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Estimating global copper demand until 2100 with regression and stock dynamics

Branco W. Schipper[a,c,*], Hsiu-Chuan Lin[a,c], Marco A. Meloni[a,c], Kjell Wansleeben[d], Reinout Heijungs[a,b], Ester van der Voet[a]

[a] Institute of Environmental Sciences, Leiden University, Einsteinweg 2, 2333 CC, Leiden, The Netherlands
[b] Department of Econometrics and Operations Research, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV, Amsterdam, The Netherlands
[c] Faculty of Technology, Policy and Management, Technical University Delft, Jaffalaan 5, 2628 BX, Delft, The Netherlands
[d] Department of Spatial Planning, Municipality of Pijnacker-Nootdorp, Oranjeplein 1, 2641 EZ, Pijnacker, The Netherlands

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ABSTRACT

Future global copper demand is expected to keep rising due to copper's indispensable role in modern technologies. Unfortunately, increasing copper extraction and decreasing ore grades intensify energy use and generate higher environmental impact. A potential solution would be reaching a circular economy of copper, in which secondary production provides a large part of the demand. A necessary first step in this direction is to understand future copper demand. In this study, we estimated the copper demand until 2100 under different scenarios with regression and stock dynamics methods. For the stock dynamics method, a strong growth of copper demand is found in the scenarios with a high share of renewable energy, in which a much higher copper intensity for the electricity system and the transport sector is seen. The regression predicts a wider range of copper demand depending on the scenario. The regression method requires less data but lacks the ability to incorporate the expected decoupling of material use and GDP when the stock saturates, limiting its applicability for long-term estimations. Under all considered scenarios, the projected increase in demand for copper results in the exhaustion of the identified copper resources, unless high end-of-life recovery rates are achieved. These results highlight the urgency for a transition towards the circular economy of copper.

1. Introduction

Resource scarcity is one the main challenges facing human society in this century. Improving living standards, together with a world population that is expected to reach 9 billion in the year 2050 and could pass the 10 billion mark before the end of the century (UNDESA, 2015), are expected to push the demand for resources into unchartered waters.

One of these resources is copper, a ubiquitous metal in modern society. Copper demand has been growing rapidly all through the 20th century with no signs showing that it will be slowing down anytime soon. It is used in a broad range of applications, mainly because of its unique electricity conducting properties, which also makes it difficult to substitute. It will become even more crucial for the society in the future, given the expected increase of copper-intensive low carbon energy and electrification of transport technologies.

The rapidly rising demand may cause future supply problems and may contribute to environmental issues. For example, declining ore grades result in higher energy requirements for the same amount of copper extraction (Memary et al., 2012; UNEP, 2013a), thus increasing greenhouse gas emissions.

Circular economy has been proposed as an answer to tackle the challenges brought by the increasing resource demand (European Commission, 2015). Closing the material loop would help avoid resource supply problems, and would also reduce environmental impact by cutting the need for mining and energy use: secondary copper production requires only 20% of the energy used for primary copper production (International Copper Study Group, 2013).

A prerequisite for a circular economy of copper is an understanding of societal copper metabolism: the inflows and outflows, and the accumulated stocks. This provides essential information on the potential for closing the loop. There has been significant research in stocks, flows, and environmental impacts of metals (Daigo et al., 2009; Graedel et al., 2002; Kral et al., 2014; Lifset et al., 2002; UNEP, 2013a, 2013b, 2011, 2010; Wen et al., 2015). In addition, other research has suggested that around 85% of the copper that has been produced since the beginning of the 20th century is still in use (Wen et al., 2015), highlighting the

* Corresponding author at: Institute of Environmental Sciences, Leiden University, Einsteinweg 2, 2333 CC, Leiden, The Netherlands.
E-mail address: b.w.schipper@umail.leidenuniv.nl (B.W. Schipper).

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Table 1
Socio-economic, population and technology development for each of the five Shared Socio-economic Pathway scenarios. Modified from O'Neill et al. (2014).

SSP scenario	Economy and social equality	Population	Technology
SSP1	High sustainable development with low inequalities. Fast technological innovation and change towards environmentally friendly and lower carbon intensive industries and energy sources.	Moderate population growth.	Fast technological innovation towards low carbon energy sources and industries.
SSP2	Intermediate between SSP 1 and 3.		
SSP3	Moderate economic growth and high inequalities.	Fast population growth.	Slow change in the energy sector, leading to high emissions.
SSP4	Heterogeneous development due to isolated economies. High social inequalities.	Intermediate population growth.	Heterogeneous technological development. Fast change towards low emitting technologies in key regions, but less development in lower emission regions.
SSP5	High economic growth and social equality.	Low population growth.	Carbon based fuel technologies, leading to high emissions.

potential of urban mining and copper recycling in general. But even if all the copper were to be recovered, it would not be enough, given that the copper demand is still growing, and it is only possible to reach a circular economy of a resource when the demand stabilizes. In this context, understanding how the copper demand will develop in the future is one of the central factors that will determine how and when a circular economy of copper can be achieved.

This paper explores how copper demand might develop until the year 2100 under different socio-economic and technology scenarios. Two methods are adopted to study this question, a top-down method, based on a regression model, and a bottom-up method, based on a stock dynamics model. Several studies have applied both a top-down and bottom-up approach in finding a demand or stock of copper, and give future prospects of the two (Auping et al., 2012; Elshkaki and Graedel, 2013; Zhang et al., 2015). Our aim, besides estimating copper demand, is to point out the differences in prospects between the two approaches in the long term. Moreover, a comparison of the results from the two methods provides an insight of the factors that are important in determining copper demand.

2. Methods

We employ two methods to answer our research question. The top-down method establishes the relationship between copper demand and general development variables such as GDP and population. The future trend can be extrapolated from the estimated relationship on the basis of empirical data from the past, similar to the approach employed by Halada (Halada et al., 2008). The advantages of this method include its transparency, its small number of assumptions, and most importantly its limited data requirement. Because of the lack of specificity in available inflow data in many cases, the regression method is less useful for regional estimations (Müller et al., 2014).

Bottom-up methods are usually applied in small-scale case studies, to estimate the stock dynamics of metals, and assess the environmental impact of the flows (Bergbäck et al., 2001). Here we have used such an approach in order to estimate future demands. The bottom-up method yields more detailed results than the top-down approach, i.e. results that can be related to the level of individual applications, but it also requires more data and assumptions.

The copper in-use stock estimation conducted by Zhang et al. (2015) uses both top-down and bottom-up analysis from 1952 to 2012 and looked into the historical events leading to societal changes corresponding to the stock development. Zhang et al. (2015) conducted top-down, bottom-up, and spatial distribution to strengthen its retrospective results regarding the copper stock in the past 60 years. Zhang et al. (2015) also used a bottom-up method to estimate future copper stock until 2050. The total in-use stock in Zhang et al. (2015) study peaks at 2030 and declines towards 2050. For this paper, we aim to point out the differences (or similarities) between the methods in a long term prospective estimation.

2.1. Scenarios for demand

In terms of the estimation for future demand, both methods need assumptions on how the society will develop. In this paper, we use the Shared Socio-economic Pathways (SSPs) scenarios (O'Neill et al., 2014), which explore how population and GDP, among other variables will develop in five different future social pathways. The SSPs consist of a narrative storyline and quantified measures of development, and describe feasible alternative development paths for the society and the planet during the 21 st century (O'Neill et al., 2014). The SSPs were developed in order to help climate research and policy makers in assessing the effects of climate change mitigation and adaptation measures for the research framework developed by van Vuuren et al. (2014). These scenarios were made based on two axis: the level of radiative forcing on the climate system and a variety of different possible global development trajectories (van Vuuren et al., 2014). Descriptions of the five scenarios can be found in Table 1. Both the bottom-up and top-down analysis use the scenarios in Table 1.

2.2. Stock dynamics method

The stock dynamics method starts from the stock of applications, and calculates demand as a derivative. The actual in-use-stock of the copper-containing products is the essential variable, and not the production. Demand is then calculated based on two considerations: (1) replacing the products discarded from the stock, and (2) allowing for net stock increase as a result of population and welfare growth.

The first step of the stock dynamics method is to establish the categories of products that contain copper. Next step is to collect data on the copper content and the quantities of these categories of products to determine the past and present stock of copper in use. Then, the future stock is calculated based on the assumptions of population and welfare growth as well as stock dynamics and stock saturation. Hereafter, steps are explained in more detail. Note that not all categories have had their copper demand calculated with this stock dynamics method. Describing the method as 'bottom-up' would be more correct, and so we mostly refer to it as such.

Besides the demand-side analysis, we performed an estimation of the secondary production of copper to provide further understanding of the role that secondary supply could play under the demand scenarios and potential depletion. The secondary production is derived using the same dataset of the demand estimation, although the estimation method is relatively less sophisticated, such comparison gives some information on whether the society would be able come close to circle the economy. Under the circular economy framework, we wish to explore to what extent mining from the societal stock could relieve the pressure exerted on natural reserve.

2.2.1. Category definition

We use the categories of copper applications as have been defined by Joseph and Kundig (1999) based on the weight percentage share per

Table 2
Category definition.

Category	Parameter description	Share of total copper stock by weight (%)
Building construction	1) Residential buildings 2) Service buildings	50%
Infrastructure	1) Power generation 2) Distribution & transmission 3) Traffic & street lights 4) Rail systems	22%
Transportation	1) Cars 2) Trains 3) Aircraft 4) Vessels 5) Heavy-duty vehicles	5%
Consumer durables	1) TVs 2) Refrigerators 3) Air conditioners 4) Washing machines 5) PCs 6) Electric heaters 7) Microwave ovens 8) Printers 9) Cellphones 10) Landlines 11) Others	5%
Commercial durables	1) Commercial durables	10%
Industrial durables	1) Agricultural machinery 2) Industrial machinery	8%

category and since then adopted by others such as Gerst (2009), UNEP (2013a), and Zhang et al. (2011). They are listed in Table 2.

2.2.2. Calculation method and data

Studies using bottom-up methods obtain results by multiplying the number of products-in-use with the average product weight and the copper content of the product (Gerst and Graedel, 2008; Rauch et al., 2007; Zhang et al., 2014, 2011). To obtain the total number of products-in-use, product ownership data can be applied (Rauch et al., 2007). We adopt this approach to calculate past and present copper stock-in-use. To estimate future stock-in-use, studies that develop models to predict appliance ownership at the household level based on macroeconomic variables (Letschert and Mcneil, 2010) were used. In brief, the method amounts to the following:

- We recognize that each product category is different; therefore, a model is developed, along similar principles, for each product category separately.
- In-use stocks are estimated based on the size of the population and the household product ownership.
- It is assumed that the ownership of most household appliances have reached at least a current Western level in 2100.
- Demand is derived from stock dynamics: stock growth and stock replenishment. Stock growth follows the previously mentioned population growth and product ownership. Stock replenishment takes into consideration the replacement of end-of-life products, using an average product lifespan.
- The general equation for the product stock model is shown as Eq. (1).

$$D_a = \sum_{i=1}^{6} (N_{i,a} - N_{i,a-1,})\cdot m_i + (N_{i,a-1}/T_{res,i})\cdot m_i \quad (1)$$

Here, D_a is the demand for copper (in tonne/year) in year a, $N_{i,a}$ is the stock (in tonne) of the application i in year a, m_i is the copper content (in tonne/tonne) of the application i, and $T_{res,i}$ is the residence time (in year) of the application i.

- The outflow of copper is calculated by dividing the initial stock of the previous year by the lifetime, similar to the method utilized by Elshkaki and Graedel (2013).
- Two exceptions are the electricity generation and electricity distribution estimations, which are not calculated from stock dynamics.
- The detailed calculation for all (sub)categories is summarized in Supporting Information (SI) A. This includes data sources used to estimate model parameters.

A feature of the bottom-up approach is the growth rate of per capita (or household) ownership and is assumed to be decreasing towards 2100, resulting in the per capita ownership of copper-containing products to be approaching saturation. It is assumed that after a household obtained certain products, the demand would be met until the product needs replacement. For example, even with increasing affluence level, the household would not need a second or third washing machine. We have applied this for categories of transportation, consumer durables, and subcategories of infrastructure. Overall, this allows for the bottom-up approach to lead to stock saturation (See SI).

Attention to precision and higher levels of details in data collection is given to applications of copper that represent a larger percentage in all stock. For example, the subcategory of cars contributes to a large part of the overall copper demand while personal computers are less significant. Therefore, in the car estimation, future technology development of increasing share of electric vehicles is taken into consideration, attempting to reflect scenarios that could better represent the trend of the copper application. However, this is sometimes limited by data availability, which varies among different applications of copper. In case of absence or the lack of reliable data, growth percentages of stock of applications are estimated based on GDP growth projections.

2.3. Top-down method

The top-down method uses regression analysis. A regression model establishes a linear relationship between two or more variables, one or more explanatory variables and one explained variable. In a bivariate linear regression, the data points of two variables can be graphed and a straight line can be drawn through the points such that it optimally agrees with the data points. The formula for this straight line is the regression model, and the difference between this line and any other possible line, is that it reduces the squared distances between each point and the line to a minimum. The sum of the squared distances between the line and the data points is also used to calculate the R^2 value, which describes the proportion of the variance that is explained by the model. The closer R^2 is to one, the closer it is to explaining all of the variance. R^2 indicates how well the regression model fits the data, but beyond the range of the data, the model will only be accurate if all other conditions remain constant. In our case, the assumption underlying this method is that all other explanatory factors besides GDP and population (for instance, level of technology and preferences) will remain the same. In this section of the study we report a series of regressions to model world copper demand, using GDP and population as explanatory variables. Copper production data, both primary and secondary, for the period 1950–2012, was obtained from US Geological Survey database (U.S. Geological Survey, 2013). Although in this study we focus on copper demand and not production, on a worldwide scale, the variables should be equivalent as all copper that is produced is consumed.

Past population data was obtained from the World Population Prospects report by UNDESA (2015). Past GDP data was obtained from the Maddison Project Database (2013), while future GDP and Population data was obtained from the aforementioned SSPs (O'Neill et al., 2014; van Vuuren et al., 2014) database (2015).

2.3.1. Regression model

We based the multivariate model on the IPAT equation (Commoner, 1972; Ehrlich and Holdren, 1971). This equation expresses the environmental impact (I) as a function of population (P), affluence (A), and technology (T):

$$I = PAT \tag{2}$$

The IPAT model has been reformulated into a stochastic form STIRPAT, which allows for non-proportional effects and statistical tool to assess the importance of the different drivers (Dietz and Rosa, 1994; York et al., 2003):

$$I = aP^bA^cT^d \tag{3}$$

Applying logarithms (Eq. (2)) results in an additive regression model that facilitates the estimation of the drivers (York et al., 2003):

$$\log I = \log a + b \log P + c \log A + d \log T \tag{4}$$

One explicit assumption to us is that technology remains constant. Thus, the terms log$a$ and $d$log$T$ will be treated as one constant, effectively reducing the equation to

$$\log I = C + b \log P + c \log A \tag{5}$$

A last step is to insert appropriate variables for I, P and A. For I, we use the copper demand, and P just means population. The affluence variable A is more complicated. While GDP is a logical candidate, the disadvantage is that GDP is strongly correlated with population P, thus introducing multicollinearity in the explanatory variables, with the risk of variance inflation and instable coefficient estimation. So we tried inserting GDP/capita for A, but this still gave an unacceptable high dependence between A and P. It turned out that GDP/capita$^{2.13}$ gave an optimal result in terms of completely removing the dependence between the explanatory variables. The general regression model is given in Eq. (6).

$$\log D = C + b \log P + c \log(GDP/capita^{2.13}) \tag{6}$$

where D is the demand for copper.

3. Results

3.1. Top-down results

To derive model parameters for the top-down regression analysis, we used time series of global copper production (as a proxy for demand), population and GDP/capita for the period 1950–2010. The result is shown in Fig. 1. We found a correlation with a high R^2 of 0.991, indicating the regression fits the time series of global copper production well. The VIF, the indicator for multicollinearity, returned a value of 1.000, indicating there is no dependence between the two explanatory variables. The coefficients, p, and t-values, corresponding to population, GDP/capita, and the constant can be found in Table 3.

Table 3
Results of the bivariate regression.

Coefficient	Estimated value	T-statistic value	P-value
C (Constant)	−16,124	−72,741	1096E-58
b (Population, P)	1808	80,846	2537E-61
c (Affluence, $GDP/capita^{2.13}$)	1164	8352	1580E-11

Applying these regression results based on past observations to equation 6 and using future projections for population and GDP/capita from the five SSPs, the future copper demand estimations were obtained. Note that this method's underlying assumption is that the relationship between copper demand, GDP and population will remain the same in the future. The estimates are shown in Fig. 1.

The top-down estimations suggest that copper demand continues to grow until the year 2100. Note that there are substantial differences between scenarios. The five SSP scenarios project a 3–21 fold copper demand increase for the year 2100 with respect to the production of the year 2012, in correspondence with the population and GDP increases in those scenarios. The largest demand is given by SSP5, the pathway with the largest GDP growth. GDP seems to be a stronger driver than population growth, determining the order of the largest to the smallest copper demand for the assessed scenarios.

3.2. Bottom-up results

Bottom-up results are derived from applying the stock-flow models per product, using the same scenario developments. In addition to the products-in-use, assumptions have been made for the developments in the energy system, since that has a significant influence on copper demand. We assumed a renewable energy system under SSP1, SSP2 and SSP4, and a primarily fossil energy system under SSP3 and SSP5. Details can be found in the SIs.

The results of our bottom-up method also show that copper demand is expected to continue growing in all scenarios (Fig. 2), but now projecting an increase from over 3.5 times to almost 5.5 times the copper demand of 2012. The range of projections is much narrower compared to the top-down approach. Another difference to top-down results is the trend; three of the bottom-up scenarios show a clear sign of decreasing

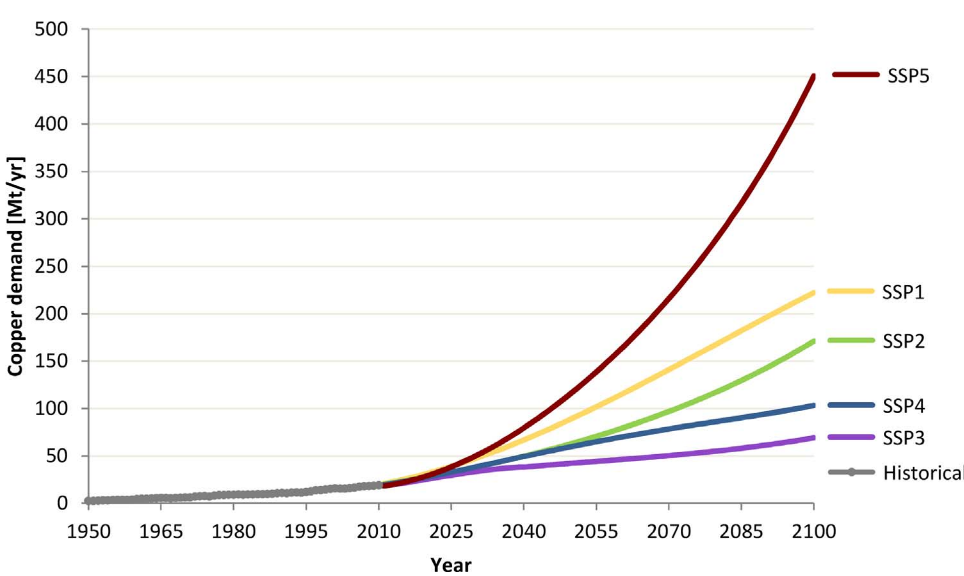

Fig. 1. Historical global copper production and predicted annual global copper demand for SSP1-5 from regressions (top-down approach) with GDP and population as explanatory variables.

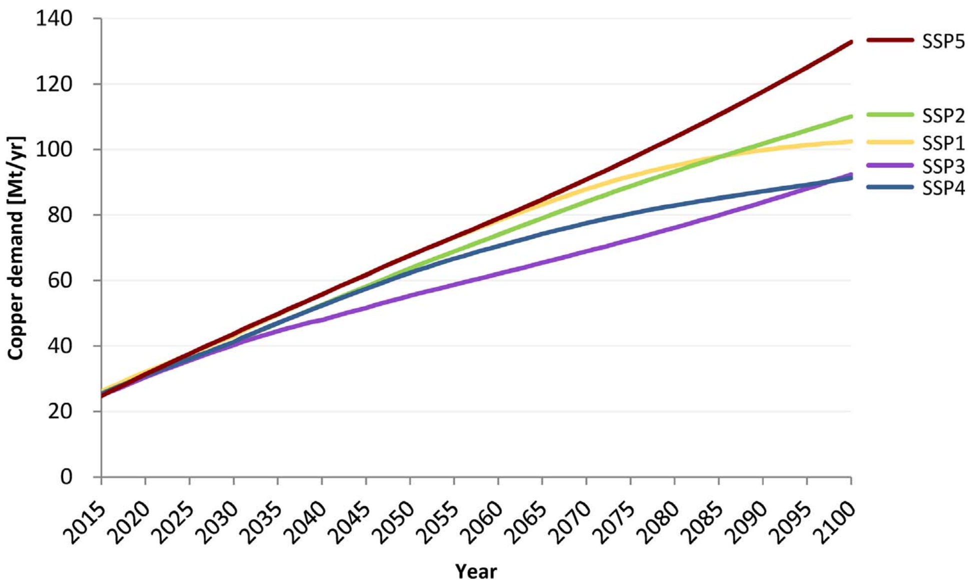

Fig. 2. Predicted annual global copper demand for SSP1-5 scenarios by the bottom-up stock dynamics method.

demand growth near the end of the 21 st century. SSP3 and SSP5 do not follow this slow-down trend. SSP5 shows the highest demand, as a result of the very high GDP growth. For the others, population stabilization and stock saturation have a dampening effect on demand.

3.3. Results per product category

In this section, we explore the behavior of the different product categories in the bottom-up model. Fig. 3 shows the overall estimated copper demand by category. SSP4 results are explored as an example. The results of SSP 1, 2, 3, and 5 are included in detail in SI B.

The total copper demand growth slows down towards 2100, trending towards a stabilization of demand. The copper demand in most underlying categories also continues to increase until 2100 except for the building construction, which stabilizes from 2060 onwards and even shows a decline in demand after 2095. Building construction remains the second highest copper demand driver given the mild decline of its annual demand. Infrastructure contributes the most to the overall copper demand towards 2100. The transition towards the relatively copper-intensive low carbon energy systems in infrastructure implies a strong rise in copper demand. The shift towards zero emission transport system, such as electric cars, electric motorcycles, and electric buses, also lead to a growing demand for copper in 2100. The results per category of other scenarios are further explored in SI B.

3.4. Outflow of copper results

Outflow of copper has been estimated for the bottom-up results, taking into account lifespan and copper stocks per category. The end-of-life copper is the maximum yearly recyclable copper. Fig. 4 shows the difference between copper inflow and outflow to the economy, i.e. the amount of primary copper that would need to be produced assuming all copper that reaches its end of life is recovered.

Amongst the scenarios, both SSP3 and SSP5, the business-as-usual scenarios, have an increasing primary copper demand, meaning these scenarios are not approaching circular economy within the studied time frame. SSP1 and SSP4, two of the renewable scenarios, show a rapidly reducing primary copper demand, and are thus approaching circular economy. SSP2 however, does not show the slowing trend clearly, despite being amongst the renewable scenarios. Another common feature of both SSP1 and SSP4 is that their GDP growth is slowing down near the end point of our calculations, while SSP2, SSP3, and SSP5, all have

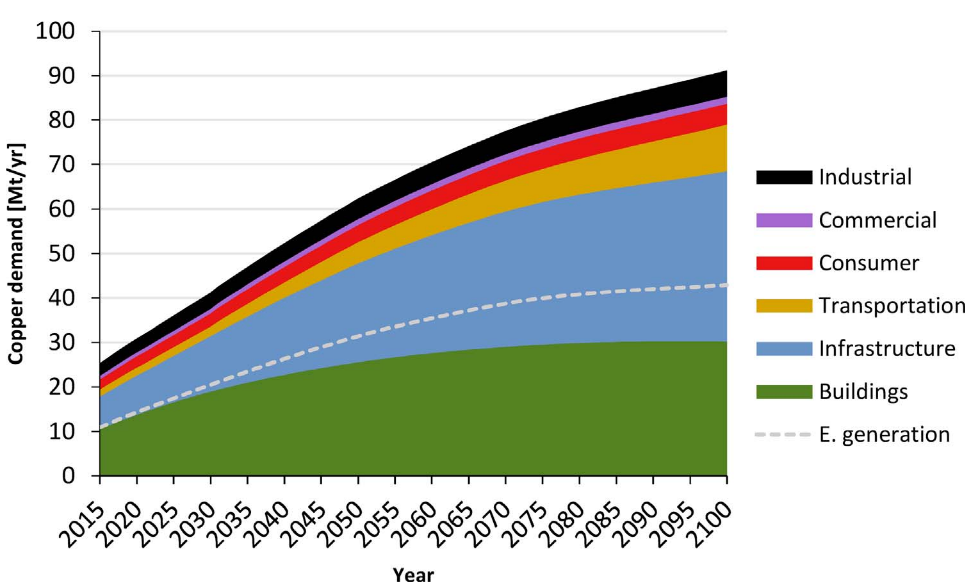

Fig. 3. Global copper demand by product category for the SSP4 scenario predicted by the bottom-up stock dynamics method. The dotted line for electricity generation visualizes the amount of copper demand in this subcategory of infrastructure and the growth that comes with increasing renewable energy production.

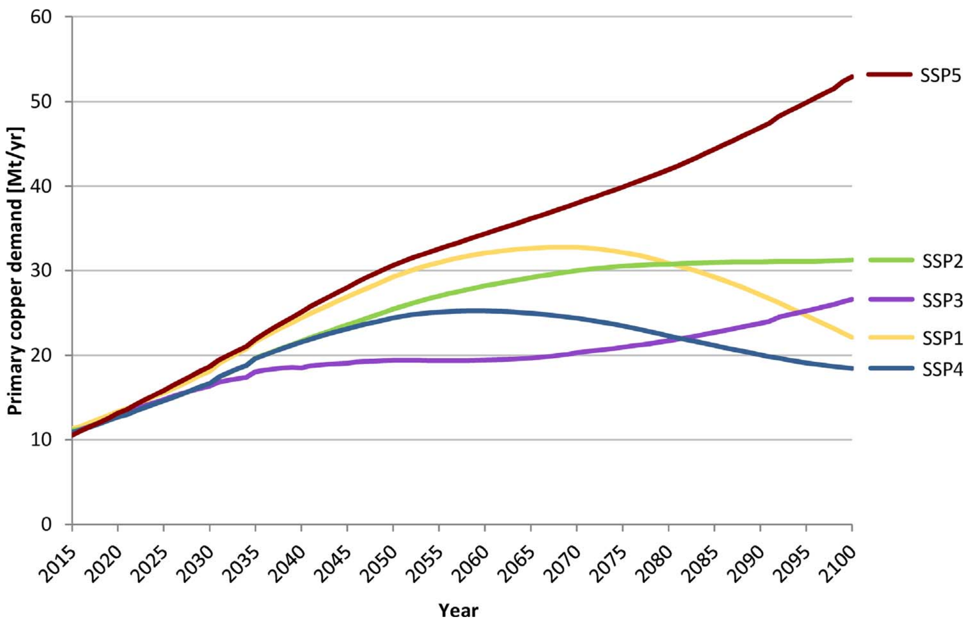

Fig. 4. Primary copper demand estimations by the bottom-up method when a speculative recycling rate of 90% is assumed.

an increasing growth rate of their GDP whilst approaching 2100 (See SI A). Nevertheless, SSP2 has stabilized its demand for primary copper with an increasing GDP growth. It seems thus, that the earlier investments are made in copper intensive renewable energy applications, the earlier growth of demand for primary copper can slow down. Furthermore, the curves of SSP1 and SSP4 are similar to the highest supply predictions by Sverdrup et al. (2014), indicating it is plausible that these scenarios could be realized.

Fig. 5 shows the cumulative copper demand for scenarios SSP1, 2 and 5, with recycling rates of 70 and 90%. While recycling rates of 70 and 90% are extremely speculative, they are used to represent an ideal situation regarding recycling. Reaching 70–90% recycling rate of copper would require significant changes in the way products are designed, and would be difficulty to acquire in short term. Additionally, the dotted line in Fig. 5 represents identified resources of copper (U.S. Geological Survey, 2014). In this study, we use the definition from Arndt et al. (2017) for resources and reserves. *Resources* "refer to various estimates of all mineral material on the planet (whether known or undiscovered, and regardless of whether it is mineable or not)", and *reserves* "refer to that part of the resource that is mineable under present conditions" (Arndt et al., 2017). Even in an ideal situation where recycling rates as high as 70 or 90% are achieved, the expected increase in demand would still result in reaching the exhaustion of the currently identified copper resources before the end of the century for all scenarios. However, new discoveries of copper deposits are expected increase the identified resources (Tilton and Lagos, 2007), so the identified copper resources should not be understood as a definite value.

3.5. Comparison of the top-down and bottom-up methods

The differences between copper demand estimates of the two methods are accentuated in the second half of the period of study (Fig. 6), with top-down estimates of copper reaching values of approximately 10 (SSP1 and 2) to up 20 (SSP5) times the mass of the current demand. These scenarios, and SSP5 particularly, are characterized by having a higher economic growth. Given that the top-down approach is influenced by GDP/c$^{2.13}$ in the same way throughout the period of study, while the bottom-up approach allows for stock

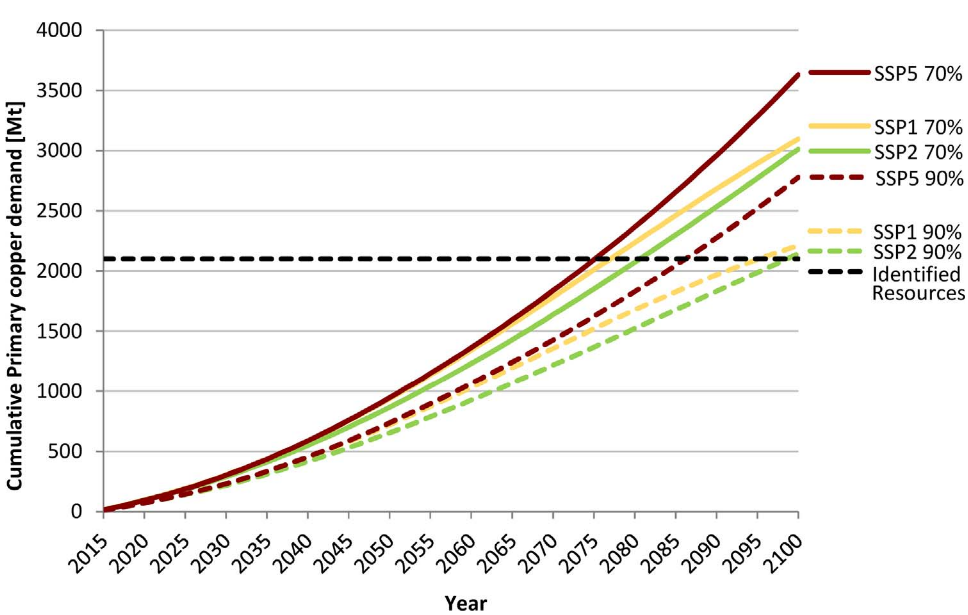

Fig. 5. Cumulative copper demand estimations using the bottom-up method with 70% and 90% recycling rates. The dashed line indicates the identified copper resources.

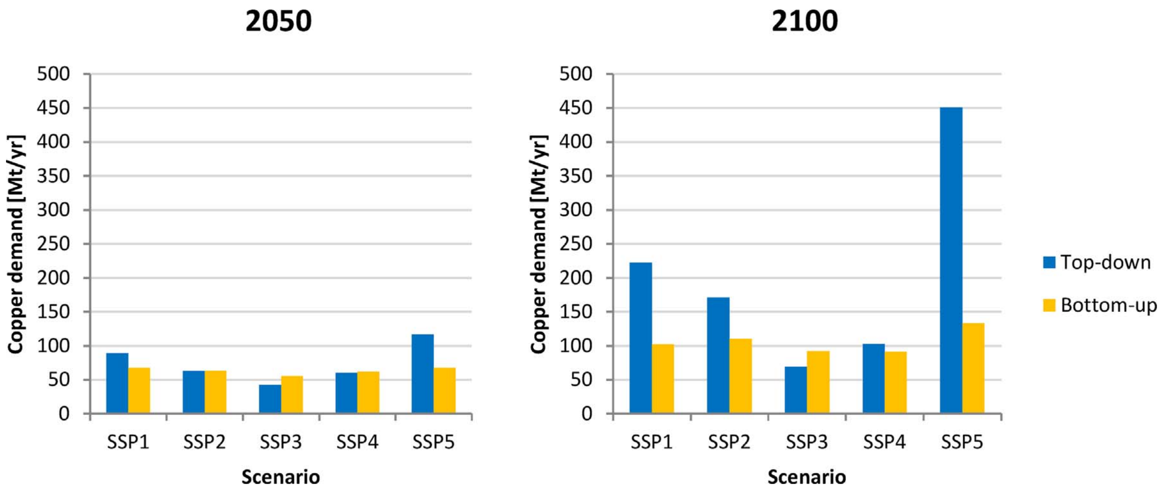

Fig. 6. Comparison of the copper demand estimation by top-down (regression-based) and bottom-up (stock-dynamics-based) methods for 2050 and 2100.

saturation, GDP growth influences the top-down method results more in the later years of the study period. Including stock saturation in the bottom-up approach allows to explore the decoupling of affluence from copper demand (i.e. a changing relationship between affluence and copper demand).

4. Discussion

In this research we explored copper demand until the year 2100 using different scenarios, providing an important piece of information for a transition towards a circular economy. We used, compared, and evaluated two different methods for this purpose. The top-down method, based on regression analysis, is easy to apply and requires little data, but also offers limited insights. With the bottom-up stock dynamics method, detailed projections of demand per category and even per appliance have been conducted. Through the dynamics of copper demand of each product category we can identify copper-containing products that will be interesting for future urban mining operations. Both approaches have been applied on the global level. Future research can enrich this study by adding information at a regional scale and looking into regional or national differences. General findings are discussed in the following subsections of this chapter.

4.1. Implications of scenarios

The five scenarios differ in the development of population, affluence, and in the uptake of renewable energy technologies. SSP3 and SSP5 are assuming a mainly fossil-based energy system, while SSP1, 2 and 4 include a significant amount of renewables. In the bottom-up method, this implies that copper demand will initially increase in SSP1, 2 and 4 to build up a more copper-intensive energy system. However, in the long run, the highest demand is projected for SSP5, due to its large increase in affluence. For SSP5, the future affluence is expected to grow 13 times the current size whereas the population grows only by 0.8%. Despite having the highest population, SSP3 is projected to have the lowest copper demand. This is because very low economic growth is expected for SSP3, showing the important role of affluence in the copper demand projections. The five scenarios predict a cumulative copper demand that would surpass the current global copper reserve. Moreover, based on the bottom-up projections, even with high recovery and recycling rates, the cumulative demand of copper would surpass the identified resources before the end of the century.

The top-down method with SSP5 projects 450 million tonnes of annual copper demand by the year 2100. This implies that 21% of the identified resources would be consumed in one year. Even with large scale new mine explorations and extensive urban mining activities, it would be unlikely that such an amount of copper would be available or could be supplied.

SSP1, 2, and 4 introduce various levels of low carbon technologies. The estimated copper demand for these technologies in 2100 in these three scenarios is quite consistent (100 ± 10 million tonnes) for the bottom-up method. However, the top-down method shows large variations. This mainly is the result of not including any technology specific detail in the regression analysis (recall that technology, *T* in IPAT, is in the regression constant). Large technological transitions, with large consequences for copper demand, therefore are out of the picture. The more distant the time horizon, the more likely it is that basic changes in society's metabolism may occur. Top-down methods cannot include such changes as they are based on past relationships. Bottom-up methods may be better, as they take into account a renewable energy system, but are unable to deal with unforeseen large changes as well.

In all scenarios, the identified resources of copper are exhausted before the end of the century, with higher recycling rates delaying the time when this milestone would be reached. These results agree with other research (Fellner et al., 2017) reporting that even if a circular economy is reached, the demand for primary resources can be significant in the present and near future. On the supply side risks, in order to assess when a raw material enters critical market condition, Rosenau-Tornow et al. (2009) developed indicators to better inform market players for their decision making.

It is important to mention that although new resources of copper are expected to be found before the identified resources are exhausted, the consumption of these resources would be linked with decreasing ore grades (Northey et al., 2014), use of less accessible mines, higher energy demand for metal extraction, and consequently, higher environmental impact (Norgate and Haque, 2010). In this context, trade-offs with other problems, such as climate change and fossil energy depletion should be considered and the substitution of copper for some applications should be evaluated.

4.2. Methodological comparison

Both methods show an increase of copper demand for 2100 compared to the present, by at least a factor of three. The bottom-up results are mutually quite consistent: they do not show extreme differences between the scenarios. Regression results show much higher variation, with a demand range of almost 400 million tonnes. Considering these scenarios are not predictions but explorations of potential futures, there is no way of "validation". Nevertheless, the projection from the top-down approach reaching a 450 million tonnes annual copper demand seems unrealistically high and may be incompatible with geological and technological possibilities, since the current identified resources are just under five times larger than that annual demand (U.S. Geological Survey, 2014). The only way in which this supply could be met would be by having copper cycle in fully closed, five year long loops. However, shorter lifecycles of copper stock would drive up demand even more, and although identified resources can still grow, as more sources of copper are discovered, easy sources of copper are being depleted, and ore grades are decreasing (Northey et al., 2014). Consequently, we consider that sufficing a demand of 450 million tonnes of copper in 2100 is infeasible.

An important difference between the two approaches is the driving forces behind the demand growth. Based on extrapolation of past trends, GDP is the major driving force in the top-down approach. However, the tight coupling between GDP and copper demand will probably not continue in the long term as stock saturation may occur with rising GDP/capita. Stock saturation is included in the bottom-up approach. On that basis, we conjecture that the top-down regression method seems suitable in the short term while the bottom-up stock dynamics method could give a more reliable picture in the long run.

Besides this, two other major differences have been observed, data intensity, and capacity of interpretation. The top-down method is simpler and requires less data. On the other hand, it does not provide mechanistic explanations like the bottom-up method does. The bottom-up method is more data-intensive, but at the same time, gives results that provide information about how demand develops per category, and sheds light on where policy measures should be focused to manage the future demand. Additionally, it has the potential to provide copper demand information with spatial resolution in different product categories. For example, household ownership of TVs is based on market research study from 68 countries, making it possible to compare copper demand for TVs per country.

4.3. Limitations

One of the limitations of our research is the lack of geographical detail in both methods. By leaving regional details out of the analysis, regional effects are averaged out. While in some places copper demand is still increasing due to buildup of infrastructure, for example in growing economies such as China and India, in other places where the infrastructure is already at a built up level (e.g. western Europe), copper demand could be trending towards a stable level. By collecting regional data, individual projections could be made that take into account regional characteristics and dynamics. This could improve estimates of future copper demand, while at the same time allows for a more targeted assessment of the copper cycle, including the options to move towards a circular economy.

A second limitation involves uncertainties due to unknown transitions (for example: future technologies). Currently, the energy production system is transitioning towards replacing fossil fuels in many countries. This has been included in our scenario analysis. Other innovations may have consequences for future copper demand as well, certainly in view of the very long time horizon. These have not been included and their effect on the copper demand therefore was not estimated.

A third point is that feedback loops between supply and demand have not been included in this study. Decreasing ore grades, uncertainty of supply, and overproduction result in price fluctuations. There is no consensus whether prices affect the use of resources. The impact that supply or prices might have on copper demand has not been considered.

4.4. Secondary copper supply

Given the results from the end-of-life copper calculations, can we reach a circular economy before the year 2100? To reach a circular economy, one vital prerequisite is that the stock of the material no longer grows. However in all investigated scenarios the demand for primary copper is still present, which means the copper stock would still be growing in 2100. Nevertheless, SSP1 and SSP4 in particular, show that their demand for primary copper is decreasing, and circular economy would be in reach. In both of these scenarios the drivers of copper demand are approaching stable levels, and consequently the stock of copper should stabilize as well. The recycling rate is another aspect of the discussion. In our calculation, an optimistic recycle rate of 90% is assumed, however, reaching such rates would be challenging. Material is lost throughout the phases of a products life, including the end of life phases and recycling. Current global recycling rates of copper are above 50% (Reck and Graedel, 2012; UNEP, 2011; Glöser et al., 2013), while higher rates have been achieved in Western Europe (Ciacci et al., 2017; Ruhrberg, 2006). Recycling rates of 70–90% are feasible; however, they would require significant changes in the way products are designed. Alloys and complexity of products make recycling of metals increasingly difficult. Designing products for recycling would help mind would help reach the rates needed for a circular economy (Exner et al., 2015).

4.5. Uncertainties

Uncertainties are inherent to any future projections, more so at longer timescales. In this study we have tried to control this factor by using different future development scenarios and being transparent about our assumptions. The top-down approach works by establishing a relationship between variables, while in the extrapolation part of the methodology this relationship is extended into the future. Thus we assume here that the correlation of the past is extended to the future, whilst it is uncertain and unlikely that the relationship between copper demand and the drivers such as population and GDP/capita will stay fixed in the future. Extrapolating a top-down method far into the future generally generates uncertain and to an extent meaningless results.

For the bottom-up method, the main concerns regarding uncertainty include the amount of data and their quality, and technological development of new applications. Vast amounts of data are required for the bottom-up method. Data such as stock size, copper content, lifespan, and the development trends of these specifications are required for each application. This data is not always of a high scientific source or available at the required timescale, in which case assumptions will have to fill the gaps, increasing the uncertainty of the method. Also technical development of new applications in the longer distant future cannot be foreseen.

5. Conclusion

In this research we employed and compared two methods to estimate future copper demand: A top-down, regression-based, and a bottom-up, stock-dynamics-based, method. The copper demand estimation for the year 2100 depended strongly on the method used, in particular for extreme scenarios and a long prediction time. The estimations resulted in a range of between 3 and 21 times the current copper demand; however it is highly unlikely the highest estimate could be supplied.

The scenarios' differences in terms of population, welfare and uptake of renewable energy technologies cause the differences in copper demand estimates. The top-down estimates were mainly driven by GDP growth, and therefore were particularly high for the SSP5 scenario, which resulted in the highest estimates, while the other scenarios resulted in copper demand estimates of between 3 to 10 times the current demand. The bottom-up approach, on the other hand, was driven mainly by the buildings and infrastructure sector, which included the additional burden of renewable energy systems.

In terms of the advantages and disadvantages of the methods, the top-down approach is simpler and requires less data, making it quicker and easier to apply. On the other hand, it does not provide mechanistic insight nor helps identify the key applications contributing to copper demand. Similarly, it does not allow the inclusion of technological developments, in particular the decoupling of GDP and copper demand, which could have a very significant effect during the next 100 years. In this light, top-down methods seem more suitable for short-term predictions in which technology is relatively constant, while long-term predictions require a bottom-up approach to allow for changes in the relationships between the variables. Furthermore, the bottom-up method, which is more data and time intensive, gives insight into the applications and sectors that are expected to contribute the most to copper demand, and can therefore help in the development of strategies and policies aimed at urban mining and circular economy.

Finally, we emphasize the role of such scenario analyses. The generated timelines until 2100 must in no way be interpreted as predictions or even forecasts. They should be interpreted as stories exploring the impacts of potential futures on copper demand. The value of this is that we see what relevant variables for copper use are, and where potential measures to improve society's copper metabolism might be taken.

Author contributions

The manuscript was written with equal contributions from Branco W. Schipper, Hsiu-Chuan Lin and Marco A. Meloni. All authors have given approval to the final version of the manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2018.01.004.

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