Journal of Cleaner Production 264 (2020) 121460

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

# Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates

M.L.C.M. Henckens[*], E. Worrell

*Utrecht University, Copernicus Institute of Sustainable Development, Princetonlaan 8A, 3584CB, Utrecht, the Netherlands*

ARTICLE INFO

*Article history:*
Received 9 August 2019
Received in revised form
24 March 2020
Accepted 30 March 2020
Available online 8 April 2020

Handling editor: Prof. Jiri Jaromir Klemeš

ABSTRACT

Copper and nickel are important metals for our society. Developing countries depend on copper and nickel for the construction of their infrastructure. Copper and nickel are also key elements for the transition to a fossil free electric energy production, which might lead to increased demand for these metals. The purpose of this paper is to investigate whether and at which conditions a sustainable production rate of copper and nickel can be combined with an increase of the service level of the two metals for the entire future world population to the same level as in developed countries in 2020. We consider three ambition levels with regard to a sustainable production rate for copper and nickel: 1000 years, 500 years and 200 years of guaranteed, sufficient and affordable supply to the entire world population at a service level, which, in all countries, is equal to the service level in developed countries in 2020. The conclusion is that the highest sustainability ambition (1000 years) is only achievable with a combination of an optimistically large amount of available resources in combination with a high end-of-life recycling rate. Whether the required amount of resources will be available for an affordable price, remains uncertain.

© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

**Contents**

---

[*] Corresponding author.
*E-mail address:* M.L.C.M.Henckens@uu.nl (M.L.C.M. Henckens).

https://doi.org/10.1016/j.jclepro.2020.121460
0959-6526/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Both copper and nickel are essential metals for our society. Copper is needed for e.g. the transmission and distribution of electricity, while nickel is essential in the production of e.g. stainless steel. The annual production of both copper and nickel grows quickly. See Fig. 1 and Fig. 2.

We observe that, although both copper and nickel consumption are stabilizing in developed countries, primary copper and nickel production are increasing rapidly. Since 1965 copper production doubled every 25 years, or a 2.8% annual increase (US Geological Survey, 2017a). The average annual increase of nickel production is even faster. Between 1980 and 2015 the world nickel production increased with 3.1% annually (US Geological Survey, 2017b).

If the average production growth rates in the period between 1980 and 2015 are extrapolated to the year 2100, copper production in 2100 will be eleven times higher than in 2018, and nickel production twelve times. Although the real production growth of copper and nickel can be slower (but also higher), the obvious question is whether such growth rates are sustainable. Copper and nickel may become so expensive for future generations that the services provided by them, will be hardly attainable for poor nations and poor people.

Thinking, and both reassuring and warning, about future scarcity of resources is not new. A wide number of studies addressed the issue, e.g. Malthus (1798), Ricardo (1817), Mill (1848), the Conservation Movement in the USA (Tilton and Coulter, 2001), Barnett and Morse (1963), Meadows et al. (1972, 1992), Simon (1980, 1981), Smith (1982), Maurice and Smithson (1984), Ayres et al. (2002), Kesler (1994), Beckerman (1995), Hodges (1995), Diederen (2009), Gunn (2011), Bardi (2013), Diamandis and Kotler (2012).

The purpose of this paper is to investigate whether, and at which conditions, the production rate of copper and nickel can be made sustainable, while simultaneously increasing the global service level of copper and nickel to the same level as in developed countries in 2020. We define the production (or extraction) of a mineral resource as sustainable if a world population of 10 billion can be provided with the resource for a period of at least 200/500/1000 years in such a way that during that period every country can enjoy the same service level of that resource as enjoyed by developed countries in 2020, at an affordable price. The chosen period of guaranteed, sufficient and affordable supply, in this paper 200, 500 or 1000 years, is defined as the sustainability ambition level. Care for future generations is the result of a political debate. Scientists have the role to provide the choice options, dilemmas, and the technical consequences of decisions (or non-decisions). The responsibility for future generations needs to be balanced with the responsibility for the current generation. However, we consider a time horizon of 100 years or less, within which humanity would allow the exhaustion of all available copper resources, as too short (Henckens et al., 2014). It may be that additional copper and nickel resources are discovered in the future, but in this study we will not speculate on such a development.

We base ourselves on a literature review on the economically extractable amounts of copper and nickel and on data regarding the substitutability and recyclability of copper and nickel and the potential material efficiency increase. The added value of this article is that it presents the relation between three different operational sustainability ambitions, different assumptions regarding the ultimately available copper and nickel resources, the required end-of-

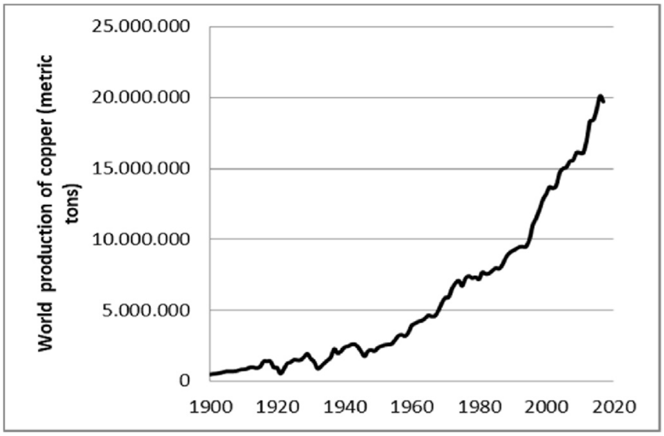

**Fig. 1.** World copper production between 1900 and 2017 (US Geological Survey, 2017a).

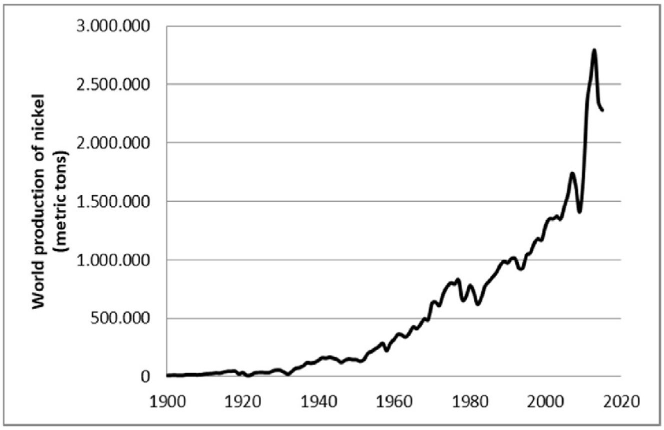

**Fig. 2.** World nickel production between 1900 and 2017 (US Geological Survey, 2017b).

**Table 1**
Subdivision of copper end-uses (Copper Alliance, 2019). The percentages represent the shares of global copper use in 2017.

| | | | | | |
|---|---|---|---|---|---|
| Building Construction | | Plumbing | Water distribution, heating, gas, sprinkler | 4% | 28% |
| | | Building Plant | Air conditioning tube | 1% | |
| | | Architecture | Roofs, gutters, flashing, decoration | 1% | |
| | | Communications | Wiring in buildings | 1% | |
| | | Electrical Power | Power distribution, earth, ground, light, wire device | 21% | |
| Infrastructure | | Power Utility | Power transmission and distribution network | 14% | 17% |
| | | Telecommunications | Telecom network | 3% | |
| Equipment Manufacture | Industrial | Electrical | Industrial transformers and motors | 6% | 11% |
| | | Non Electrical | Valves, fittings, instruments and in plant equipment | 5% | |
| | Transport | Automotive Electrical | Harnesses, motors | 8% | 13% |
| | | Automotive Non Electrical | Radiators and tubing | 1% | |
| | | Other Transport | Railroad, shipping and marine | 4% | |
| | Other Equipment | Consumer & General Products | Appliances, instruments, tools and other | 9% | 32% |
| | | Cooling | Air conditioning and refrigeration | 8% | |
| | | Electronic | Industrial/commercial electronics and PCs | 5% | |
| | | Other | Ammunition, clothing, coins and other | 10% | |

life recycling rates and the achievable copper and nickel service levels.

## 2. Copper

### 2.1. Applications and production

The most important applications of copper are in wiring for generation, transmission and distribution of electricity. See Table 1.

The transition to a low-carbon economy will require an additional amount of copper on top of the amount of copper used for current applications. The required extra amount of copper depends on the pathway of the energy transition that is followed: more or less nuclear energy, carbon storage, wind or solar energy. The building of a low-carbon energy system capable of supplying the world's electricity needs in 2050 will require an additional amount of copper equivalent to between two and ten years of the current global copper production (Hertwig et al., 2015; Vidal et al., 2018; Kleijn et al., 2011). However, despite this development, total copper demand in the world will still be mainly determined by a growing global economy and wealth (GDP per capita and world population). Without the energy transition, the annual copper demand in 2050 is estimated to be about three times higher than in the year 2000 and with the necessary energy transition, 3.3 times as high (De Koning et al., 2018).

The average copper concentration in the Earth's crust is about 50 ppm.[1] The main copper producing countries in 2017 were Chile, Peru and China. Chile is also the country with the largest copper reserves (see Fig. 3).The 2017 copper production amounted to 20 Mt. The 20th century accounted for 90% of all copper mined and put into service throughout human history, of which 70% in only the last 70 years and 50% in only the last 25 years of the 20th century (Lifset et al., 2002).

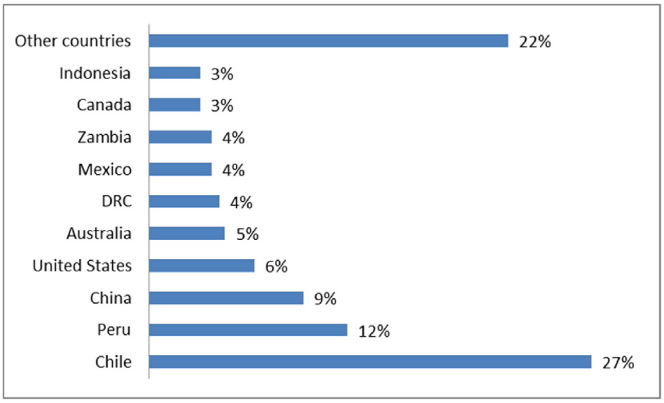

**Fig. 3.** Top ten copper producing countries in 2017 (US Geological Survey, 2018a).

### 2.2. Copper resources

The total amount of copper in the earth's crust is enormous. With an average concentration of 50 ppm, the upper 3 km of the earth's continental crust contains about 60,000 billion metric tons of copper. However, in practice, only a very small fraction of this amount can be economically extracted. It is difficult to predict the ultimate extractability of a mineral resource. This depends on a number of factors, which are reflected in the extraction costs, which, at their turn, are determined by material and energy requirements and the costs for mitigation of environmental, climate and social impacts. It cannot be predicted what market price the consumer is prepared to pay for copper, which, at least, covers the production costs. Currently, most copper mines operate with minimum copper concentrations of between 0.4 and 0.8%. These concentrations are a factor 80 to 160 higher than the average crustal abundance of copper. To the extent copper mining and production technology further develops, the extraction of lower graded copper and in deeper mines may become feasible. For the ultimate copper resources different estimates can be found in the literature:

- 5600 Mt (identified plus undiscovered resources) (US Geological Survey, 2018a),
- 6400 Mt (Singer, 2017),
- >1781 Mt (Northy et al., 2014),
- 2459 Mt (Schodde, 2010),
- 1861 Mt (Jowitt and Mudd, 2014)
- 2800 Mt (Sverdrup et al., 2014)

A thorough assessment of US copper resources in 1998 indicated 540,000 kt of copper in the upper 1 km of the continental crust in the US (260,000 kt identified and 290,000 kt undiscovered) (US Geological Survey, 2000). This means that the ratio between total estimated copper resources and identified copper resources in the US in 1998 was 550,000/260,000 = 2.12. To

---

[1] The scientific literature provides different values for the crustal abundance of elements. We have taken the average value of seven sources: McLennan (upper crustal abundance), 2001; Darling, 2007; Barbalace, 2007, Webelements, 2007; Jefferson Lab, 2007, Wedepohl, 1995, Rudnick and Fountain, 1995.

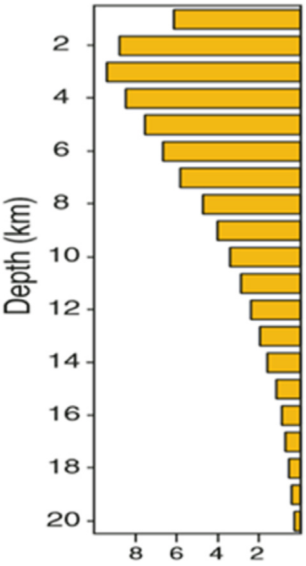

**Fig. 4.** Porphyry copper endowment at different depths in the Earth's crust (Gt) (Kesler and Wilkinson, 2008).

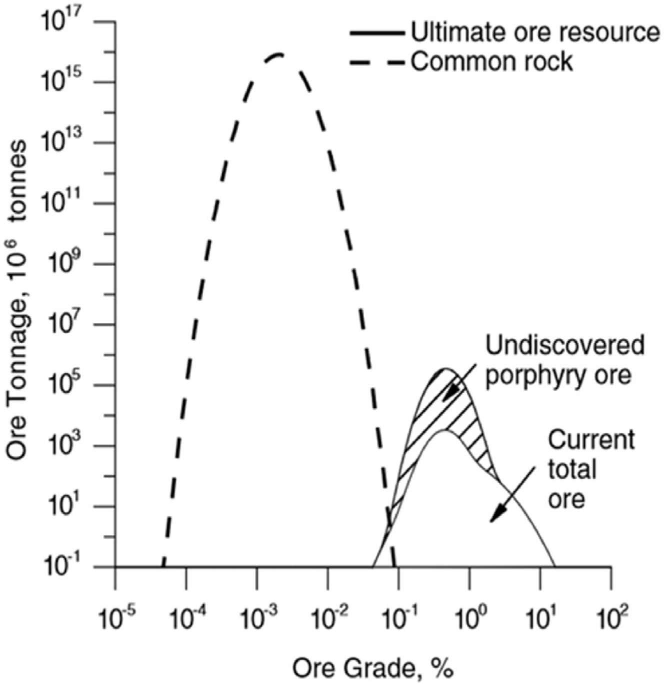

**Fig. 5.** Grade-tonnage density curves for copper in the Earth's crust (British Geological Survey, 2007; Gerst, 2008). The "current total ore" area represents the currently known copper ore resources.

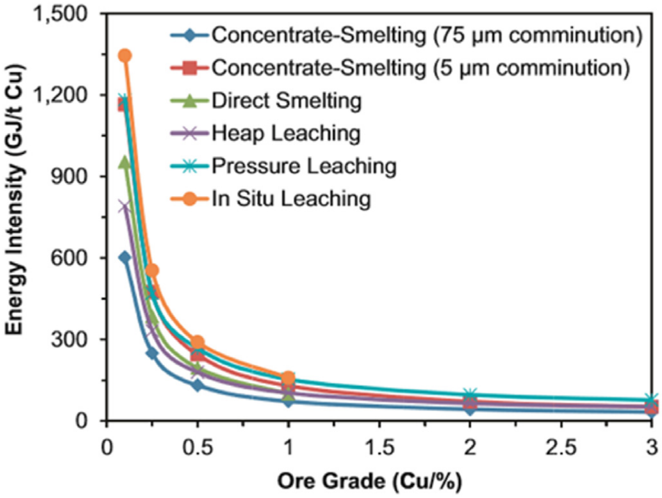

**Fig. 6.** The amount of energy required to produce copper by different processing pathways (Norgate and Jahanshahi, 2010). Data are from 2010.

estimate the ultimate copper resources in the world we apply this ratio of 2.12 to the most recent data on identified global copper resources (2.1 Gt) (US Geological Survey, 2018a). This results in about 10 Gt (rounded) of ultimately available copper resources in the upper 3 km of the continental Earth's crust (3 × 2.12 x 2.1 = 13.3 Gt).

A generic approach is that the economically extractable amount of a mineral is a maximum of about 0.01% of the total amount of that mineral occurring in the upper 1 km of the continental earth's crust (UNEP, 2011; Erickson, 1973; Skinner, 1976). Based on this approach, the extractable amount of copper in the upper 1 km of the Earth's crust is about 2 Gt. Assuming that in the future technological development makes copper mining feasible until a depth of 3 km, the available copper resources according to this approach could reach 6 Gt, which is close to the figures provided by US Geological Survey (2018a) and Singer (2017).

A theoretic study estimates porphyry copper resources at 300 Gt in the entire continental Earth's crust (Kesler and Wilkinson, 2008). Based on this study, Fig. 4 presents the supposed distribution of porphyry copper in the Earth's crust. Fig. 4 shows that the upper 1 km of the continental crust would contain an amount of between 6 and 7 Gt of porphyry copper resources. Porphyry copper deposits are estimated at about 60% of total copper deposits (US Geological Survey, 2014). This means that, according to this approach, the total amount of copper resources in the upper 1 km of the Earth's crust could be about 10 Gt. If copper resources were economically extractable until a depth of 3 km, then, according to the approach of Kesler and Wilkinson (2008), humanity still has about 40 Gt of copper resources at its disposal. However, thus far, only gold is mined at these depths. It is extremely challenging, costly and comes with large environmental impacts to mine so deep.

The above mentioned copper resources include resources in the continental earth's crust and exclude copper at ocean bottoms in deep sea nodules and submarine massive sulfides. In deep sea nodules, the global copper resources are estimated at 700 Mt and in submarine massive sulfides at 30 Mt (Hannington et al., 2011). Though these amounts are not negligible, they are only in the order of 10% of the identified and non-identified resources in the upper 1 km of the continental Earth's crust. In addition, from an environmental protection point of view, it is a challenge to exploit these resources in an environmentally sustainable manner.

The grade-tonnage distribution of copper in the earth's crust is illustrated in Fig. 5. There are vast amounts of copper in common rock, but with a very low grade and moreover in a different, less easily extractable matrix. Copper ores mined currently are sulfide and oxide minerals, whereas in crustal rock copper usually occurs in a silicate matrix. The energy required to separate copper from a silicate matrix is 100–1000 times higher than the current energy required for primary copper production (Skinner, 1987; Gordon et al., 1987).

Extracted copper ore grades were 10–20% until late in the 19th century. Then they decreased to 2–3% in the early part of the 20th century. Since about 1950 extracted copper ore grades have declined to below 1%. Currently, extraction of copper ores with grades as low as 0.4% is already quite common (Kerr, 2014).

The gradual depletion of higher ore grades is characteristic for all mineral resources. It is not the amount of a mineral in the earth's crust as such that may lead to a scarcity problem, but the effort needed to extract the mineral in terms of energy use, water use, waste generation and landscape degradation. Energy use in relation to copper ore grade is presented in Fig. 6. Fig. 6 clarifies that, roughly spoken, halving copper ore grades, will double the energy requirements for copper production. However, energy efficiency increases may save 30% of the energy used currently for copper extraction (Elshkaki et al., 2016). Taking this energy saving potential into account, energy demand for copper production may – nevertheless - increase to 1% of total energy demand of society by 2050 or even reach 2.4% of total energy demand in 2050 compared to only 0.3% currently (Elshkaki et al., 2016). It is expected that the $CO_2$ footprint of copper production will at least triple by 2050 (Kuipers et al., 2018).

### 2.3. Copper consumption

Copper consumption growth is distributed quite unevenly around the world. Copper consumption in developed countries is nearly stable, whereas in industrializing countries like China and India copper consumption growth rates are very high. China's copper consumption in 1995 was 10% of the world consumption. By 2014, China consumed about half of world's copper production, although a part of this copper is exported again in copper containing products. Since the 1980s copper consumption of the USA remained a little more than 2 Mt per year. China's copper consumption increased from about 200,000 tons in the 1980s to 5 Mt in 2008. See Fig. 7.

From a given level of per capita income, the annual consumption of copper stabilizes (Halada et al., 2008; Bleischwitz et al., 2018; Pan Pacific Copper, 2019) (see Fig. 8). The explanation is that to the extent a country gets wealthier, its infrastructure (electric, water, transport) has been completed and only needs maintenance and its inhabitants spend relatively more money to immaterial things, such as culture, travelling, sports, health and education, requiring less material per unit of GDP/capita than to tangible objects, such as electric infrastructure and washing machines. As shown in Fig. 8, the consumption of copper starts stabilizing at 10–12 kg/capita/year from a GDP of approximately 15,000 USD/capita/year (purchasing power 2008) (Halada et al., 2008). Bleischwitz et al. (2018) and Pan Pacific Copper (2019) came to similar conclusions.

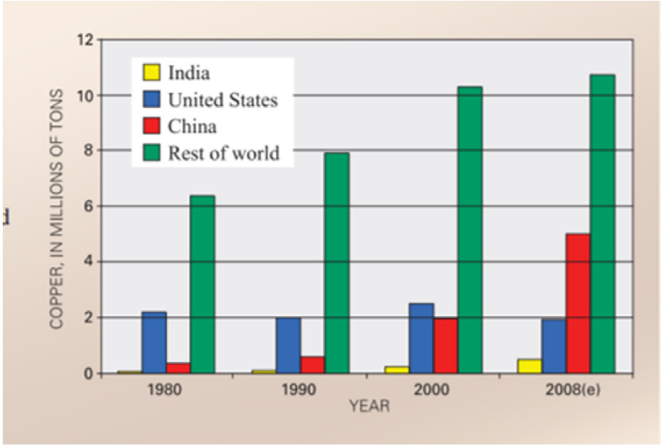

**Fig. 7. Copper consumption changes between 1980 and 2008, Mt (US Geological Survey, 2009). From left to right in respectively 1980, 1990, 2000 and 2008: India, US, China, Rest of the world.**

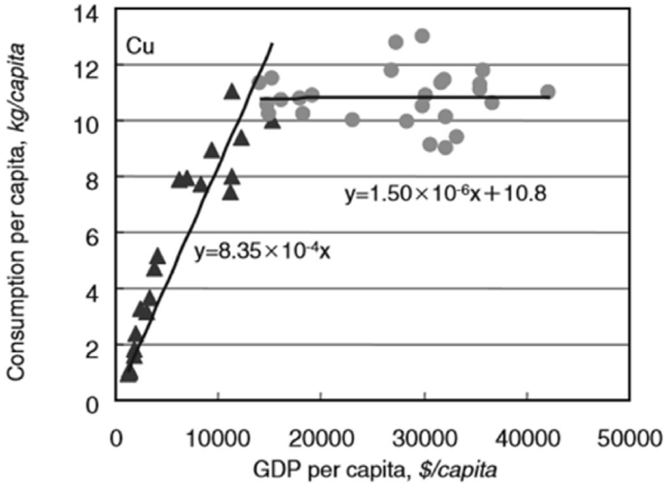

**Fig. 8.** Annual copper consumption per capita depending on GDP per capita in Japan (Halada et al., 2008).

According to the most recent population prospects of the United Nations (2017), world population will increase from 7.6 billion people now to about 9.8 billion people in 2050 and 11.2 billion people in 2100. It is uncertain whether world population will continue increasing after 2100, or whether it will stabilize or even decrease. If we assume that, at long term, the future world population stabilizes at 10 billion people and that these people, on an average base, consume as much copper as an average inhabitant of an developed country in 2020 (about 11 kg/capita/year), the consumption of copper on the planet will be 110 Mt annually provided that no saving measures, such as substitution, material efficiency measures and additional recycling, are taken. With the current end-of-life recycling rate of copper of about 45%, that would result in an annual primary copper need of about 85 Mt. With 3% growth annually, this level of primary copper use will be reached within about fifty years from now, or in about 2070. If we assume that from then on global primary copper consumption stabilizes, copper resources of 6 Gt will be exhausted some fifty years later, so within a century from now, unless the end-of-life recycling rate is increased.

### 2.4. Current copper stocks and flows

#### 2.4.1. Copper recovery efficiency at the mining and production stage

The current losses of copper at the mining and production stage through tailings and slag are about 16% (Lifset et al., 2002; Glöser et al., 2013).

#### 2.4.2. In-use stock

In 2010, the average expected lifetime of copper products was slightly over 25 years (Glöser et al., 2013). This is based on the

**Table 2**
Copper product in-use residence times (Spatari et al., 2005).

| Copper end-use | Residence time (years) |
|---|---|
| Plumbing | 40 |
| Wiring | 25 |
| Build-in appliances | 17 |
| Industrial EEE | 20 |
| Consumer EEE | 10 |
| Infrastructure | 50 |
| Motor vehicles | 10 |
| Other transport | 30 |

average lifetimes of different types of copper applications as shown in Table 2.

The global in-use- stock of copper was estimated at 57 kg/capita in the year 2000 (Gerst, 2009). This varies between 9 kg/capita in Africa and 160 kg/capita in Europe in 2014 (Soulier et al., 2018) to 206 kg/capita in North America in 2000.

The current global annual increase of the copper in-use stock is estimated at about 1.4 kg/capita/year (Glöser et al., 2013). The increase of the copper in-use stock slows down to the extent that a country gets more industrialized and copper consumption stabilizes. The above data lead to the conclusion that the global in-use amount of copper must have been about 7.6 x $(57 + 17 \times 1.4) = 600$ Mt in 2017. This represents as much as about 85% of all copper mined since 1900.

### 2.4.3. *Dissipative uses of copper*

The three main routes of in-use dissipation of copper are via food, chemicals and corrosion. Additionally a part of copper is dissipated by copper down-cycling from discarded copper containing products to other metal cycles. Humans require 1.5–3 mg of copper per day with food. Animals and plants need copper as well. Pigs about 12 mg/kg fodder. Copper in chemicals are e.g. wood preservatives, fungicides, pigments, antifouling paint for ships. Dissipation (excluding down-cycling) is estimated at 2% of copper consumption (Glöser et al., 2013). Down-cycling is treated in a separate section (see below).

### 2.4.4. *Recycling of copper from end-of-life products*

Estimated copper recycling rates in different parts of the world vary. In Western Europe about 80% of copper in end-of life products is collected for recycling. Of this amount about 80% is recycled to the copper loop (Soulier et al., 2018). The rest, 20% of the collected copper in copper containing end-of-life products, goes to non-copper metal loops, such as aluminum and steel (about 1/3) and to disposal sites (about 2/3) (Ruhrberg, 2006). The resulting recycling rate of copper from End of Life products in Western Europe is estimated at rates between 48% and 65% (Ruhrberg, 2006; Bertram et al., 2002). The end-of-life recycling rate in Australia is estimated at 56% taking into consideration that about 20% of the collected copper is not recycled into the copper loop (Van Beers et al., 2007). The EoL copper recycling rate in North America is estimated at 42% (Spatari et al., 2005; Goonan, 2009). Worldwide, the end-of-life recycling rate is estimated at 45% (Glöser, 2013). Assuming a global end-of-life recycling rate of 45% as point of departure, and that this corresponds with 80% of copper in separately collected end-of-life copper products, then the other 20% (or about 11% of the initial amount of copper in EoL products) goes to down-cycling and disposal. Hereof, 1/3 or 4% is down-cycled and 2/3 or 7% disposed. The total amount of separately collected copper is $10/8 \times 45\% = 56\%$, which means that 44% of copper is not separately collected and is disposed of in landfills and waste incinerators. Taking also into consideration the disposed part of separately collected copper, leads to the conclusion that, currently and globally, more than 50% of copper is disposed of in landfills and waste incinerators (see Fig. 9).

### 2.4.5. *Down-cycling*

In 2006, about 4% of copper in EoL products went to the steel and aluminum loops (Ruhrberg, 2006). In the steel loop this is mainly from shredded cars and large household appliances, such as washing machines (Ruhrberg, 2006). In the iron and aluminum smelting processes, copper remains in the liquid phase together with iron or aluminum. However, copper is considered an undesired impurity in steel and aluminum. Steel properties, e.g. for machine and automobile construction, are negatively impacted by copper. In steel, copper content may not be higher than a few tenths of percent (0.25%–0.5% according to Ruhrberg (2006) and 0.1%–0.3% according to Ayres et al. (2002) and in aluminum, copper content may not be higher than 2.5% (Ruhrberg, 2006). Removal of copper traces from secondary steel is difficult (Ayres et al., 2002). Hence, it is in the interest of steel and aluminum makers to keep copper as much as possible out of their raw materials, and to limit copper down-cycling.

In summary, Fig. 10 presents current copper flows in a simplified way. It is striking that a circular copper economy is still far away: more than 50% of EoL copper is not reused. Characteristic for the current situation is also the important build-up of copper in the anthropogenic stock: the annual output from the usage phase is only 60% of the annual input.

## 2.5. *The sustainable use of primary copper*

For the different assumptions of copper resources availability we will investigate whether and under which conditions it is possible to combine a sustainable copper production rate with increasing the current service level of copper for an average person in the world to the average copper service level in developed countries in 2020. Current copper consumption per capita in developed countries is about 11 kg per person per year and more or less stable (Halada et al., 2008; Bleischwitz et al., 2018; Pan Pacific Copper, 2019) (see Fig. 8).

Table 3 shows that the required end-of-life recycling rate for achieving a sustainability level of 1000 years of sufficient copper supply to the world population is respectively 93%, 89% and 55% with available copper resources of respectively 6 Gt, 10 Gt and 40 Gt. However, in practice, it will be difficult to realize an EoL copper recycling rate of more than 85%. With an end-of-life recycling rate of 85%, the required available copper resources must be

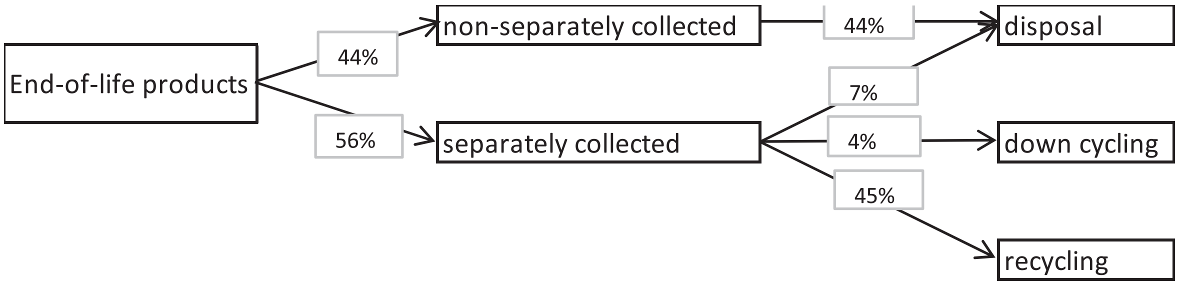

**Fig. 9.** The current fate of copper in copper containing end-of-life products. The picture is based on a global EoL recycling rate of 45%. Additionally it is assumed that 80% of copper is recycled from separately collected EoL products, 1/3 of non-recycled copper in separately collected EoL products is down-cycled and 2/3 of non-recycled copper in separately collected EoL products is disposed of. These figures are based on research analyzed in this section. All figures are indicative.

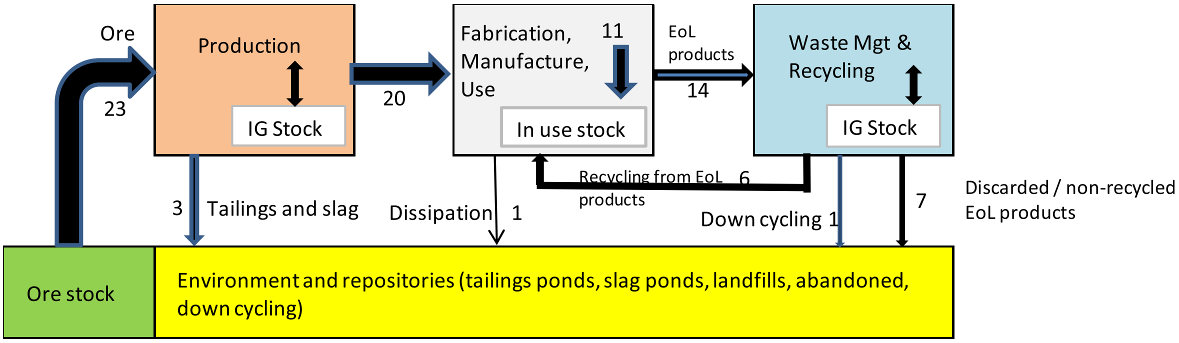

**Fig. 10.** Simplified global copper flows for the year 2017. Based on 2010 estimates concerning these flows (Glöser, 2013). Flows are in million metric tons. End-of-life recycling rate is 45%, tailings and slags are 16% of ore; build-up in anthropogenic stock is 44%. Dissipation is 2%. The arrow widths are a rough indication of flow magnitudes. IG stock is industrial, commercial and governmental stocks. The figures are indicative.

**Table 3**
Required end-of life recycling rates for different assumptions regarding the ultimately extractable copper resources. Primary copper production in 2017 was 20 Mt. Further assumptions: Copper substitution compared to 2017 is 10%; material efficiency increase compared to 2017 is 10%. Sustainability ambition level is 1000 years of copper supply.

| | Unit | Currently | Available copper resources | | |
|---|---|---|---|---|---|
| | | | 6 Gt | 10 Gt | 40 Gt |
| Sustainable copper production | Mt/year | | 6 | 10 | 40 |
| Annual copper consumption (1) | Mt | 26 | 89 | 89 | 89 |
| Accumulation in in-use-stock | % | 44% | 0% | 0% | 0% |
| Annual accumulation in in-use-stock | Mt | 11 | 0 | 0 | 0 |
| Dissipation | % | 2% | 1% | 1% | 1% |
| Dissipation | Mt | 1 | 0.9 | 0.9 | 0.9 |
| End-of-life copper | Mt | 14 | 88,2 | 88,2 | 88,2 |
| EoL recycling | Mt | 6.5 | 83.1 | 79.1 | 49.1 |
| **Required EoL recycling rate** | **%** | **45%** | **94%** | **90%** | **56%** |
| Copper consumption level (1) | g/capita/year | 3400 | 8900 | 8900 | 8900 |

(1) Current per capita copper consumption level in developed countries is 11 kg/capita/year. With copper substitution and material efficiency increase of both 10% future copper consumption will become 8.9 kg/capita/year, while keeping current copper services at the same level. This corresponds to a future consumption of 89 Mt annually assuming ten billion world inhabitants.

**Table 4**
Minimum amount of available copper resources (Gt) for different sustainability ambition levels and different end-of-life recycling rates.

| Sustainability ambition level | 45% | End-of life recycling rate | | |
|---|---|---|---|---|
| | | 65% | 75% | 85% |
| 200 years of copper supply | 10 | 6 | 5 | 3 |
| 500 years of copper supply | 25 | 16 | 12 | 7 |
| 1000 years of copper supply | 49 | 32 | 23 | 14 |

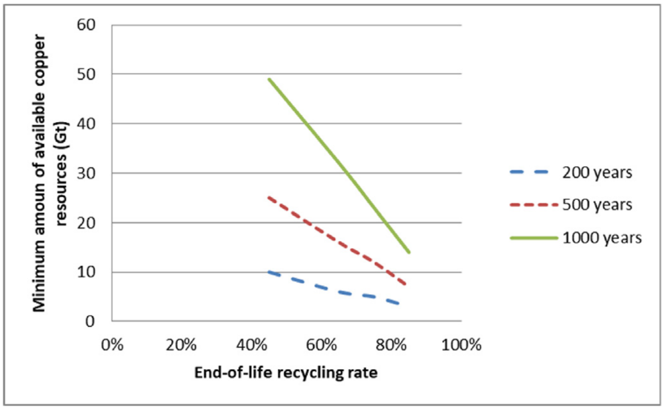

**Fig. 11.** Required end-of-life copper recycling rates depend on the available copper resources and the chosen sustainability option (200, 500 or 1000 years). Assumptions: copper service level is equal to the present-day copper service level in the developed countries, copper substitution is 10%, material efficiency improvement is 10%, and dissipation is 1%.

minimum 14 Gt to be sufficient for supplying a world population of 10 billion during 1000 years. To the extent that the sustainability level paradigm is less ambitious, e.g. 500 years or 200 years of sufficient copper supply, instead of 1000 years, the required amount of copper resources is lower (see Table 4).

Fig. 11 presents the required end-of life copper recycling rates in relation to the available copper resources and the chosen sustainability options. The conclusion is that at the current end-of-life copper recycling rate (45%), the amount of available copper resources needed should be at least 10 Gt to ensure there are sufficient copper resources to sustain a copper service level for ten billion people over the next 200 years. This is equal to the present-day copper service level in developed countries. If the amount of available copper resources is 6 Gt, then the end-of-life recycling rate of copper must increase to at least 65% to guarantee copper supply during a period of 200 years at a level that enables a copper service level throughout the world that is equal to the present-day copper service level in the developed countries. The ambition to have sufficient copper available for 1000 years for a world population of ten billion at the present-day level of the developed world seems hardly attainable, if at all. Such an ambition would require an end-of-life recycling rate of 85% with an available amount of copper resources of about 14 Gt, which is quite optimistic.

**Table 5**
**End-uses of nickel in the USA and worldwide in 2015** (US Geological Survey, 2018c).

| | Primary + secondary nickel application in the USA in 2015 | | Global primary nickel use |
|---|---|---|---|
| | Metric tons of contained nickel | % | % |
| Stainless steel | 129,000 | 65% | 66% |
| Super alloys | 25,600 | 13% | 10% |
| Other Ni & Ni alloys | 13,000 | 7% | |
| Electroplating | 7490 | 4% | 9% |
| Other (cast iron, chemicals, Electric Magnet Expansion alloys, Ni–Cu and Cu–Ni alloys, alloy steel, batteries, catalysts, ceramics, coinage, other alloys containing nickel) | 23,897 | 12% | 15% |
| Total | 198,987 | 100% | 100% |

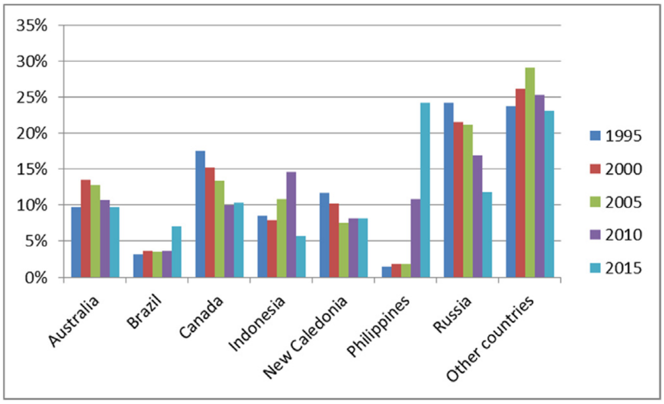

**Fig. 12.** Main nickel producing countries (US Geological Survey, 2018d).

## 3. Nickel

### 3.1. Applications

Nickel is mainly used to make stainless steel and other alloys stronger and better able to withstand high temperatures and corrosive environments. More than 65% of nickel is used in stainless steels (Aalco, 2005). Nickel containing grades make up 75% of stainless steel production (Nickel Institute, 2019). In super-alloys, nickel is mainly used for the production of turbines, vital for power generation, aerospace and military applications (British Geological Survey, 2008). Copper-nickel alloys (75%/25%) are used for coins. Computer hard discs are reliant on nickel plating as well as CD and DVD masters (British Geological Survey, 2008). A growing share of nickel is used in batteries for electric vehicles. The current use of nickel in batteries is estimated at 3–4% of global nickel consumption (British Geological Survey, 2018). Vehicle electrification is expected to accelerate demand for nickel in its use in batteries (Roskill Information Services Ltd, 2017). Currently, the most important type of battery used in electric vehicles is the lithium nickel manganese cobalt oxide type (NMC). The cathode of these lithium-ion batteries (LIB) consists of 30–72% nickel (British Geological Survey, 2018). In 2016, 39% of Li-ion batteries contained nickel. This is expected to rise to around 58% in 2025 (Nickel Institute, 2018). Although it is sure that the future share of electric vehicles use in transport will increase drastically, it is still speculative to take current use of raw materials as a point of departure for the future. Research into higher performance batteries is intensive and the chemistry of vehicle batteries may change. One forecast is that between 2017 and 2025 nickel use in batteries for electric vehicles will grow with 39% annually (Hamilton, 2018). With such growth rates, nickel demand for electric vehicles will be 1.1 Mt in 2030 (British Geological Survey, 2018). This is more than 50% of the 2017 global nickel production (Glencore, 2018). Nickel end-use in the USA and globally is depicted in Table 5.

### 3.2. Production

The average reported concentration of nickel in the Earth's crust is 68 ppm$^2$. Nickel is a carrier metal. This means that nickel is mainly mined for its own purpose. The main by-products of nickel mining are silver, gold and copper. Nickel concentration in sulfide deposits ranges mostly between 0.2 and 2% nickel (Hoatson et al., 2006; European Commission, 2014) and between 1.0 and 1.6% in lateritic ores (European Commission, 2014). At present, sulfide deposits are the primary source of mined nickel (British Geological Survey, 2008), although 60% of nickel is found in laterites (British Geological Survey, 2008). Extensive nickel resources are also found in manganese crusts and nodules on the ocean floor (US Geological Survey, 2018c).

Global nickel production in 2017 was 2.1 Mt (US Geological Survey, 2018b). The main nickel producing countries are the Philippines, Russia, Canada, New Caledonia, Indonesia, Australia and Brazil (see Fig. 12).

### 3.3. Nickel resources

Mudd and Jowitt (2014) estimate total nickel resources at 296 Mt. If we use the approach that the extractable nickel resources are a maximum of about of 0.01% of the total amount of nickel in the upper 3 km of the Earth's crust (based on the approach of UNEP, 2011; Erickson, 1973; Skinner, 1976), nickel resources are much higher: 8000 Mt (rounded). A third approach for estimating the ultimately extractable nickel resources is to extrapolate the results of assessments of the extractable resources of other elements. US Geological Survey (2000) compared the results of 19 assessments of the estimated total (identified plus undiscovered) deposits of gold, silver, copper, lead and zinc in the United States of America in the upper 1 km of the continental crust of the USA (a) with the identified resources of the same elements in the USA that far (b). The ratios a/b were 4.82 for zinc, 3.88 for silver, 2.67 for lead, 2.2 for gold and 2.12 for copper. The average is 3.14. We applied this average ratio to the most recent USGS data regarding the identified global resources of nickel. These are 130 Mt (US Geological Survey, 2018b). Extrapolating the result to the upper 3 km crust, this approach results in globally available nickel resources of 3 × 3.14 x 130 = 1000 Mt (rounded). Hence, we have three – rather divergent - estimates for the ultimate nickel resources: 300 Mt (rounded),

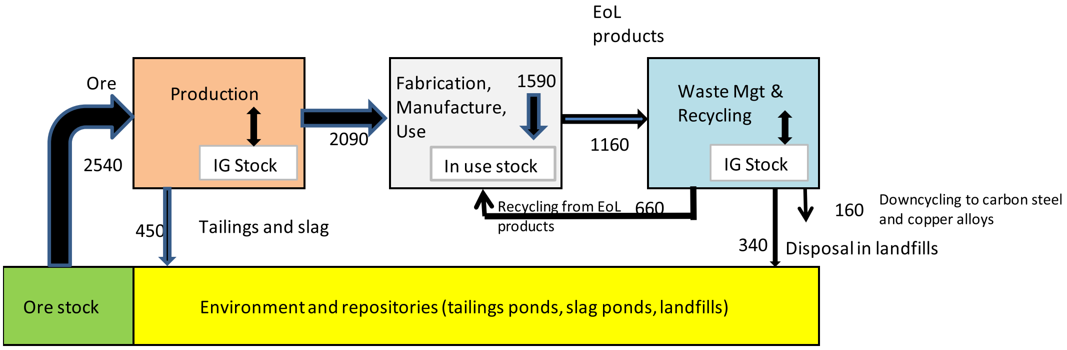

**Fig. 13.** Simplified global anthropogenic nickel cycle for 2016. The quantities are in 1000 metric tons of contained nickel. The arrow widths are a rough indication of flow magnitudes. Point of departure is a nickel production of 2090 kt in 2016 (Nickel Institute, 2019). The picture is based on relative flows in 2000 (Reck et al., 2008). Recovery efficiency: 82%. End-of-life recycling rate: 57%. Build-up in in-use stock: 59%. IG stock is industrial, commercial and governmental stocks.

1000 Mt and 8000 Mt.

### 3.4. Current nickel stocks and flows

According to data from the year 2000 (Reck et al., 2008; Reck and Gordon, 2008), the nickel recovery rate in the nickel production stage was 82%, the End-of-life recycling rate 57% and the increase of the nickel in-use-stock about 59% of the annual nickel consumption. There is relatively little dissipation of nickel to the environment through usage, due to the non-dissipative usage of nickel in steel, alloys and batteries. In 2000, down-cycling of nickel was about 14% of EoL nickel (Reck et al., 2008). We have extrapolated these data to the 2016 nickel flows resulting in the simplified global anthropogenic nickel cycle for 2016 depicted in Fig. 13.

### 3.5. The sustainable use of nickel

We will assume that the world population stabilizes at ten billion people. For the ultimately available nickel resources we consider three estimates: 0.3 Gt, 1 Gt and 8 Gt. We make calculations for three time horizons: 200 years, 500 years and 1000 years. For the different assumptions we will investigate whether and at which conditions it is possible to combine a sustainable nickel production rate with increasing the services of nickel for the average citizen of the world to the level in developed countries in 2020. Current nickel consumption per capita in developed countries is about 1500 g per person per year (Halada et al., 2008) (see Fig. 14).

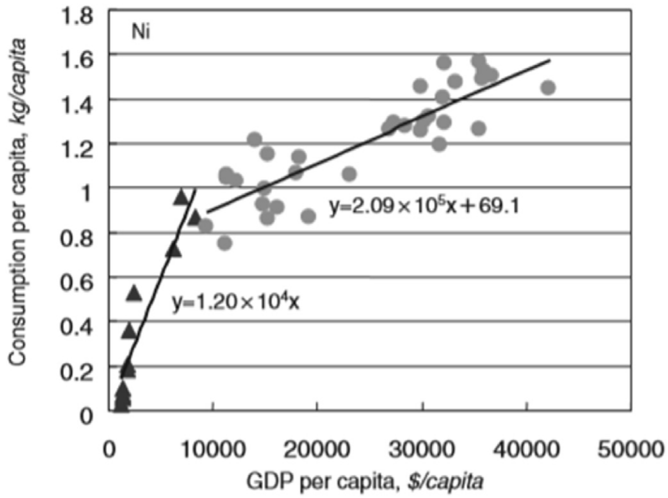

**Fig. 14.** Nickel consumption/capita/year depending on GDP/capita/year (Halada et al., 2008).

The consumption of nickel by an average person in the world in 2017 was 2.75 × $10^6$ ton divided by 7.6 billion people equals 362 g/capita/year, which is about four times less than in developed countries. Table 6 presents the necessary EoL nickel recycling rate at different amounts of available nickel resources given a sustainability ambition level of 1000 years of guaranteed, sufficient and affordable nickel supply.

The conclusion is that the required end-of-life recycling rate for combining a sustainability ambition of 1000 years of nickel supply with a global service level of nickel, which is equal to the nickel service level in developed countries in 2020, is respectively, 98%, 93%, and 41% with available nickel resources of respectively 0.3 Gt, 1 Gt and 8 Gt. However, in practice, it will be difficult to realize an EoL nickel recycling rate of more than 85%. With an end-of-life recycling rate of 85% the required available nickel resources must be minimum 2 Gt to be sufficient for supplying a world population of 10 billion during 1000 years. To the extent that the sustainability level paradigm is less ambitious, e.g. 500 years or 200 years of sufficient nickel supply, the required amount of nickel resources is lower.

Table 7 clarifies that at the current global end-of-life recycling rate of almost 60%, nickel resources need to be at least 1.1 Gt to supply nickel for at least 200 years to a world population of 10 billion people at a nickel service level equal to that of citizens in developed countries nowadays.

## 4. Economizing on primary copper and nickel use

Whether action is needed to economize copper and nickel use to safeguard the availability of these metals for future generations depends on:

- The sustainability ambition: 1000 years, 500 years, 200 years or even less? For copper, the 1000 year sustainability ambition is only achievable if the available copper resources are 14 Gt minimum and the end-of-life recycling is at least 85%. For nickel the 1000 year ambition.is only feasible, if the available resources are at least 2 Gt in combination with an end-of-life recycling rate of 85%.
- The extractable resources, i.e. whether 14 Gt of copper and 2 Gt of nickel are economically extractable from the earth's crust is uncertain.

Below we present an overview of the technical and policy options to reduce primary copper and nickel use.

**Table 6**
Required end-of life recycling rates for different assumptions regarding the ultimately extractable nickel resources. Primary nickel production in 2016 was 2.1 Mt. Further assumptions: Nickel substitution compared to 2016 is 0%; material efficiency increase compared to 2016 is 10%. Sustainability ambition level is 1000 years of nickel supply.

| | Unit | Currently | Nickel resources availability | | |
|---|---|---|---|---|---|
| | | | 0,3 Gt | 1 Gt | 8 Gt |
| Sustainable nickel production (1) | Mt/year | | 0,3 | 1 | 8 |
| Annual nickel consumption | Mt | 2.75 | 13.5 | 13.5 | 13.5 |
| Accumulation in in-use-stock | % | 59% | 0% | 0% | 0% |
| Annual accumulation in in-use-stock | Mt | 1.6 | 0 | 0 | 0 |
| End-of-life nickel | Mt | 1.15 | 13.5 | 13.5 | 13.5 |
| EoL recycling | Mt | 0.7 | 13.2 | 12.5 | 5.5 |
| **Required EoL recycling rate** | **%** | **57%** | **98%** | **93%** | **41%** |
| Nickel consumption level (2) | g/capita/year | 362 | 1350 | 1350 | 1350 |

(1) Point of departure: sufficient nickel supply for 1000 years.
(2) Current nickel consumption level in developed countries is 1500 g/capita/year; material efficiency increase of 10% results in a future nickel service level of 1350 g/capita/year.

**Table 7**
Minimum amount of available nickel resources (Gt) required at different sustainability ambitions and different end-of-life recycling rates.

| Sustainability ambition (years of nickel supply) | End-of-life recycling rate | | |
|---|---|---|---|
| | 60% | 75% | 85% |
| 200 | 1.1 | 0.7 | 0.4 |
| 500 | 2.7 | 1.7 | 1 |
| 1000 | 4.7 | 3.4 | 2 |

### 4.1. Increase of recovery efficiency at the mining and production stage

The current copper recovery efficiency at the production stage is 84% (Lifset et al., 2002; Glöser, 2013) and for nickel 80% (Reck and Gordon, 2008; Reck et al., 2008). With a further decreasing ore grade, it will be difficult to increase recovery efficiency substantially. Recovery efficiency is the result of a balance between higher costs, mainly for energy, and higher returns for the extracted commodity. In this paper we have assumed that the future recovery rates of copper and nickel will remain the same as the present ones. Recovery of some extra copper and nickel from slag and tailings, which have been produced in the past, may become a positive business case at some point in the future.

### 4.2. Substitution

In power cables, electrical equipment, automobile radiators and cooling and refrigeration tubes, copper can be replaced by aluminum. In heat exchangers copper can be substituted by titanium and steel. In telecommunication, copper can be replaced by optical fibers. In water pipes, drain pipes and plumbing fixtures copper can be replaced by plastic (US Geological Survey, 2018a). However, so far, substitution is minimal, because, mostly, copper has superior properties. In 2015, 2016, net copper substitution was about 1%, mainly in cables and wiring (International Copper Association, 2017; Dewison, 2016). For high voltage overhead transmission lines aluminum is now preferred instead of copper, because of the lower weight of aluminum. For underground lines this advantage of aluminum disappears. Because overhead transmission lines are considered ugly and because of the concerns of health impacts of overhead transmission lines, in the future high voltage transmission may happen more through underground copper lines than through overhead aluminum lines (Ayres et al., 2002). For interior wiring, copper is preferred to aluminum, because aluminum has led to problems of overheating and fires. In telecommunication, copper wires are replaced by glass fiber, because of its higher performance. Copper can also be replaced in roofing. In some applications copper seems virtually irreplaceable such as for local distribution of electric power, interior wiring, motor-generator windings, electronic circuitry, and for some kinds of heat-exchangers (Ayres et al., 2002).

Currently, copper production is less energy-intensive than that of aluminum. However, below an ore grade of 0.1% this advantage for copper compared to aluminum will disappear (Ayres et al., 2002). In Tables 3 and 4 we have assumed a maximum copper substitutability of 10%, especially in applications that are not related to electricity generation, transmission, distribution and use, such as in roofs, gutters, radiators, ammunition, water distribution, chemicals and other applications.

Though substitution of nickel by other materials is possible in some cases (US Geological Survey, 2018b), nickel is so essential in its different applications that large scale substitution does hardly seem possible without a substantial loss of quality (European Commission, 2014; British Geological Survey, 2008).

### 4.3. Increasing material efficiency

Apart from recycling, a main tool for improving material efficiency is to increase product life times. The potential of so-called nickel saving stainless steels is also interesting in this respect (Oshima et al., 2007). It is supposed that, apart from recycling, a 10% material efficiency improvement is feasible in the future. In a general way, this estimate is underpinned by Henckens (2016).

### 4.4. Reduction of in-use-dissipation

Currently, in-use-dissipation of copper is about 2%. The only way to reduce in-use-dissipation is banning of certain copper applications, such as in chemicals (wood preservatives, fungicides, pigments and antifouling paints). Corrosion of copper/bronze products and the use of copper as micronutrient cannot be avoided. In Section 2.5 we have assumed that a minimum copper in-use dissipation rate of 1% is achievable. Nickel does not have a significant in-use dissipation.

### 4.5. Increasing recycling

#### 4.5.1. Copper

Currently, about half of EoL copper ends in landfills, partly in ashes of waste incineration plants. This is a substantial amount. Copper in EoL products is included in seven types of waste: municipal solid waste, construction and demolition waste, industrial waste, hazardous waste, waste from electrical and electronic equipment, end-of-life vehicles and sewage sludge (Graedel et al., 2004). For 1994 it was estimated that Waste from Electronic and

Electrical Equipment and end-of-live vehicles together contain 70% of discarded copper (Graedel et al., 2004). Globally, EoL copper recycling is 45% (Glöser et al., 2013). To the extent that the copper content in an EoL product is lower, it will be more complicated and less rewarding to recover copper.

There are three ways to reduce the amount of copper, which is currently lost for recycling: (1) by increasing the fraction of separately collected copper containing end-of-life products, (2) by increasing the recycling efficiency of copper from the separately collected copper containing fraction, (3) by recovery of copper from landfills and incinerators. Copper concentrations in fly ash from municipal solid waste incinerators vary between about 200 mg/kg and 11,000 mg/kg with an average of about 1200 mg/kg (Jung et al., 2004; Lam et al., 2010). Copper concentrations in bottom ash from municipal solid waste incinerators (MSWIs) vary between 80 and 13,000 mg/kg with an average of almost 3000 mg/kg (Jung et al., 2004; Lam et al., 2010). Currently, grades of extracted copper ore are as low as 4000 mg/kg. This means that bottom ashes of MWSIs may become interesting as a future source for secondary copper. Simultaneously, by removing heavy metals such as copper from MSWI bottom ashes, their potential utility in other applications increases, because of the decreased leaching of heavy metals. However, improved copper collection and recycling rates will reduce the copper content of MSWI bottom ashes and may affect a potential business case. It can be expected that, to the extent that copper prices will increase in the future, due to a combination of a higher copper demand and higher extraction costs because of a further decrease of copper ore-grades and deeper mining, copper recycling will become financially more attractive. The question is whether the market mechanism on its own will be sufficient and timely enough to prevent a situation that future generations will be confronted with rocketing copper prices because of depletion of economically extractable copper resources.

### 4.5.2. Nickel

Currently, nickel content of nickel bearing scrap is about 8–9%. The nickel scrap processing industry consists of only a few companies operating on an international level. They collect nickel containing scrap from all over the world (International Nickel Study Group, 2019). Nickel is recycled by blending steel scrap with different nickel concentrations. The purpose is to obtain a mix with a nickel content that can be used again for the production of stainless steels. The current nickel recycling rate from End-of Life products is 57%. If nickel is a minor constituent, e.g. in low alloy steels and in plating, it is economically not yet attractive to include these products in the nickel cycle, which is the case for about 20% of total nickel scrap (Reck et al., 2008). In these cases nickel becomes a constituent of carbon steel or copper scrap cycles and is in fact *down-cycled*. Actually, this nickel is dissipated outside the nickel cycle. It becomes unrecoverable for uses taking advantage of nickel's properties. The EoL recycling rate of nickel can be increased in the same ways as mentioned for copper: by increasing the fraction of separately collected nickel containing EoL products and by increasing the nickel recycling efficiency.

### 4.5.3. Policy measures

To realize a substantial increase of the end-of-life recycling rates of copper and nickel the following policy measures will be helpful to realize a business case with positive financial returns (Henckens et al., 2019):

- Making the producers of copper and nickel containing products responsible for recycling copper and nickel from their products
- Obliging recycling oriented design of copper and nickel containing products (Van Schaik and Reuter, 2014).
- Obliging electronic labeling of copper and nickel containing product parts
- Obliging separate collection and selective dismantling of copper and nickel containing products
- Prohibiting or taxing the disposal of copper and nickel containing products
- Subsidizing the use of recycled copper and nickel
- Taxing the sale of primary copper and nickel
- Agreeing on worldwide production quota of copper and nickel

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

The authors thank two anonymous reviewers for their comments that helped to improve the manuscript. Despite their efforts, any remaining errors are the sole responsibility of the authors.

## References

Aalco, 2005. Stainless steels – introduction to grades, properties and applications. May 20 2005. https://www.amazon.com/article.aspx?Article. ID=2873, sponsored by Aalco – Ferrous and non-ferrous metals stockist.
Ayres, R.U., Ayres, L.W., Rade, I., 2002. The Life Cycle of Copper, its Co-products and By-Products, vol. 24. International Institute for Environment and Development. January 2002.
Barbalace, K., 2007. Periodic Table of Elements. http://environmentalchemistry.com/yogi/periodic. retrieved 14-4-2007.
Bardi, U, 2013. Plundering the Planet, In 33rd Report for the Club of Rome. Chelsea Green Publishing, White River Junction.
Barnett, H., Morse, C., 1963. Scarcity and Growth, the Economics of Natural Resource Availability. Johns Hopkins University Press, for Resources for the Future, Baltimore, MD.
Beckerman, W., 1995. Small Is Stupid. Duckworth, London.
Bertram, M., Graedel, T.E., Rechberger, H., Spatari, S., 2002. The contemporary European copper cycle: waste management subsystem. Ecol. Econ. 42, 43–57.
Bleischwitz, R., Nechifor, V., Winning, M., Huang, B., Geng, Y., 2018. Extrapolation or saturation – revisiting growth patterns, development stages and decoupling. Global Environ. Change 48, 86–96.
British Geological Survey, 2007. Copper. www.mineralsuk.com. June 2007.
British Geological Survey, 2008. Nickel. www.mineralsuk.com. September 2008.
British Geological Survey, 2018. Battery Raw Materials. www.MineralsUK.com. May 2018.
Copper Alliance, 2019. Global 2018 Semis End Use Data Set. https://copperalliance.org/trends-and-innovations/data-set/. downloaded on 14-1-2019.
Darling, D., 2007. Elements, Terrestrial Abundance. http://www.daviddarling.info/encyclopedia/E/elterr.html, 10 April 2007.
Dewison, P., 2016. Realities of Substitution in the Global Copper Market. Metals Research and Consulting, 2016.
De Koning, A., Kleijn, R., Huppes, G., Sprecher, B., Van Engelen, G., 2018. Metal supply constraints for a low-carbon economy?, *Resources*. Conserv. Recycl. 129, 202–208.
Diamandis, P.H., Kotler, S., Abundance, 2012. The Future Is Better than You Think. Free Press, New York, 2012.
Diederen, A., 2009. Metal Minerals Scarcity: a Call for Managed Austerity and the Elements of Hope. TNO, The Hague, The Netherlands.
Elshkaki, A., Graedel, T.E., Ciacci, L., Reck, B.K., 2016. Copper demand, supply, and associated energy use to 2050. Global Environ. Change 39, 3050315.
Erickson, R.L., 1973. Crustal Occurrence of Elements, Mineral Reserves and Resources, vol. 820. USGS Professional Paper, pp. 21–25.
European Commission, 2014. Report on critical raw materials for the EU, non-critical raw materials profiles. DG Enterprise and Industry.
Gerst, M.D., 2008. Revisiting the cumulative grade-tonnage relationship for major copper ore types. Soc. Econ. Geol. Inc., Econ. Geol. 103, 615–628.
Gerst, M.D., 2009. Linking material flow analysis and resource policy via future scenarios of in-use-stock: an example for copper. Environ. Sci. Technol. 43, 6320–6325.
Glencore, 2018. The EV Revolution and its Impact on Raw Materials. IEA Seminar on e-mobility. March 2018.
Glöser, S., Soulier, M., Espinoza, L.A.T., 2013. Dynamic analysis of global copper flows. Global stocks, Postconsumer material flows, recycling indicators, and uncertainty evaluation. Environ. Sci. Technol. 47, 6564–6572.
Goonan, T.G., 2009. Copper recycling in the united state in 2004, 1196-X. US

Geological Survey Circular, p. 2009.

Gordon, R.B., Koopmans, J.J., Nordhaus, W.B., Skinner, B.J., 1987. Towards a New Iron Age. Harvard University Press, Cambridge MA, 1987, cited by Elshkaki et al. (2016).

Graedel, T.E., Van Beers, D., Bertram, M., Fuse, K., Gordon, R.B., Gritsinin, A., Kapur, A., Klee, R.J., Lifset, R.J., Memon, L., Rechberger, H., Spatari, S., Vexler, D., 2004. Multilevel cycle of anthropogenic copper. Environ. Sci. Technol. 38, 1242–1252.

Gunn, G., 2011. Mineral scarcity – a non-issue? 2011. British Geol. Survey.

Halada, K., Shimada, M., Ijima, K., 2008. Decoupling status of metal consumption from economic growth. Mater. Trans. 49, 411–418.

Hamilton, C., 2018. Battery raw materials, the fundamentals, Presentation at the International Energy Agency workshop on batteries for electric mobility. BMO Capital Markets.

Hannington, M., Jamieson, J., Monecke, T., Petersen, S., Beaulieu, S., 2011. The abundance of seafloor massive sulfide deposits. Geology 39, 1155–1158.

Henckens, M.L.C.M., 2016. Managing Raw Materials Scarcity: Safeguarding the Availability of Geologically Scarce Mineral Resources for Future Generations. PhD Thesis. Utrecht University. http://dspace.library.uu.nl/handle/1874/339827.

Henckens, M.L.C.M., Biermann, F.H.B., Driessen, P.P.J., 2019. Mineral resources governance: a call for the establishment of an International Competence Center on Mineral Resources Management. Resour. Conserv. Recycl. 14, 255–263.

Henckens, M.L.C.M., Driessen, P.P.J., Worrell, E., 2014. Metal scarcity and sustainability, Analyzing the necessity to reduce the extraction of scarce metals. Resour. Conserv. Recycl. 93, 1–8.

Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated Life-cycle assessment of electricity supply scenarios confirms global environmental benefit of low-carbon technologies. PNAS 112, 6277–6282 cited by De Koning et al., 2018.

Hoatson, D.M., Subhash, J., Jaqyes, A.L., 2006. Nickel sulphide deposits in Australia, Characteristics, resources and potential. Ore *Geol. Rev.* 29, 177–241 cited by British Geological Survey, 2008.

Hodges, C.A., 1995. Mineral resources, Environmental issues and Land use, 1995. Science 268 (5215), 1305–1312.

International Copper Association, 2017. Global Copper Substitution and Regulatory Trends. April 2017.

International Nickel Study Group, 2019. Recycling of Nickel Containing Products. http://www.insg.org/recycling.aspx, 7-1-2019.

Jowitt, S.M., Mudd, G.M., 2014. Global gold: current resources, dominant deposit types and implications. In: Proc. Gold14@Kalgoorlie, pp. 56–58. Kalgoorlie, Western Australia.

Jung, C.H., Matsuto, T., Tanaka, N., Okada, T., 2004. Metal distribution in incineration residues of municipal solid waste (MSW) in Japan. Waste Manag. 24, 381–391.

Kerr, R.A., 2014. The coming copper peak. Science 343 (6172), 722–724.

Kesler, S.E., 1994. Mineral Resources, Economics and the Environment. Macmillan, New York.

Kesler, W.E., Wilkinson, B.H., 2008. Earth's copper resources estimated from tectonic diffusion of porphyry copper deposits. *Geology*, March 255–258, 2008.

Kleijn, R., Van der Voet, E., Kramer, G.J., Van Oers, l, Van Der Giesen, C., 2011. Metal requirements of low-carbon power generation. Energy 36, 5640–5648.

Kuipers, K.J.J., Van Oers, L.F.C.M., Verboon, M., Van der Voet, E., 2018. Assessing environmental implications associated with global copper demand and supply scenarios from 2010 to 2050. Global Environ. Change 49, 106–115.

Lab, Jefferson, 2007. Its Elemental, the Periodic Table of Elements. http://education.jlab.org/itselemental/index.html, 29-4-2007.

Lam, C.H.K., Ip, A.W.M., Barford, J.P., McKay, G., 2010. Use of incineration MSW ash: a review. Sustainability 2, 1943–1968.

Lifset, R.J., Gordon, R.B., Graedel, T.E., Spatari, S., Bertram, M., 2002. Where has all the copper gone: the stocks and flows project, Part 1. JOM 21–26. October 2002.

Maurice, C., Smithson, C.W., 1984. The Doomsday Myth, 10,000 Years of Economic Crises, Hoover Institution Press. Stanford University, 1984.

Malthus, T., 1798. An Essay on the Principles of Population, 1798.

McLennan, S.M., 2001. Relationships between the trace element composition of sedimentary rocks and upper continental crust. G-cubed 2. April 20th.

Meadows, D.H., others, 1972. The Limits to Growth. Universe Books, New York.

Meadows, D.H., others, 1992. Beyond the Limits. Chelsea Green Publishing, Post Mills, VT.

Mill, J.S., 1848. Principles of Political Economy.

Mudd, G.M., Jowitt, S.M., 2014. A detailed assessment of global nickel resource trends and endowments. Econ. Geol. 109, 1813–1841.

Nickel Institute, 2018. Nickel energizing batteries. Nickel 33 (1), 2018.

Nickel Institute, 2019. Stainless Steel: the Role of Nickel. https://www.nickelinstitute.org/about-nickel/stainless-steel/7-1-2019.

Norgate, T., Jahanshahi, S., 2010. Low grade ores- smelt, leach or concentrate? Miner. Eng. 23, 65–73.

Northey, S., Mohr, S., Mudd, G.M., Weng, Z., Giurco, D., 2014. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resour. Conserv. Recycl. 83, 190–201.

Oshima, T., Habara, Y., Kuroda, K., 2007. Efforts to save nickel in austenitic stainless steels. ISJI 47 (3), 359–364, 2007.

Pan Pacific Copper, 2019. downloaded 30-1-2019. https://www.metalbulletin.com/events/download.ashx/document/speaker/7570/a0ID000000X0kAJMAZ/Presentation.

Reck, B.K., Gordon, R.B., 2008. Nickel and Chromium Cycles: Stocks and Flows Project Part IV. www.tms.org/jom.html, 2008 July, 55-59.

Reck, B.K., Müller, D.B., Rostowski, K., Graedel, T.E., 2008. Anthropogenic nickel cycle: insights into use, trade and recycling. Environ. Sci. Technol. 42, 3394–3400.

Ricardo, D., 1817. Principles if Political Economy and Taxation.

Roskill Information Services Ltd, 2017. Nickel Market Beware – Batteries Can No Longer Be Ignored. Roskill Information Services Ltd, press release, London, UK. April 20, 2017, cited by US Geological Survey, 2018c.

Ruhrberg, M., 2006. Assessing the recycling efficiency of copper from end-of-life end-of-life products in Western Europe, Resources. Conserv. Recycl. 48, 141–165.

Rudnick, R.L., Fountain, D.M., 1995. Nature and composition of the continental crust, a lower crustal perspective. Rev. Geophys. 33 (3), 267–309.

Schodde, R.C., 2010. The key drivers behind resource growth: an analysis of the copper industry over the last 100 years. In: Presentation to the Mineral Economics & Management Society (MEMS) session at the 2010 SME Annual Conference, 2010, March p2010.

Simon, J.L., 1980. Resources, population, environment: an oversupply of false bad news. Science 208, 1431–1438.

Simon, J.L., 1981. The Ultimate Resource. Princeton University Press, Princeton, NJ.

Singer, D.A., 2017. Future copper resources. Ore Geol. Rev. 86, 271–279.

Skinner, B.J., 1976. A second iron age ahead? Am. Sci. 64, 158–169.

Skinner, B.J., 1987. Supplies of geochemically scarce metals. In: MacLaren, D.J., Skinner, B.J. (Eds.), Resources and World Development, pp. 305–325. John Wiley and Sons, Chichester, UK, 1987, cited by Elshkaki et al., 2016.

Smith, K., 1982. Scarcity and Growth Reconsidered, second ed. Resources for the Future Inc. John Hopkins Press, Ltd London. 1982.

Soulier, M., Glöser-Chahoud, S., Goldman, D., Espinoza, L.A.T., 2018. Dynamic analysis of European copper flows, *Resources*. Conserv. Recycl. 129, 143–152.

Spatari, S., Bertram, M., Gordon, R.B., Henderson, K., Graedel, T.E., 2005. Twentieth century copper stocks and flows in North America: a dynamic analysis. Ecol. Econ. 54, 37–51.

Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2014. On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. Resour. Conserv. Recycl. 87, 158–174.

Tilton, J.E., Coulter, W.J., 2001. Manuscript for the Workshop on the Long-Run-Availability of Mineral Commodities, Sponsored by Mining, Minerals and Sustainable Development Project and Resources for the Future. Washington DC, April21–23, 2001.

UNEP, International Panel on Sustainable Resources management, 2011. Estimating long-run geological stocks of metals. In: International Panel on Sustainable Resources Management, Working Group on Geological Stocks of Metals, Working Paper, April 2011.

United Nations, 2017. World Population Prospects, UN Department of Economic and Social Affairs, 2017.

US Geological Survey, 2000. 1998 Assessment of undiscovered deposits of gold, silver, copper, lead and zinc in the United States. Circular 1178, 2000.

US Geological Survey, 2009. Copper – A Metal for Ages, Fact Sheet 2009-3031. May 2009.

US Geological Survey, 2014. Estimate of Undiscovered Copper Resources of the World, 2013, Fact Sheet 2014-3004, January 2014.

US Geological Survey, 2017a. Copper Statistics, January 2017.

US Geological Survey, 2017b. Nickel Statistics, January 2017.

US Geological Survey, 2018a. Copper. Mineral Commodity Summaries. January 2018.

US Geological Survey, 2018b. Nickel. Mineral Commodity Summaries. January 2018.

US Geological Survey, 2018c. Nickel, 2015 Minerals Yearbook. June 2018.

US Geological Survey, 2018d. Nickel. Mineral Commodity Summaries, 1996-2018.

Van Beers, D., Kapur, A., Graedel, T., 2007. Copper and zinc recycling in Australia: potential quantities and policy options. J. Clean. Prod. 15, 862–877.

Van Schaik, A., Reuter, M.A., 2014. Material-centric (aluminium and copper) and product-centric (cars, WEEE, TV, lamps, batteries, catalysts) recycling and DfR rules. In: Worrell, E., Reuter, M.A. (Eds.), Handbook of Recycling. Elsevier, Amsterdam, pp. 307–378.

Vidal, O., Le Boulzec, H., François, C., 2018. Modelling the material and energy costs of the transition to low-carbon energy. EPJ Web Conf. 189 https://doi.org/10.1051/epjconf/201818900018, 00018, 2018.

Webelements, 2007. Abundance in Earth's crust. http://www.webelements.com/webelements/properties/tekst/image-flah/abund-crust.html, 9 March 2007.

Wedepohl, K.H., 1995. The composition of the continental crust. Geochimica et Cosmochimica 59, 1217–1232.