with chemical analysis conforming to official specifications: trading incidents concerning the quality of shipments are not infrequent [4].

The Nickel Institute (NI) is a non-profit association of mining, concentrating, smelting, refining, and trading companies with head office in Toronto (Canada), founded in 2004 by the union of Nickel Development Institute with NiPERA, an independent science division committed to supporting research on the health and environmental effects associated with production, use, and disposal of the metal [5].

The International Nickel Study Group (INSG) is an intergovernmental organization established in 1990 and headquartered in Lisbon (Portugal). Membership comprises countries producing, working, and trading nickel: main objective is to collect and publish information and statistics on markets, industrial facilities, environmental issues, and regulations [6].

Raising relevance has recently spurred a flurry of scientific, institutional, technical, and economic literature: the present note aims at a concise update about uses, production, market, and reserves.

Uses

The global market for nickel was at 2.96 million metric tons in 2022 and demand is estimated to increase by 8% in 2023 [7]. In 2022, the stainless-steel industry accounted for more than 65% of all primary nickel usage, the batteries industry for 17%, alloys and superalloys for 8%, and electroplating for 5% (Fig.1) [8].

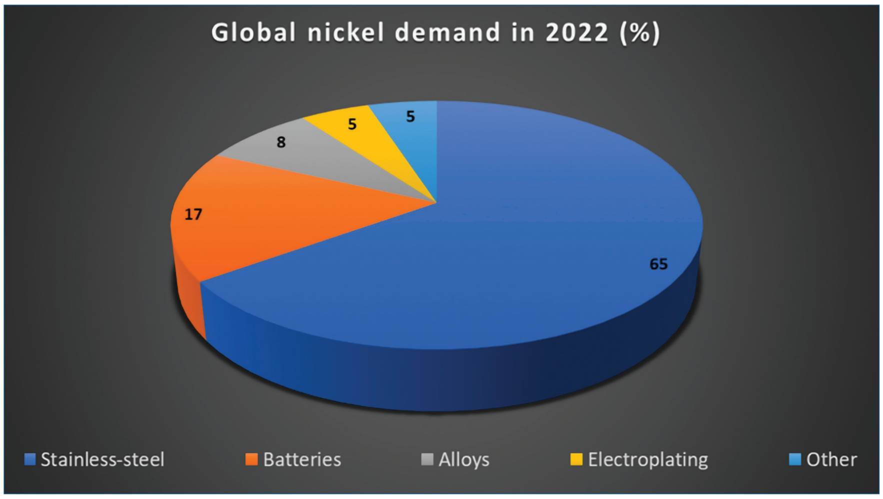

Fig. 1 - Global nickel demand, in % (from https://nickelinstitute.org/)

Overall demand is driven by manufacturing, metallic products, transports, building, and electronics: according to the megatrends, consumption will expand significantly with steelmaking the principal sector and batteries on a rising cycle entailing sensibly higher growth rates and a modification of the product mix. Long-standing use in austenitic stainless steel (200- and 300-series) with concentrations between 1-25 wt% is due to its unique properties to improve workability, corrosion resistance and strength in harsh environments, such as chemical plants, jet engines, and power generation facilities. Nickel is also necessary to produce certain types of disposable and rechargeable batteries, which can be found in electric vehicles (EVs), energy storage systems (ESS) - *e.g.*, from solar and wind renewables -, and portable consumer electronics [9]. With a market share of 68% in 2022 prevailing battery types for EVs use are the lithium-ion nickel manganese cobalt oxide (NMC) and the lithium-ion nickel cobalt aluminum oxide (NCA), where nickel is the most important constituent for high energy density and great storage capacity at a low cost, also making batteries lighter and smaller: as a reference case, a 58 kWh battery in a current automotive model uses around 37 kg of nickel. Economic reasons draw the attention to the potential for nickel to replace expensive cobalt in lithium-ion batteries (LIB): while NMC batteries originally contained equal molar amounts of nickel, manganese and cobalt, nickel concentration grew over the years to reach 80%. The chemical compound used in cathodes manufacturing is high-purity nickel sulphate, whose synthesis can be executed via specific feedstocks with relevant cost consequences. Batteries typically account for 30% to 40% of the value of an EV and Ni contributes to cathode cost proportionately to its content. Therefore, LIBs are very sensitive to nickel price and, since commercial, technological, and compositional changes are ongoing, any sectorial long-term forecast is to be treated cautiously [10].

The catalytic properties of nickel are exceptional: although catalysts constitute less than 1% of its use, nickel catalysts represented over 15% of the global market in 2021 and the applications in hydrotreatment, steam reforming, and hydrogenation will be briefly described.

Catalytic hydrotreating (HDT) is a key process in the petroleum refining industry and the market is expected to expand despite the progress of electric mobility. It concerns the conversion and removal of organic sulfur, nitrogen, oxygen, and metals from petroleum crudes at high hydrogen pressures accompanied by hydrogenation of unsaturated as well as minor cracking of high molecular hydrocarbons [11]. The nitrogen content of petroleum crude is usually in the range of 0.1-0.9 wt% and must be reduced by hydrodenitrogenation (HDN) to few parts per million to avoid inhibition of hydrosulfurization (HDS), hydrodearomatization (HDA), and poisoning of acid catalysts during the successive catalytic cracking (FCC) and hydrocracking (HCK). Nitrogen is generally concentrated in heavy fractions and often associated with metals: it is the most difficult heteroatom to remove by hydroprocessing since preliminary aromatic ring saturation is necessary [12].

A reaction scheme for HDN is the following:

$$R_3\text{-}N + 3H_2 \rightarrow 3R\text{-}H + NH_3$$

where R stands for a hydrocarbon chain or ring. Main variables and process parameters are feedstock type, temperature, pressure, liquid hourly space velocity (LHSV), and H_2/Oil ratio, all differing according to the oil fraction. In the case of HDN, molybdenum and nickel are the preferred couple of active elements due to high hydrogenation activity and the composition is usually 8-16 wt% Mo and 1-4 wt% Ni on a γ-alumina support. Catalysts need to be sulfided *in situ* before achieving the active state: such as in the case of Co-Mo catalysts for HDS, Ni promoter atoms are present on the edges of the MoS_2 triangular slabs and facilitate the formation of catalytic centers enhancing H_2 activity and mobility. Main deactivation factors include sintering and decomposition of the active phase, fouling, coking, and metal sulfides deposits [13].

Steam reforming is the first step in large-scale chemical processes such as methanol, ammonia, oxo synthesis, Fischer-Tropsch, and hydrogen syntheses: the end use determines the specific technology. The reaction produces synthesis gas (syngas), a mixture of hydrogen and carbon monoxide with a typical H_2/CO ratio of 3:1 to 5:1; when hydrogen is the only desired product, CO is converted to CO_2 via the water-gas shift reaction [14]. According to the feedstock (natural gas or alkane chains), the following endothermic reactions proceed:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2$$
$$C_nH_m + nH_2O \rightleftharpoons nCO + (n+m/2)H_2$$

This development took place in Germany at the beginning of the Twentieth century and nickel-based catalysts are most suitable, although certain platinum group elements display higher activities. The process operates at high temperatures (650-950 °C) and pressures (25-40 bar) in tubular reactors surrounded by gas-fired furnaces supplying the required heat. Typical commercial catalysts contain 10-20 wt% Ni dispersed on a support resistant to the severe conditions, such as calcium aluminate [15]. Nickel oxide must be reduced, usually with hydrogen, before use and the metal is dispersed as relatively small crystallites. Catalysts are sensitive to sintering and poisons such as sulfur, arsenic, and chloride but the main deactivation cause due to process thermodynamics is coke accumulation by hydrocarbon decomposition [16].

Use of nickel in hydrogenation dates to the end of XIX century, when hydrogen was first reacted with carbon dioxide to produce methane and water and the formidable catalytic properties of nickel compared to a "spirited horse". In the 1920s, a fine nickel powder, known as Raney nickel, was prepared by the action of a base on a nickel-aluminum alloy, which is widely used today for reactions such as the conversion of nitriles to amines and the hydrogenation of carbonyl functions (ketones, aldehydes). The advantages of nickel catalysts with respect to platinum group elements are low cost and high selectivity towards desired products even at relatively high temperatures and pressures. The spectrum of compositions and reactivities is vast and a pivotal role is played in several industrial technologies, such as hydrogenation of unsaturated fatty acids from edible fats and oils and nylon synthesis via hydrogenation of benzene to cyclohexane [17, 18].

Nickel is also one of the most frequently used elements in homogeneous transition metal catalysis, and organonickel complexes display high selectivities for many reactions, including carbonylation, oligomerization, and polymerization [19].

Production & market

In 2022, the world primary nickel production was just over 3 million metric tons and active mines as well as smelting and refining plants are present in 30 countries, although relevant activities are concentrated [20].

Nickel does not occur free in nature and similarity of the ionic radius of nickel to that of iron and magnesium allows the three elements to substitute for one another in the crystal lattices of some minerals. Since its geochemical character is both siderophile and chalcophile, most minerals are in combination with iron and sulfur and are hosted in two main ore deposits: primary sulfide orebodies (such as in Canada and Russia) and secondary laterite deposits (predominantly in South-East Asia). In both cases, the presence of co- and by-products (*e.g.*, platinum group elements in the case of sulfides and cobalt in the case of laterites) is important to determine the minimum grade of exploitable ore and the overall profitability of operations. The sulfide orebodies originate from magmatic activity and the metal content ranges approximately between 1.5-3 wt%.

Fig. 2 - Pyrrhotite hexagonal crystals from Primorskiy Kray (Russia) Photograph by R.M. Lavinsky, distributed under a CC-BY 3.0 license

Main minerals are pentlandite [$(Ni,Fe)_9S_8$] and pyrrhotite [$(Fe,Ni)S_{1-x}$] (Fig. 2), and this ore represents around 20% of currently mined global output and 40% of reserves. Laterites are residual sedimentary rocks resulting from the weathering of ultramafic igneous rocks and the principal minerals are limonite [$(Fe,Ni)O(OH)\cdot nH_2O$] and the hydrous silicate garnierite [$(Ni,Mg)_3Si_2O_5(OH)_4$]. Laterite deposits (exploitable nickel concentration between 0.7-2.5 wt%) account for around 80% of currently mined ores and 60% of the reserves: their usage is more resource intense than that of sulfides, especially concerning energy and greenhouse gas emissions. Sulfides orebodies were the dominant source until around a decade ago; nowadays, the shift to lateritic ores reflects transformations both in geo-economics and processing technologies [21-23].

The value chain of primary nickel consists of three main segments: extraction of ore, metallurgical treatment, and final processing to several types of refined products: Class I nickel (99.8 wt% Ni), nickel sulfate (22 wt% Ni), nickel oxide (75 wt% Ni), ferronickel (20-40 wt% Ni), and nickel pig iron (NPI) (5-17 wt% Ni). As a result of the specific genesis, sulfidic ore deposits are usually mined by underground techniques and laterites by massive open-pit earth-moving with large-scale industrial operations. The metallurgy depends on the specific ore, and both pyrometallurgical (smelting) and hydrometallurgical processes are used. The sulfide ore is generally transformed into nickel (III) sulfide, Ni_2S_3, which is roasted in air to give nickel (II) oxide, NiO, while the laterite ore is often treated directly in pyrometallurgical processes to give NiO. In both cases, the metal is obtained by high-temperature reduction with carbon and refining occurs by electrolysis or by the Mond process. Electrorefining uses a sulfate or chloride electrolyte and nickel electrodeposits on pure nickel cathodes. In the Mond process, carbon monoxide is passed through the matte at temperature up to 60 °C yielding nickel carbonyls and, after separation, nickel carbonyl vapor is decomposed in pure metal pellets [24, 25].

The pyrometallurgical route is preferred in the case of low-grade products such as NPI for use in stainless-steel. Batteries manufacturing requires high-grade nickel of 99.8% purity (Class I), which was traditionally obtained from sulfidic nickel ores; today, cost-effective hydrometallurgical processes such as high-pressure acid leaching (HPAL) allow to produce from lateritic ores the intermediate mixed hydroxide precipitate (MHP) - where Ni is the major component along with minor amounts of Co, Zn, Cu, Mn, and Mg -, used as a feedstock for nickel sulfate in battery applications.

In 2022, almost all the global mine production increase by about 20% occurred in Indonesia, the top producer with 48% of output. Primary nickel production locally expanded 4.5-fold over the last years and new projects are under development to produce battery-grade nickel sulfate. The sector is assuming a national strategic importance although figures are still low with respect to the other mining activities. The country also became the second most important nickel user in 2020 with an important position in stainless-steel manufacturing and development of an integrated electric vehicle (EV) supply chain. However, restrictive policies (*e.g.*, banning export of ores), productive practices (*e.g.*, deep-sea tailings disposal), as well as environmental and social impacts (*e.g.*, use of coal in energy production, exploitation of biodiversity areas) raise sustainability concerns (Fig. 3) [26].

Fig. 3 - Satellite image of laterite open-pit mines -reddish areas- on Sulawesi Island (Indonesia) in 2019 (courtesy of NASA/METI/AIST/Japan Space Systems and U.S./Japan ASTER Science Team)

In 2022, the successive main productive countries, the Philippines and Russia, follow with shares respectively at 10% and 7%: altogether, the three leading countries comprise 65% of the metal extracted from minerals. Asia accounted for 85% of global primary nickel usage. China used 60% of the world's primary nickel in 2022: the share is forecast to increase, and supply is guaranteed by control of most nickel projects in Indonesia and the Philippines.

The world reserves are estimated over 100 million metric tons, of which Indonesia and Australia approximately provide 20% each and Brazil 15%: European reserves are insignificant although mine deposits are present in Finland, Greece, Albania, and the French territory New Caledonia in the South Pacific was ranked fourth producing region in 2022 (Fig. 4). Deep-ocean polymetallic sources might gain a substantial role, but the exploitation remains unaccomplished and debatable [27].
Nickel price saw relevant changes over the last years. In 2007, a year of market surplus, nickel saw an extraordinary record around 7 times higher than the average prices in the previous decade. In 2022, the annual average LME nickel cash price was estimated to have heightened by 35% compared to 2021: prices skyrocketed after the conflict in Eastern Europe, surging to a 250% increase in a single day and disrupting trade on LME. Although average prices declined and stabilized at a relatively high level ever since, a strong volatility index was confirmed, and the entire transmission system will be affected in the long term [28, 29].
A burn-off time of around 30 years (defined as the ratio between proven reserves and average annual mining rate at the current consumption rates) is limited: furthermore, mines location, electromobility growth, and sustainability policies make the commodity highly critical and many countries such as Japan (with inclusion in the critical minerals list already since 1984 but re-confirmed within the top 10 priority minerals in 2020), the USA (2022), and the EU (2023) included the metal within the respective lists, lately as a "compelling case". Mineral supply disruptions are not unprecedented and short-term perspectives are risky in the case of a geographic concentration vulnerable to political and social factors: in the automotive sector, companies announced direct investments in supply from primary producers [30-32].

Recovery & Sustainability

Recycling is essential in the life cycle of resources. In the case of nickel, there are multiple advantages: CO_2 emissions reduction by one third with respect to primary production, limited depletion of the earth's resources, lower energy consumption with

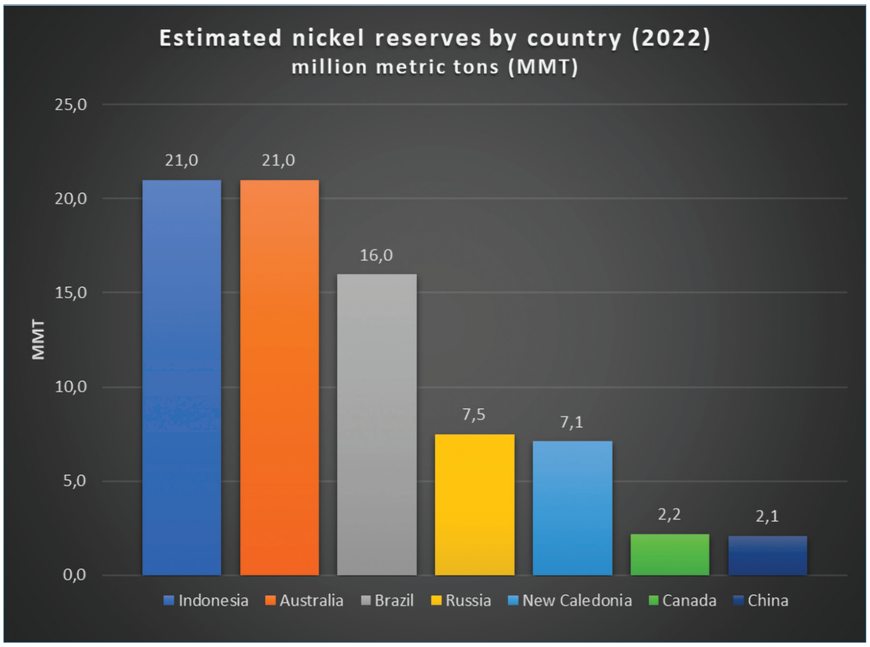

Fig. 4 - Nickel reserves in million metric tons (from U.S. Geological Survey, Nickel, Mineral Commodity Summaries, January 2023)

respect to ore production, absence of mine wastes, and preservation of land and marine environments. Recovery potential is enormous: out of 70 million metric tons of historically mined nickel, it is reputed that 57% is still in use due to the long lifetime of its predominant end product. Thus, its case resembles manganese and secondary production is mainly associated with the recycling of steel, a well-established network supported by a system of collectors and companies utilizing the scrap as a valuable raw material. Since nickel is one of the most expensive elements in stainless steel, scrap prices reflect the trend of nickel prices and availability is affected by price elasticity: anyway, steel recovery rates display over 85% of end-of-life (EOL) recycling. Therefore, unlike various metals, the main recycling chain might be considered efficient: the end-of-life recycling rate (EOL-RR), defined as the fraction of metal in discarded products that is reused retaining its functional properties, is over 70% [33]. However, secondary supply of nickel from stainless steel recycling is sectorial and unavailable for other uses, especially due to the purity required by Li-ion batteries application.
Spent heterogeneous catalysts are treated for the recovery of base metals enclosing nickel, but volumes are low with respect to the global business of the specific metal and its value is rather limited due to the necessity of profitability: in practice, recycling is generally part of a closed-loop process involving the stakeholders in the chemical sector of interest [34].
Considering the increased availability of EOL batteries after the current decade (only 7 years passed since the first “gigafactory” started operations) as well as progressive demand for raw materials, battery recycling is becoming an important legislative theme, not only in the effort to provide domestic supply chains for countries without primary resources, but also for environmental reasons due to toxicity and safety concerns [35]. The EU has just adopted the new battery regulation 2023/1542 integrating the previous directive 2006/66/EC to make minimum recycled contents (in the case of Ni, 6% by 2031 and 15% by 2036) mandatory for battery producers. However, batteries recycling is complex: due to lack of standardization in chemistries and design, a four-stage separation process is usually required: collection/sorting; pretreatment (mechanical/thermal processing); first-material extraction (mechanical/pyrometallurgical route); second-material extraction (hydrometallurgical treatment to produce individual metal streams). State-of-the-art technologies can yield recovery rates over 90% for most materials and in Europe and the US several companies are operative industrially. Countries dominating primary nickel production do not focus on recycling due to low value generated by current extraction rates: in China, the world’s largest EV market, the share of recycled nickel was lower than 10% in 2019. In this context, the strong stimulus to recycling should help to improve both methods and recovery rates and material from EOL batteries is expected to become a major source of nickel by 2040 [36].
Nickel was in the past dubbed as Kupfernickel (Old Nick’s copper) because Saxon miners couldn’t recover the desired red metal, but time is powerful and today the metal is a most wanted element for the future.

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Nichel: prospettive

Il nichel, metallo di transizione dalle particolari proprietà fisico-chimiche, è un elemento chiave critico che svolge un ruolo importante nella produzione di acciaio, batterie, leghe speciali e catalizzatori. Il presente articolo si propone di fornire un sintetico aggiornamento su principali usi attuali e futuri, produzione, riserve e prospettive di riciclo.