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Published Version:
Ciacci L., Fishman T., Elshkaki A., Graedel T.E., Vassura I., Passarini F. (2020). Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28. GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS, 63, 1-10 [10.1016/j.gloenvcha.2020.102093].

Availability:
This version is available at: https://hdl.handle.net/11585/779261 since: 2023-05-25

Published:

DOI: http://doi.org/10.1016/j.gloenvcha.2020.102093

Ciacci L.; Fishman T.; Elshkaki A.; Graedel T.E.; Vassura I.; Passarini F., Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28, «GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS», 2020, 63, Article number: 102093, pp. 1 – 10.

The final published version is available online at: **https://dx.doi.org/10.1016/j.gloenvcha.2020.102093**

Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28

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Abstract

Copper is widely used in modern technology, but declining ore grades and depletion of natural deposits have raised concerns regarding sustainable demand-supply balance in the long term. The vulnerability to primary copper supply restrictions amplifies for countries dependent on imports, notably many EU Member States. Recycling of post-consumer scrap can provide a valuable source of essential material to the European industry. However, a considerable fraction of collected and processed copper old scrap is exported, while the remaining fraction is either not recovered or lost due to nonfunctional recycling undermining the implementation of a circular economy. In this work, material flow analysis, regression analysis, and life cycle assessment are combined to explore the possible evolution of four scenarios of copper demand in Europe to year 2050 and the potentials for greenhouse gas emissions reduction under material circularity conditions.

The results show that for three of the four scenarios, secondary production would not comply with the carbon dioxide emissions reduction target of 50% below 2000 levels neither in case of combined aggressive recycling, moderate decarbonization of electricity, and energy efficiency improvements. In particular, for the scenario that describes a "business as usual" approach, the modelled future domestic demand can only be met by increasing primary inputs and, despite strong efforts to improve recycling at end-of-life, the fraction of old scrap in total metal demand seems likely to achieve 65% at best. Should that scenario ensue, the GHG emissions embodied in EU copper demand might result in an emissions gap of more than 15 $TgCO_2eq$ or about +260% the carbon dioxide reduction target. In contrast, the lowest environmental impacts are associated with a scenario emphasizing green technology and more equitable lifestyles. In that scenario, the secondary copper flows will gradually approach the expected demand, laying the foundation for achieving a circular economy with considerable potential for preserving natural capital and mitigating climate change. This possible future, however, requires dramatic changes in the current pattern of material production and consumption, as we discuss.

Keywords: Material flow analysis; Life cycle assessment; Sustainable Development Goals; Global Warming; Circular Economy; Scenario Analysis

1. Introduction

The industrial revolution, a turning point in human history, stimulated a transition to a new manufacturing system, based on extensive and easily accessible resources. The result was a progressive and unprecedented improvement in the quality of life and well-being. Such an industrial system has kept the characteristics of a linear model of resource consumption (also known as "take-make-dispose") ever since, although exhortations advising a more sustainable use of natural capital have arisen over time. In particular, the limits of a linear production-consumption pattern have become evident in recent years when demand for natural resources has raised severe concerns of long-term sustainability due to the continued growth of the world population and economic activities, the depletion of natural deposits (Northey et al., 2014; Vieira et al., 2012), and the scarcity of many elements employed in everyday applications (Allwood and Cullen, 2012; Ciacci et al., 2015).

In this context, the latest proposed strategy of long-term sustainability contrasts with the linear model by suggesting a more circular production and consumption pattern or a "circular economy". According to a typical definition, "a circular economy is an industrial system that is restorative or regenerative by intention and design" (Ellen Mac Arthur Foundation, 2013) in which the value and durability of products is maximised through circular design, inner material cycles, reuse, remanufacturing, recycling, and cascade uses of materials and energy. A considerable part of the current literature discussing the implementation of a circular economy approach, and the transition from a destructive to a regenerative industrial system has also gained interest in most of world regions (Su et al., 2013). In pursuing such a system, reusable and recyclable resources are expected to decrease natural resource inputs and reduce emissions levels and other environmental burdens associated with primary material processing.

Metals, in particular, are essential for the current technology and quantitative understanding of their life cycles lays the foundation to enhance recovery and circularity. However, end-of-life recycling is scarce to non-existent for many specialty and high-tech metals, and recycling efficiencies for base metals and precious metals are modest with global average rates no more than 50% in most cases (Reck and Graedel, 2012).

Of interest here, copper is an element that possesses two properties that could enable efficient recovery: it has a wide presence in modern society and has a relatively high economic value. Despite these attributes, dissipative uses and inefficient recycling amount to around one fourth of annual global primary copper inputs to metal production (Ciacci et al., 2016; Ciacci et al., 2015). By global production volume, copper is the third metal after iron and aluminium. It is widely used in many traditional applications including construction and infrastructure, but it is also a strategic material in emerging technologies such as wind generators and solar photovoltaics, which could drive copper demand in the coming years.

Recently, several studies have quantified possible future developments patterns of copper demand, recycling and associated environmental impacts at global level (Elshkaki et al., 2016; Elshkaki et al., 2018; Kosai and Yamasue, 2019; Kuipers et al., 2018; Voet et al., 2018). There is a general agreement that, should global copper demand keep growing at current rates, limitations and supply restrictions could arise and pose threat to long term sustainable demand and supply for the metal. This issue magnifies for countries with a copper import dependence like many European Member States (Passarini et al., 2018; Soulier et al., 2018).

Europe, indeed, is a significant example of a highly industrialized macro-region that depends on imports of primary copper forms to satisfy the domestic demand. The amount of secondary copper constitutes only about 40% of the metal demand in this region, a performance attributed to increasing copper use, long lifetimes of its applications, societal, technological and economic constraints, and export of copper old scrap to other countries, mainly China (Ciacci et al., 2017). Although the copper recycling industry is consolidated in the EU-28, the region is far from closing copper flows, and the improvement of efficiencies at end-of-life is extensively debated within the European copper industry (International Copper Study Group, 2010).

With the aim of turning waste into resources within the EU boundaries, the European Commission has adopted the "Circular Economy Package" (European Commission, 2017a). This ambitious action plan supports the closure of material cycles, the achievement of benefits for both the EU economy and the environment, and the realization of the UN sustainable development goals (SDGs) on production and consumption patterns (United Nations Environment Programme, 2019). Achieving a carbon neutral and circular economy is also part of the roadmap of policies and measures needed to foster the European Green Deal (European Commission, 2019a).

The European Commission has also identified a list of critical raw materials in which the dependency on imports is among the key indicators that determine the potential vulnerability of the region to supply risks (European Commission, 2017b). By volume, such a net import dependency primarily affects fossil fuels and metallic minerals (Haas et al., 2015). While a progressive shift towards renewable energy sources will likely reduce the import reliance on fossil resources from trade partners in favour of greener energy sources, the potential for the replacement or substitution of metals like copper is limited in most applications (Graedel et al., 2015). Moreover, although copper does not rank as a critical raw material for the EU, the anticipated global copper mine production peak (Northey et al., 2014) and decreasing copper ore grade (Vieira et al., 2012) could result in further constraints for primary metal supply to Europe in the next decades.

Notwithstanding the increased awareness about the universal efforts to securing access to copper sources and contrasting environmental pressures, little effort was devoted to prospects for sustainability at the regional level. Although the global analysis provides significant information, regional analysis considering current competition for metals resources (Gulley et al., 2018) may provide significantly different prospective for the aggregated demand and supply of metals and those related to specific sector and consequently the global environmental implications (Dong et al., 2019). In addition, intensive demand for copper, a non-self-sufficient supply chain, high dependence on imports of copper forms, and exports of copper old scrap at end-of-life make the EU a perfect case study to discuss the implications and hindrances to approach achieving circularity in the copper cycle. In particular, scenario analysis and forward-looking perspectives may provide guidance and sustain the progress towards resilience and environmental sustainability in the copper cycle as well as anticipate relevant changes in demand and supply dynamics to inform long term horizon criticality assessments (Schrijvers et al., 2020).

This paper intends to address this gap in the current literature. More specifically, we have evaluated the implications that could occur under more efficient closure of the copper cycle in the EU-28 by addressing the following questions: How could the demand for copper evolve in the coming years? What might be the maximum contribution of domestic recycling in satisfying such demand? What environmental benefits, in terms of GHG emissions reductions, could be derived from a near-perfect recycling of copper old scrap in the region? To answer these questions, we model four scenarios of copper demand in the EU-28 to year 2050 and compute the amount of scrap generated at end-of-life and available for recycling. The potential for reaching a circular economy for copper in the region is then explored by assuming aggressive recycling. Lastly, life cycle assessment (LCA) indicators are used to estimate GHG emissions reduction potential associated with domestic copper recycling in each scenario. We believe that the analysis described in this paper will contribute to the circular economy discussion and to strengthening guidance in regional climate mitigation strategies.

2. Material and methods

2.1 Dynamic modelling of future copper demand: rationale and limits

The system boundaries of our research are the EU-28, in order to support policy and decision-making within this (relatively) coherent socio-economic and political body. Since these system boundaries are administrative by nature, our results must be interpreted in context of the greater geographic and global economic trade systems.

The future of copper in the EU-28 was explored by building the foreseeable demand upon past trends. First, annual copper flows into use from 1960 to 2010 were estimated by means of material flow analysis (MFA) techniques. According to material flow accounting, the historical domestic production, imports and exports, and the apparent consumption (i.e., production + import – export) of copper within primary forms (e.g., ores, concentrates, refined metal) and within semi-finished and finished goods were identified and quantified. The total demand for copper was disaggregated into its major end-use application segments including building and construction, electrical and electronic products, industrial machinery and equipment, transportation equipment, and consumer and general goods using the MFA model described in (Ciacci et al., 2017) and subsequently further developed (Passarini et al., 2018; Soulier et al., 2018).

Next, time-series regression analysis was applied to estimate the historical copper flows into use for each end-use segment as a function of a set of explanatory variables that included population, Gross Domestic Product (GDP) (Binder et al., 2006), and the urbanization rate (defined as the percentage of total population living in urban areas). Details of the regression analyses are provided in the Supporting Information (SI).

Finally, a set of well-regarded scenarios for the explanatory variables from the present to 2050 was applied to the regression results so as to model four development paths for copper demand (see chapter S2 in the SI for more details). These scenarios (referred as “Major Metals [MM] scenarios” hereafter) constitute an enhanced version of the GEO-4 climate scenarios of the United Nations Environment Programme (United Nations Environment Programme, 2007) and have been previously utilized for major metals (Elshkaki et al., 2016; Elshkaki et al., 2018). In short, the four scenarios describe different narratives of future socio-economic, political, technological, and environmental priorities, and are titled the Markets Rule (MR) scenario, Toward Resilience (TR) scenario, Security Foremost (SF) scenario, and Toward Equitability (TE). Details about the scenarios are given in the SI.

The extension of copper flows to the future based on historical correlation trends embodies an implicit assumption of a certain technological and industrial invariance in the relations of copper and the explanatory variables over time. Our scenarios relate sectoral Cu demands to macroeconomic indicators rather than sector-specific mechanisms or phenomena, since these are relatively poorly understood and lack long-term data. For the sake of efficacy, this simplification provides a balance between representation of actual trends, modelling complexity, and the goals of this study.

In effect, we constrain our scenario results to a limited interpretation of the original scenario narratives by omitting potential changes to the past correlations. We believe that the approach is reasonable for copper. Beyond reasons of modelling and analytical parsimony, from the technological-industrial perspective copper has reached a consolidated industrial status in the region and process-related variables tend to change slowly, as with other major metals (Elshkaki et al., 2018). This is certainly the case with copper use in buildings, infrastructure, and industrial machinery, which have long in-use lives. Even with this potentially restrictive assumption, the results of the four scenarios are amply diverse due to the divergence of the trends of the explanatory variables in the four scenarios and thus are fitting for the objectives of this study. It is worth recalling that the MM scenarios describe plausible evolutions of societal and material demand-supply patterns. As with any other scenario, they should not be intended as accurate predictions, but rather as stories of possible futures that provide food for thought and a basis for further exploration, and our interpretations of the scenario results are conducted in this context.

2.2 Circularity potential in the copper cycle and embodied GHG emissions

In today' European Union, the end-of-life recycling rate for copper is of order 60% (Soulier et al., 2018; Passarini et al., 2018). Given the demand for copper in each major end-use application segment, the MFA model for copper stocks and flows in Europe was applied to quantify the expected amount of total scrap and waste (i.e., old scrap) generated at end-of-life to 2050. The sum of copper contained in these flows represents the theoretical maximum amount of secondary copper from domestic sources available for recycling and constitutes the potential amount to be exploited for the attainment of a circular economy for copper in the EU-28.

As socioeconomic conditions and technology have implications on climate change (Moss et al., 2010), LCA was combined with the elemental cycle information to generate first-order energy inputs and GHG emission reduction potentials. To this aim, GHG emission reduction potentials are computed as a result of (i) current end-of-life recycling rate of copper, and (ii) near-perfect recycling conditions (i.e., as a hypothetical combination of 90% collection rate and 90% recycling rate). A summary of LCA accounting procedures and assumptions follows below. A detailed description of the LCA model developed is provided in the chapter S4 of the SI.

The amount of energy required per unit of copper was determined for primary production and secondary production. From fabrication onwards, additional energy requirements are considered to be the same per unit of copper for both primary and secondary sources.

For primary copper production, energy requirements are computed as function of primary energy and final energy inputs to mining (drilling, blasting, and hauling), mineral processing (crushing, grinding and beneficiation), metal extraction (smelting) and refining. Global and European specific mix of process alternatives (i.e., reverberatory furnace, flash smelting furnace, other pyrometallurgical processes, solvent extraction and electrowinning) were considered to enable a representative modelling of primary copper production. The partitioning between copper domestic supply and imports from foreign countries was determined by the MFA model. For the transition to 2050, the energy required for mining and mineral processing was modelled according to the relations between the metallurgical process, ore grade, and the cumulative copper production previously described (Mudd et al., 2013; Norgate and Jahanshahi, 2011; Schodde, 2010), and aligned to global estimates (Elshkaki et al., 2016). The energy required for metal extraction and processing is assumed to remain constant, as the declining ore grade is unlikely to affect smelting and refining processes (United Nations Environment Programme, 2013). In a second run of the assessment, the sensitivity of the model was tested by assuming an improvement in energy efficiency of 30% as the midpoint value among the potential energy savings in copper production resulting from best practices implementation (Norgate and Haque, 2010). The same assumption was also adopted in (Elshkaki et al., 2016).

For secondary copper production, the total energy required depended upon scrap quality and the resulting partitioning between scrap use by fabricators for direct melting and for secondary cathode production as dictated by the MFA model. Direct melting of copper old scrap includes the energy required to collect and sort, and prepare end-of-life products plus energy inputs for melting and the energy penalty associated with primary copper input for diluting purposes. Indeed, the presence of impurities and tramp elements may prevent the complete utilization of copper scrap for new products manufacturing, thus requiring inputs of virgin material to adjust the metal composition within the limits of a given specification (Muchova et al., 2011). For secondary cathode production, energy inputs include those for collecting, sorting, and separating copper from obsolete products at end-of-life as well as the energy demanded for smelting and refining.

The energy inputs associated with direct melting and secondary cathode production are modelled to remain constant to 2050. It may be questioned if this assumption is reasonable, especially in case of aggressive recycling. Indeed, the closer material recovery efficiency approaches 100%, the greater the required energy inputs (Norgate, 2004), with the latter ones that may eventually exceed the overall energy demand for primary production (Schäfer and Schmidt, 2020). However, the additional energy requirements needed to enhance copper recovery were here assumed to be offset partially or entirely by the adoption of design for resource efficiency practices (e.g., eco-design, design for recycling, for disassembly, and similar procedures) as well as by shifting from obsolete technologies for copper scrap to best available techniques (BATs), in accordance with the principles of the circular economy perspective discussed in this work. Implementation of BATs and design for resource efficiency practices are not discussed further here but are assumed to occur similarly in all scenarios.

A first-order estimate of the potential energy-related GHG emissions is quantified using carbon intensity factors by primary and final energy (International Energy Agency, 2012). For primary energy, carbon intensity factors are listed in Table S4 and are assumed to remain constant to 2050. For final energy, the carbon intensity is computed as function of the electricity production mix for Europe and the world. The evolution of carbon intensity per unit of final energy was extrapolated to 2050 from the projections of the International Energy Agency (IEA) (International Energy Agency, 2012) and according to a correspondence between the IEA scenarios and the MM scenarios (Table S5-S11).

Total GHG emissions associated to each scenario were computed as the sum of primary and secondary production emissions according to the "recycled content" (or the "cut-off") approach and compliant with the ISO 14040 and 14044 standards (ISO, 2016; ISO, 2018). The recycled content approach is based on the share of recycled material (copper) in the manufacturing phase and it accounts for the environmental impacts (GHG emissions) at the time they occur, giving no credit to recycling for avoided primary metal production (Frischknecht, 2010). In this study, the share of recycled copper is dynamic over the time span of investigation as determined by scenario evolution.

3. Results

Figure 1 displays the historical demand for copper in the EU (1960-2010), followed by the copper demand to 2050 resulting from the four scenarios. In absolute terms, the cumulative demand for copper follows the order MR > SF > TR > TE. However, while MR and TE are extreme scenarios, the TR and SF scenarios model intermediate trends that cross around 2040 and reverse the order, based on changes in the underlying socioeconomic trends in those scenarios. The use of copper in construction activities covers about half of the total demand projected, followed by electrical and electronic products, industrial machinery and equipment, transportation equipment, consumer and general goods (Figures S1-S6 in the SI).

In Figure 2, the total amount of copper demanded by each scenario is compared with the estimate of the total scrap generated at end-of-life, computed as sum of copper outflows from use for each application sector considered in the analysis. For two of the scenarios (i.e., MR and TR), the modelled future domestic demand can only be met by increasing primary inputs because of the expected increase in the copper flow into use and the delay in the generation of secondary copper scrap. For the SF scenario and, more specifically, the TE scenario the secondary copper flows will gradually approach the expected demand, laying the foundation for achieving a circular economy in which the natural capital is preserved.

The hypothetical transition to a near-perfect end-of-life recycling system is explored in Figure 3, in which the generation of old scrap (Figure 2) determines the locus of old scrap supply from 2010 (left on Figure 3) to 2050 (right). For each scenario, several contour lines are drawn, the colors identifying the fraction of copper old scrap supply in the total metal demand in the EU-28 (hereafter referred to old scrap supply ratio, OSS) from the scenario calculations. At high recycling rates (upper part of the vertical axis) more old scrap is available to offset the need for newly-mined metal. In the Toward Equitability results (lower right diagram), the region of very high old scrap supply begins shortly after 2020 if recycling rates are high and maintains that performance by mid-century even for recycling rates in the low 70s%. From the perspective of the circular economy, the contour areas provide a measure of the degree to which domestic old scrap can satisfy the domestic demand according to different recycling performance.

It is worth noting that the OSS does not measure the share of secondary scrap in the total metal input to metal production. To this aim, more suitable indicators have been proposed (e.g., recycled content used in combination with old scrap ratio as defined by the United Nations Environment Programme (United Nations Environment Programme, 2011b)), and other metrics have been defined to measure the circularity of resources (Elia et al., 2017; Franklin-Johnson et al., 2016; Haas et al., 2015; Moriguchi, 2007). Recycled content has been quantified for many metals at the global level, but a straightforward application at the country level is difficult to impossible because there are no official statistics on what amount of traded goods arises from primary or from secondary sources.

From the perspective of the circular economy, OSS provides a measure of the degree to which domestic old scrap can satisfy domestic demand according to different end-of-life recycling rates. For the MR scenario, the expected demand for copper in the region leads OSS to slightly increase, with a maximum of 65% only achievable by aggressive recycling in 2050. Should the end-of-life recycling rate of copper remain at current levels, the OSS is estimated to consolidate at values between 40% and 50%. I.e., in a MR world, the amount of old scrap domestically supplied would meet only half of the expected demand in the region, which would still mainly rely on primary sources. In the TR scenario, the contour plot shows a peak in the estimated OSS that might cover up to about 65-70% of the domestic copper demand in case of near-perfect recycling conditions around 2030. After 2040, the OSS is expected to decrease at 60-65% at best because of delay of scrap generation. If the end-of-life recycling rate of copper remained at current levels, the domestic old scrap supply would very likely satisfy less than 50% of the predicted demand. In the SF scenario, the modelled decrease in the total copper demand in the region leads OSS to 50-55% already after 2030 at current recycling levels. Ideally, an extensive implementation of BATs to reach near-perfect recycling in EU is estimated to take the OSS up to 75% after 2030 in the SF scenario. The TE scenario is even faster in improving OSS values at constant end-of-life recycling rates, with increment in OSS to 45-50% and 50-55% occurring about a decade earlier than in SF. As dictated by contour lines, should periodic improvements of end-of-life recycling rate be achieved, approaching near-perfect recycling conditions would drive OSS almost linearly up to 75%.

Figure 4 shows total greenhouse gas emissions by process (i.e., domestic extraction, import, direct melting and secondary cathodes production) resulting from stationary copper recycling conditions (Figure 4a) and near-perfect recycling conditions (Figure 4b) in Europe in 2050. By scenario, MR and TE are the two extreme cases, in which total EU demand for copper would embody between 14.9–21.3 TgCO_2eq and 2.9–4.7 TgCO_2eq respectively. The dynamics of copper demand and supply combined with the scenario projections of energy production mix result in similar outcomes for GHG emissions in the TR and SF scenarios. The transition towards renewable energy sources modelled in TR results in lower carbon intensity per unit of energy generated, with associated decreased GHG emissions compared with SF (Figure 4a). However, at near-perfect recycling conditions (Figure 4b), the modelled decrease in copper demand counteracts the effect of carbon intensity and results in a slight advantage for the SF scenario.

By process, Figure 4a attributes the greatest GHG emissions contribution to copper imports (84% in MR, 80% in TR, 70% in SF, and 56% in TE). Secondary cathodes production, domestic extraction, and direct melting follow. The effect of reducing copper demand and of increasing copper recycling is seen in Figure 4b. In this case, the import of copper remains the main process that contributes to the total carbon emissions profile in MR (72%), TR (61%), and SF (50%) scenarios, whereas it results to be almost negligible in TE (11%). In this scenario, secondary cathodes production becomes the main process contributing to GHG emissions release (72% of the total).

Finally, Figure 5 compares total GHG emissions embodied in copper demand in the EU-28 in 2050 for each scenario in the case of current recycling conditions and near-perfect recycling conditions, and whether potential energy savings are implemented or not. The results are then compared to the policy proposal of a reduction of 50% of GHG emissions below 2000 levels, established as a target to help minimize the global average temperature increase (Fischer and Nakicenovic, 2007). To this aim, the consumption-based accounting convention was preferred to measure the embodied GHG emissions in copper flow into use in the EU-28. More precisely, total CO_2eq emissions are computed as the sum of GHG emissions associated with primary and secondary copper supplied domestically (as dictated by scenario storylines), plus net-import of copper to meet the total demand. Therefore, the emissions estimated here (i.e., 8.0 TgCO_2eq in 2010) will not be those occurring within the EU-28 boundaries and reported to GHG inventories by data production-based accounting (i.e., 4.5 TgCO_2eq in 2010 (Eurometaux, 2020)). As a result, the total demand for copper in the EU-28 was about 4,800 Gg Cu in 2000. Assuming that all sectors contribute proportionally to the 2°C target, the limit for annual GHG emissions associated with copper demand (i.e., inflow to use) in the EU-28 would amount to ~6 TgCO_2eq (see the section S4.3 in the Supporting Information for more details).

4. Discussion

The results of this study are consistent with global outcomes from earlier copper scenarios studies (Elshkaki et al., 2016; Elshkaki et al., 2018; Kuipers et al., 2018; Voet et al., 2018) and show how deeply the production-consumption models of modern society influence the demand for resources. However, while at the global level TE was the scenario with the highest copper demand (Elshkaki et al., 2016), for the EU-28 the TE scenario models the greatest transition towards dematerialization.

The EU-28 has strong industrial capacity but depends predominantly on imports of primary resources. As a result, if the mineral industry is unable to meet the expected resource demand, Europe could struggle to secure an adequate supply of copper for domestic industries. Our results show that secondary copper sources can cover a substantial part of the domestic demand if recycling rates and the recycling industry itself are suitably enhanced. Currently, the fraction of copper old scrap in total metal demand is around 40%. Depending on the future evolution of development patterns, the OSS might remain stationary, especially if the world remains driven by market-forces. MR and, to a lesser extent, TR are scenarios that would require strong efforts to improve the current OSS but seem likely to achieve 65% at best. In the other scenarios, even small improvements in end-of-life recycling efficiencies could benefit OSS considerably.

Beyond the challenge of satisfying future metal demand, the copper industry is required to reduce GHG emissions. Reducing the energy required for metal extraction and refining to approach more closely to the thermodynamic limit can mitigate GHG emissions associated with primary copper production. International benchmarks estimated the energy use for copper smelting in 7.4 MJ/kg Cu (Saygin et al., 2010), while the theoretical minimum energy required for copper production from concentrates to the metallic state is 2.1 MJ/kg Cu (Gupta, 2003). Actual energy requirements depend on the processing route and smelting efficiency so that variations may occur from plant to plant. According to Kulczycka et al. (2016), more than 70% of total copper processed in Europe is refined in plants equipped with BATs. This approach provides much better performance than occurs in the rest of the world and indicates that only moderate efforts are required to reach full BATs implementation in Europe. Furthermore, the decarbonization of electricity generation (European Commission, 2020) will enhance the environmental performance of Cu processing, particularly should the expected ore grade decrease occur.

Old scrap input can significantly reduce the total emissions associated with metal production (Gutowski et al., 2012; Liu et al., 2013), as Figure 4 and Figure 5 reveal. In 2010, the total GHG emissions attributed to copper demand in the EU-28 were about 36% greater than the emission cut target below 2000 levels. The modelled increase in GHG emissions associated with the MR scenario is so dramatic that the carbon dioxide embodied in EU copper demand in 2050 might result in an emissions gap of more than 15 $TgCO_2eq$ or about +260% the GHG emissions reduction target, should that scenario ensue (Table 1). Indicatively, the potential energy savings achievable by implementing best practices in copper production may reduce the emission gap to 10 TgCO2eq (+153%) or to 6 $TgCO_2eq$ (+98%) if combined to aggressive copper old scrap recycling. Although such an emissions reduction gap does not represent a specific climate mitigation pathway, a world that follows the dynamics as described by the MR scenario will fail to effectively address climate change even under hypothetical near-perfect recycling conditions. In the case of a more equitable world (i.e., the TE scenario) secondary copper sources could play a primary role in achieving the CO_2 target even at current recycling conditions, whereas for the other scenarios secondary copper production would likely not comply with the target neither in case of combined aggressive recycling, moderate decarbonization of electricity, and energy efficiency improvements.

The values shown in Figure 5 assume that net-import of copper derives from primary sources only. In some cases, recycled forms may replace virgin copper in production routines. However, the inclusion of the stationary global end-of-life recycling input rate would result in only marginal improvements (Table S17 in the Supporting Information). It is worth noting, however, that these results are first-order estimates and do not capture the geographical variability of national environmental profiles in the copper supply chain, which may ultimately influence the GHG emissions embodied in copper demand in the EU-28. More integrative research in this direction is needed, particularly for determining the distribution of GHG emissions reductions associated with shifting to more secondary sources of copper throughout its value chain.

The results of this study confirm that recycling can be a significant factor in reducing primary material demand and the related environmental impacts, but how feasible is it to improve current Cu recycling to near-perfect levels? The answer to this question depends on the potential for overcoming the issues that limit the closure of the Cu cycle.

The European Commission is putting great emphasis on circular economy aspects and the Circular Economy Action Plan (CEAP) recently implemented is expected to pave the road towards sustainability in products life cycle and promoting policy tools for a systemic approach across material cycles (European Commission, 2019b). The European Commission mainstreamed reuse and recycling at the center of its initiatives and strategies aiming at turning waste into valuable resources while securing access to raw materials strategic to its development. Therefore, in light of the wide use of copper in traditional as well as novel technology, the expected achievements of a region-wide transition to circular economy regulations and practices may have relevant implications across the entire value chain of copper and its products.

The design phase plays an essential role to minimizing resource use and improving feedback material loops through lifetime extension strategies including durability, reusability, reparability, remanufacturing potential, and recyclability, with these circularity criteria being largely determined in the conceptualization and manufacturing of materials and products. Addressing material circularity and environmental sustainability in the design of products means also to pursue light-weighting of products and more intensive use of products through, for instance, sharing practices and collaborative consumption. For base metals like copper, transportation, building and construction, electrical and electronic equipment are likely the end-use sectors to be affected the most by material efficiency strategies (Hertwich et al., 2019).

The ecodesign directive and energy-labelling regulation (European Commission, 2016) have addressed resource efficiency for energy-related products and are now under consideration to expand requirements to non-energy related product categories. Considering the employment of copper products in both groups, positive effects may result from future product requirements, particularly should these regulations claim for product quality standards and recycled contents for individual materials in new products manufacture. Such material requirements would reduce the related environmental impacts, protect the natural capital and likely boost the creation of markets for secondary materials if dedicated take-back schemes are implemented. To this aim, further momentum may also derive from improved knowledge on and access to data on secondary raw materials through quantitative assessments like that developed in the Raw Materials Information System (European Commission, 2020; Passarini et al., 2018).

Next, improving yield in production, manufacturing and end-of-life management have considerable potential for increasing efficiency in material cycles. These transitions, however, strive against the inertia of adapting established industry practices to new models. Circularity aspects on material use and waste prevention are addressed in BATs reference documents that provide standards on several resources, including non-ferrous metals, to the Member States. Similarly, the EU platform Information for Recyclers (European Union, 2020) is a relevant means to collect and share knowledge on new technologies about preparation for reuse and treatment of electronic waste.

Increased quality of copper scrap, as demonstrated by the results of this study, may enhance direct melting opportunities with substantial benefits for the environment. Limiting the number of alloying elements, scrap grade identification procedures, and the development of scrap-sorting by alloy type techniques may also translate ecodesign practices into increased material recovery and functional recycling (i.e., a recycling that preserves the intrinsic properties of elements in new products). There is quite consensus that these approaches are essential conditions to improve metal recycling, but also that would require significant effort if they are to change (Ohno et al., 2015; Ohno et al., 2016).

It is important to recognize that improving the current collection and separation of copper old scrap is not sufficient to guarantee recycling to occur, because an enhanced recycling industry must also be pursued. We note that current smelting production in the EU-28 is close to the installed capacity and expansion of the existing secondary copper production capacity is not expected in the region (Risopatron, 2017). In addition, a considerable fraction of copper old scrap is exported from the EU-28 to China, further reducing the amount of this metal available for domestic recycling. Similarly, although the great emphasis on material efficiency strategies, ecodesign regulations, and high standards technology requirements in the CEAP and related documents, a main limitation to the efficacy of material efficiency and ecodesign strategies may result from the globalized condition of modern production chains and the shift often occurring between the location of goods' production and that of consumption and management at end-of-life. With a considerable fraction of semi-finished and finished products used in the EU-28 being actually manufactured outside the regional boundaries, the road towards a closure of the copper cycle in the EU-28 seems quite steep at present.

In any case, as shown by the MM scenarios results, these aims should be accomplished together with a constrained growth in material resource use. As long as the copper demand increases, the benefits of recycling are likely to be obscured by the impacts of supplying virgin metal input (Ali et al., 2017). Such a goal may be achieved through the pursuit of a society based on material efficiency (Pauliuk and Müller, 2014; United Nations Environment Programme, 2011a, 2014), (e.g., providing increased services and goods while reducing the amounts of resources utilized (Allwood et al., 2010; Meinert et al., 2016)).

Policy initiatives and cultural changes may have the greatest effect in reducing progressively the individual demand for copper-containing products. The CEAP points increased information on supply chains of products and companies through reproducible and comparable methods based on LCA techniques (e.g., product environmental footprint), artificial intelligence and digitalization as means to change effectively consumers' behaviors and drive them to responsible choices towards sustainability and circularity. In addition, dedicated regulation should also focus on hibernating stock of products, the missing collection of which does not necessarily imply to a reduction in the demand for new goods (Hertwich et al., 2019).

Further options for reducing the demand for copper are promising if the use of alternative materials in certain applications is increased to higher levels. A massive replacement of copper with substitutes in its main end-use segments is still limited today, but the expansion of aluminum wires, fiber optic cables and graphene-based systems are envisaged to change traditional material requirements in power generation, network infrastructure and appliances (European Commission, 2017c).

Eventually, reducing environmental impacts and improving the conservation of natural sources are primary motivations for approach achieving a circular economy (Graedel et al., 2019). Although the geographical dimension of a circular economy dimension is still debated (Lane, 2014; Gregson et al., 2015), the implications of policies and strategies addressing circularity in resources production and consumption become effective in the regional scale they are adopted. The EU has been particularly active in promoting the transition to the circular economy to reduce its reliance on primary raw materials and imports thereof. This study, however, shows the difficulty of pursuing the principles of a circular economy even in systems in which a consolidated manufacturing and recycling industry has been reached and in which the transition towards a closure of material resource flows is underway.

A global vision is needed to avoid reduction of the potential environmental and social benefits once materials and products are traded and barriers to recycling raise. A need for international standards and harmonization is particularly compelling for materials whose supply chain is fragmented in different countries and articulated on several tiers and stakeholders. In the case of copper, increasing the use of secondary sources would certainly improve the domestic material circularity and reduce pressure on the environment, but it might also impact the ability of trade partners exporting primary copper forms to the EU-28 to reach sustainable development pathways. On the other hand, the export of end-of-life products to foreign markets may translate into valuable resources for those countries only if waste quality standards are satisfied and adequate processing capability is in play. (Kettunen et al., 2019)

We recognize that the concept of circular economy has taken on global importance and the proposed study, which adopts a Euro-centric vision, is not intended to simplify a complex problem with trade off or problem shifting that dictates the global sustainability agenda. However, even the theoretical and limited assessment provided may offer a perspective on the future challenges that lie ahead.

5. Conclusions

To our knowledge, the results of this study present the first overarching analysis of possible scenarios for copper demand, supply, and associated carbon emissions profile at the EU-28 level. The assessment of environmental implications can usefully inform policymakers and actors involved in copper recycling. Furthermore, the outcomes can be used as benchmarks for future researches from the perspective of the metal-energy-climate change nexus. Copper is utilized in conventional as well as renewable energy technology, transportation, and housing, but primary copper supply disruption can prevent the EU-28 from accessing a material essential for low-carbon energy technology. In this context, recycling of copper old scrap can satisfy a portion of that demand.

Future research to provide more spatial and temporal detail and accuracy to the historical data that drives our assessment would reduce uncertainty in the underlying assumptions. Similarly, plausible scenarios for future copper production and consumption patterns other than those explored in this work might provide other strategies for the reduction of associated GHG emissions. However, we believe that focused attention should rather be given to enhancing recycling end-of-life flows. This transition, however, requires a dramatic change in current patterns of material production and consumption and is unlikely to occur without a systems perspective supported by effective actions by all the stakeholders involved.

Competing financial interests

The authors declare no competing financial interests.

Tables

Table 1. Greenhouse gas emissions gap embodied in copper demand in the EU-28 in 2050 as percent increase from the 50% cut target below 2000 levels. MR – Market Rules; TR – Toward Resilience; SF – Security Foremost; TE – Toward Equitability.

	MR	**TR**	**SF**	**TE**
Current recycling	259%	130%	133%	-20%
Current recycling*	168%	75%	79%	-34%
Near-perfect recycling	153%	54%	36%	-50%
Near-perfect recycling*	98%	26%	16%	-52%

*With 30% energy improvements in Cu production.

Figures

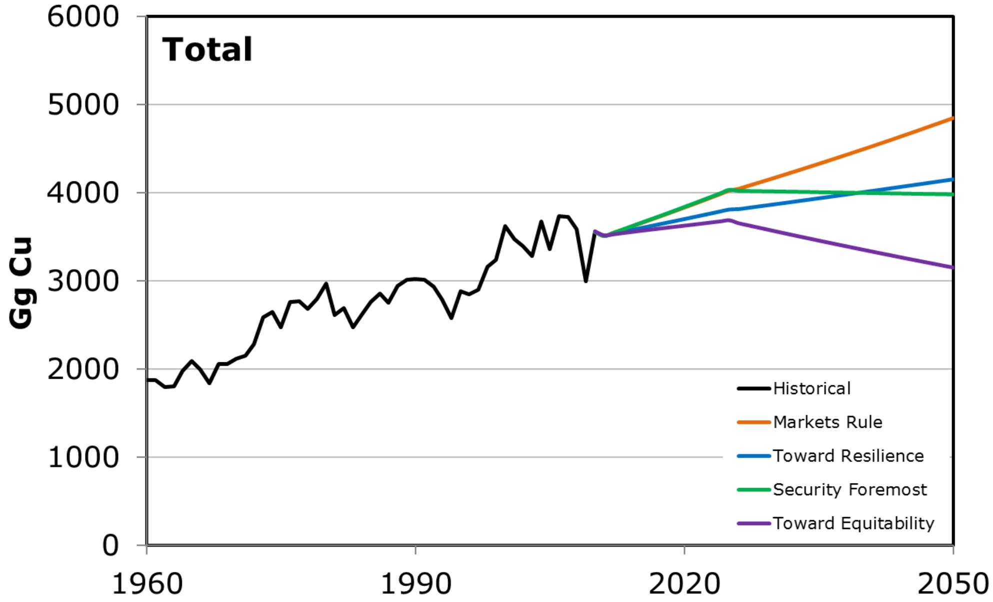


Figure 1. Total copper demand in the EU for 1960-2014 (black line) and projections to 2050 as simulated by the MM scenarios.

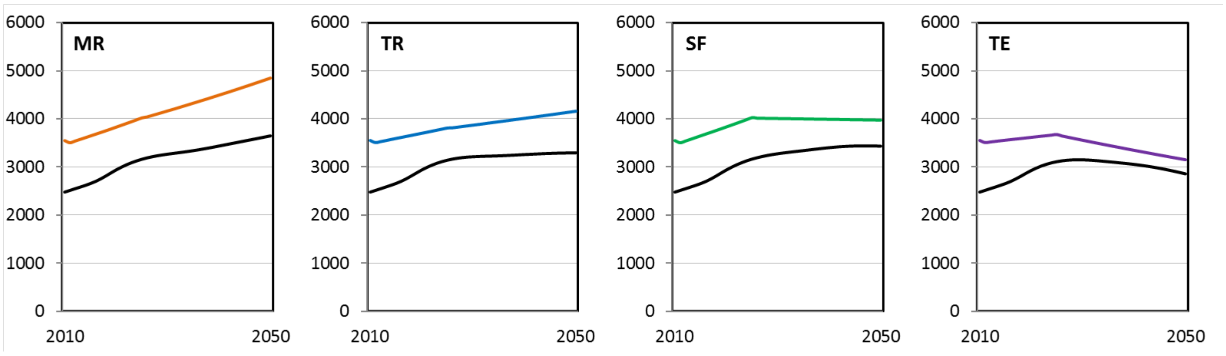


Figure 2. Total Cu demand (colored lines) and generation of old Cu scrap (in black) as estimated by the MM scenarios. Values in Gg of copper. MR – Markets Rule; TR – Toward Resilience; SF – Security Foremost; TE – Toward Equitability.

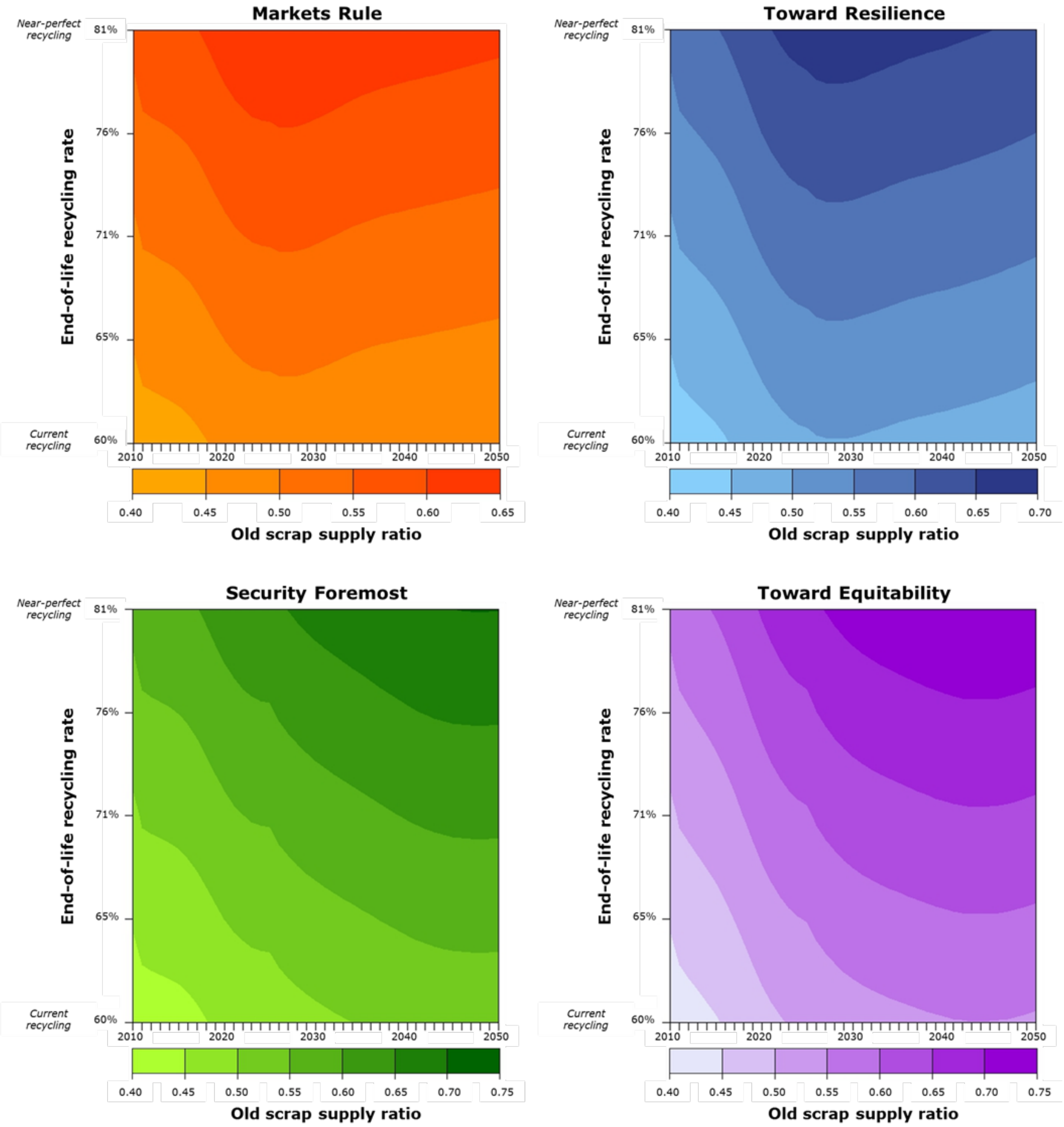
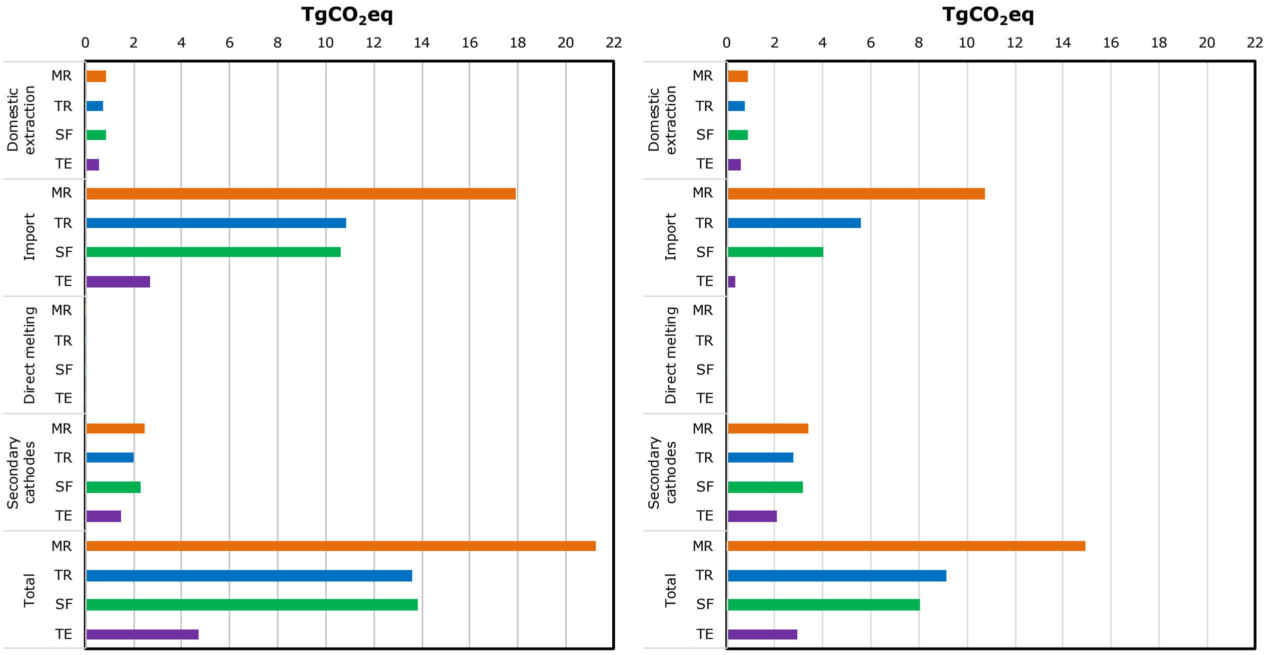


Figure 3. The theoretical fraction of old Cu scrap supply in the total metal demand in the EU-28 as a function of end-of-life recycling rates from 2015 to 2050.



(a)

(b)

Figure 4. Process contribution to total carbon profile by scenario for (a) current recycling conditions and (b) near-perfect recycling conditions in the EU-28.

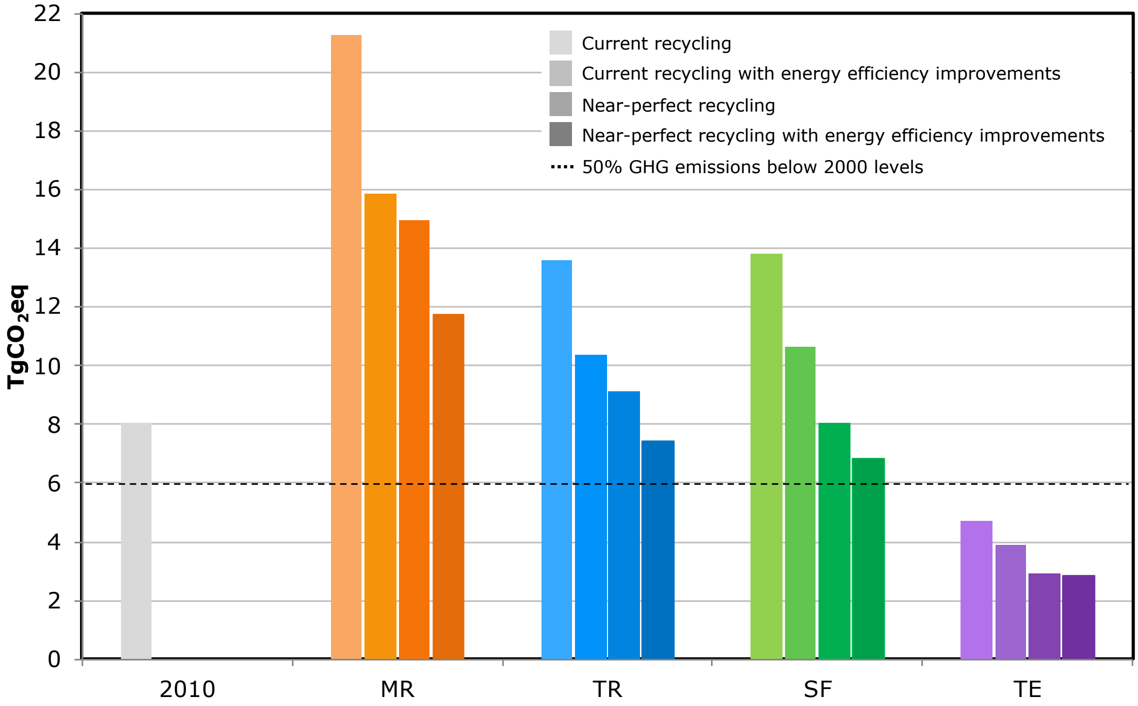


Figure 5. First-order estimates of total GHG emissions embodied in copper demand in the EU-28 in 2050. For each scenario, different recycling conditions and energy efficiency improvements are compared. The dotted line indicates 50% reduction of GHG emissions below 2000 levels as required by the 2 °C target. MR – Markets Rule; TR – Toward Resilience; SF – Security Foremost; TE – Toward Equitability.

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Supporting Information

Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28

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S1. Dynamic MFA of the anthropogenic copper cycle in the EU

This section provides a concise description of the material flow analysis (MFA) model developed to characterize the European copper (Cu) cycle (Ciacci et al., 2017). Compared to that version, in the MFA model utilized here Fabrication and Manufacturing efficiency, including new scrap generation rates, were subsequently further developed (Passarini et al., 2018; Soulier et al., 2018).

For each main phase and covered process of the Cu cycle, the model accounted for inflows and outflows, including process efficiencies and losses. A top-down approach was then followed to determine the Cu flow into use and net addition to in-use stock from 1960 to 2010. This approach considered the apparent consumption (i.e., production + import – export) of Cu within primary forms (e.g., ores, concentrates, refined metal) and within semi-finished and finished goods. Extensive data collection was required to get historical information on production and trade of Cu-containing commodities. In particular, metal statistics yearbooks provided annual data on mining, smelting and refining production volumes, while European trade records were obtained from the United Nations Commodity Trade Statistics database (United Nations, 2019). Data collection was extended to include Cu losses from each life cycle stage, including recycling rates. Given the amount of Cu demanded by each application segment and the related lifespan of products in use, the generation of post-consumer Cu waste and scrap was simulated by using statistical distributions. The model estimates for secondary Cu supply fed to domestic recycling were reconciled with historic records for secondary Cu cathode production and for direct Cu melting by fabricators by means of a scrap balance approach. The conservation of mass performed for each year of the analysis has thereby provided an estimate of the cumulative Cu in-use stock.

The results showed that copper demand in the EU nearly doubled from 1960 to the years before the financial crisis in 2009, increasing from ~1,800 Gg Cu to about 3,500 Gg Cu. A large fraction of the copper entering the use phase is imported from external countries as the domestic natural Cu reserves are not sufficient to meet the EU demand. The size of the current Cu in-use stock was estimated at about 160 kg Cu/person. Secondary copper is supplied through recycling of fabrication and manufacturing scrap (i.e., “new scrap”) and obsolete products containing copper discarded at end-of-life (i.e., “old scrap”). The end-of-life recycling rate for Cu in the EU was quantified at 60%, with the remaining fraction being not-recovered or lost through non-functional recycling. In addition, about 30% of the secondary Cu available for recycling was exported to Asian countries. Thus, compared to the total old Cu scrap generated, the Cu flow to domestic recycling was considerably reduced and represented less than 40% of the total fabrication input.

Further details on the material flow accounting procedure, data sources, and complementary results of the study are given in (Ciacci et al., 2017).

S2. The Major Metals scenario storylines

This section provides a description of the Major Metals (MM) scenario storylines. More details can be found in (Elshkaki et al., 2016; Elshkaki et al., 2018).

Market Rules **(MR)**

The Foundational Story: The central element of this scenario is the emphasis placed on economic investment and expanded trade to deliver economic, social, and environmental advances. The private sector will increasingly assume roles previously taken by governments. International trade will rapidly increase to enable the widespread use of resources whose deposits are not evenly distributed on a geographical basis.

In the case of energy, which is of course the enabler of a Market Rules, use will increase and fossil fuels will continue to dominate energy generation. Attention to global change and to other environmental protection initiatives will be limited, and equivalent emissions will increase significantly.

The Concomitant Resources Perspective: The MR scenario is consistent with a world in which per capita resource use continues to increase toward at least the levels common today in the more developed countries. The historical rates of principal uses of metals and minerals are therefore the principal driving factors of the resource scenarios. This MR scenario and the other scenarios implicitly assume that no major changes occur in today’s technologies; that is, there will be no significant levels of substitution of other materials for the present materials in their principal uses. While such an assumption is perhaps problematic for advanced technologies based on scarce materials (solar power, medical imaging, electronics, etc.), the assumption appears reasonable for development centred on infrastructure, construction, and transportation, because those sectors will constrain the materials choices to the abundant metals and materials that we address in our scenarios. These technologies are deeply embedded worldwide and very few alternative materials could be made available in the quantities required.

Toward Resilience **(TR)**

The Foundational Story: The central element of this scenario is a transition to a world of highly centralized approaches to balancing economic growth with enabling social and environmental advances. Climate change and enhanced agriculture decrease biodiversity and impact freshwater availability. Food demand causes increased marine fishing activity, and fish catches move down the food chain. Notwithstanding the goals of the governments, energy demand continues to increase, and oil and gas continue to dominate fuel supplies.

In the case of energy, a strong focus on green energy will emerge. The attention to global change and to other environmental protection initiatives will result in enhanced use of solar power, wave power, and other renewable energy sources.

The Concomitant Resources Perspective: For the major metals and construction minerals, the desire for economic growth will result in little change in per capita demand. Uses shift to some degree to favour demand related to renewable energy technologies, such as copper and aluminium for enhance grid energy distribution and iron and zinc for upgraded energy infrastructures.

Security Foremost **(SF)**

The Foundational Story: The central element of this scenario is the emphasis placed on security, which consistently overshadows other values. Conflict continues in many parts of the world. Increased restrictions on migration reduce the movement of people, and the extension of trade barriers limit the movement of goods across borders. Environmental governance and education (especially female education) are given low priority.

The Concomitant Resources Perspective: Expenditures on security grow at the expense of other investments, thus implying a transition in the ways in which major resources are employed. Infrastructure development and maintenance takes a back seat to investments in border control and military defence. Energy use per capita continues in areas with rich fossil fuel reserves but decreases in areas without such resources.

Toward Equitability **(TE)**

The Foundational Story: The central element of this scenario is that actors at all levels – local, national, regional, and international - and from all sectors, including government, private, and civil – act to support the UNEP Sustainable Development Goals and to gradually evolve so as to deliver economic, social, and environmental advances to all in an equitable manner. Social and environmental concerns become primary foci, and housing and energy availability become generally available.

The Concomitant Resources Perspective: With increased urbanism and enhanced infrastructure and housing, demands for material resources generally exceed those for the MR scenario. Energy demand increases sharply as well but is increasingly met by green energy technologies.

S3. Regression analysis results

Future total Cu demand and Cu demand in its major application segments for the four scenarios is modelled using regression analysis. At the first step, coefficients of the relationships between historical Cu demand and explanatory variables were estimated with the following time-series model:

$$Cu_{i,t} = \beta_1 pop_t + \beta_2 gdpcap_t + \beta_3 urb_t + AR_t \qquad \text{(eq. S1)}$$

Where $Cu_{i,t}$ is the Cu demand in year t of application sector i (total demand, Buildings and construction, Electrical and electronic products, Industrial machinery and equipment, Transportation equipment, Consumer and general goods); pop_t is the population in year t, $gdpcap_t$ is the per-capita GDP in year t, urb_t is the urbanization rate in year t. β are the coefficients to be estimated. AR_t is an autoregression error term included to correct for serial correlation with the following formulation (Hyndman and Athanasopoulos, 2019):

$$AR_t = \phi \, AR_{t-1} + z_t \qquad \text{(eq. S2)}$$

Where ϕ is the autoregression coefficient to be estimated, and z_t is the residual unexplained random error. This model specification ensures that the interpretation of the estimated β coefficients is unconditional on the value of previous values of Cu_i. The year t was not added as an explanatory variable to avoid including a path-dependency trend in the future scenarios.

All variables were log-transformed for the estimation, and as such the coefficients are interpreted as elasticities (a percent change in an explanatory variable leads to β percent change in Cu demand). Individual models were estimated for each application i, independent of the others. The regression models' coefficients were estimated in the R language with the *Arima* command of the *forecast* package version 8.6. The absence of autocorrelation in the residuals was tested with the Ljung-Box test. The estimation results are presented in table S1.

Data sources for historical Cu demand and Cu distribution in the principal application sectors is estimated based on metal yearbooks and end-use statistics (Thomson Reuters GFMS; U.S. Geological Survey, 2005; World Bureau of Metal Statistics, 2010). Historical per capita GDP values (constant at 2010 US$) for the EU were obtained from the World Data Bank database (World DataBank). The same reference provided regional records of the urbanization rate, which is defined as the fraction of inhabitants living in urban areas in the total population.

At the second step the estimated coefficients were used with future values of the explanatory variables for each scenario to estimate the future values of Cu demand in each scenario. The historical Cu demand, corresponding fitted values, and future scenarios of all sectors are presented in figures S1 – S6.

Table S1. Regression coefficient estimation results. Standard errors in parentheses. β_1 – Population; β_2 – Per capita gross domestic product; β_3 – Urbanization rate; ϕ – Autoregression coefficient.

Model (end-use sector *i*)	β_1	β_2	β_3	ϕ
Total demand	0.9375	0.8104	-2.8633	0.5634
	(0.8846)	*(0.3785)*	*(3.6075)*	*(0.1709)*
Buildings and construction	2.3428	1.77	-9.6933	0.8514
	(1.2309)	*(0.5347)*	*(5.0164)*	*(0.0916)*
Electrical and electronic products	1.2991	1.0596	-4.8958	0.8132
	(1.3941)	*(0.6203)*	*(5.7276)*	*(0.1123)*
Industrial machinery and equipment	3.8679	2.187	-15.5916	0.6639
	(1.4312)	*(0.6291)*	*(5.8497)*	*(0.12228)*
Transportation equipment	3.3043	1.7966	-12.9913	0.8463
	(2.1043)	*(1.0227)*	*(8.8423)*	*(0.1206)*
Consumer and general goods	3.8309	1.621	-14.2032	0.783
	(2.3511)	*(1.1036)*	*(9.8153)*	*(0.1641)*

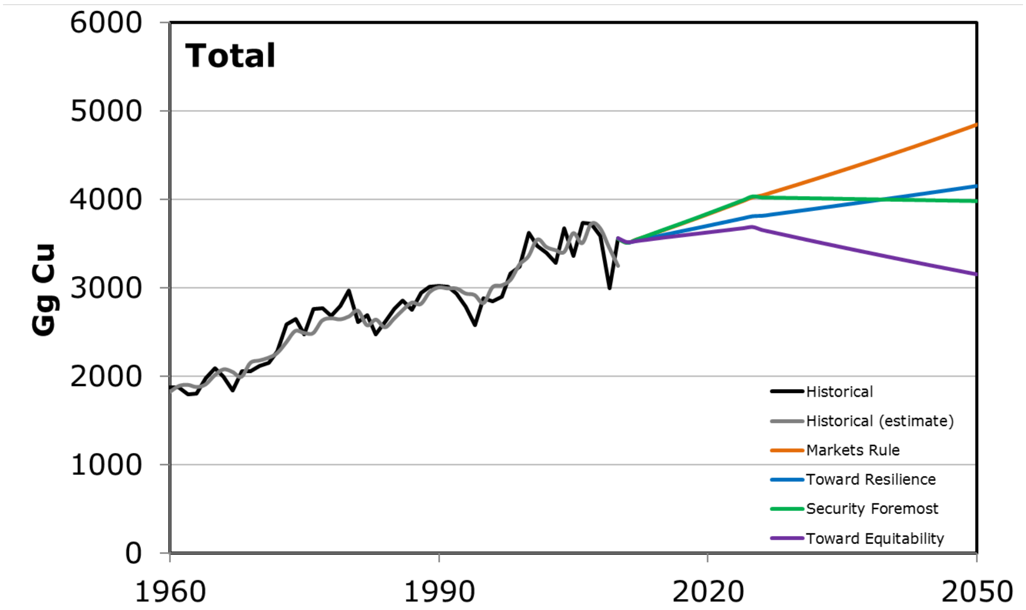

Figure S1. Total European copper demand for 1960-2010 (black line) compared with demands estimated by the regression model (grey line) and projections to 2050 as simulated by the MM scenarios (coloured lines).

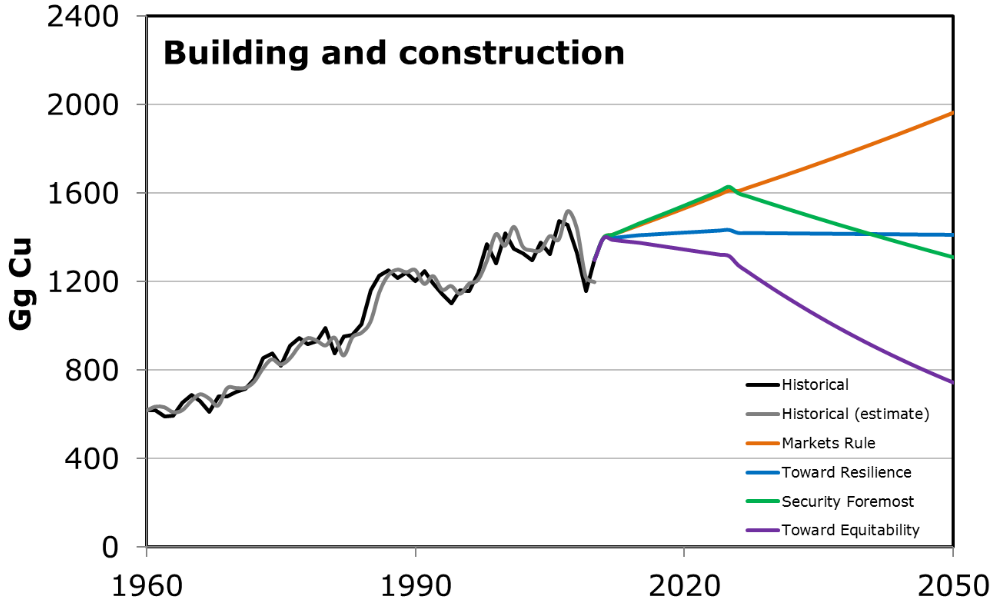

Figure S2. The European copper demand in building and construction for 1960-2010 (black line) compared with demands estimated by the regression model (grey line) and projections to 2050 as simulated by the MM scenarios (coloured lines).

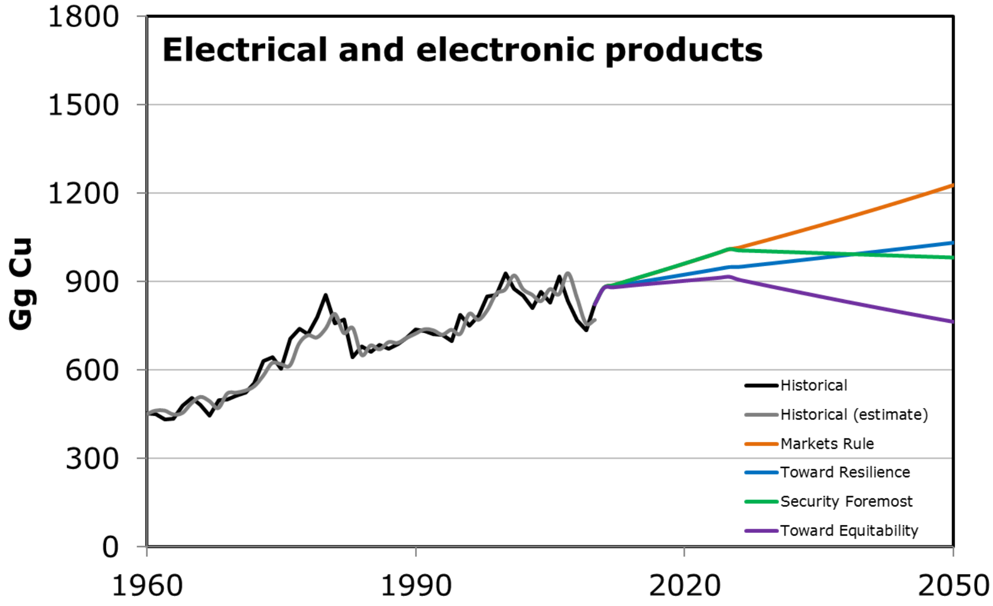

Figure S3. The European copper demand in electrical and electronic products for 1960-2010 (black line) compared with demands estimated by the regression model (grey line) and projections to 2050 as simulated by the MM scenarios (coloured lines).

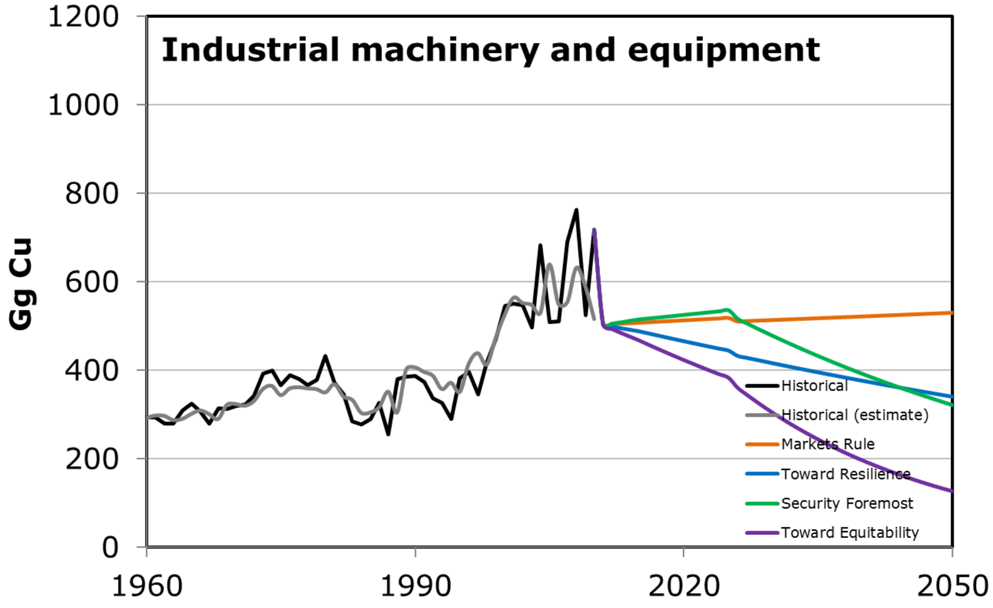

Figure S4. The European copper demand industrial machinery and equipment for 1960-2010 (black line) compared with demands estimated by the regression model (grey line) and projections to 2050 as simulated by the MM scenarios (coloured lines).

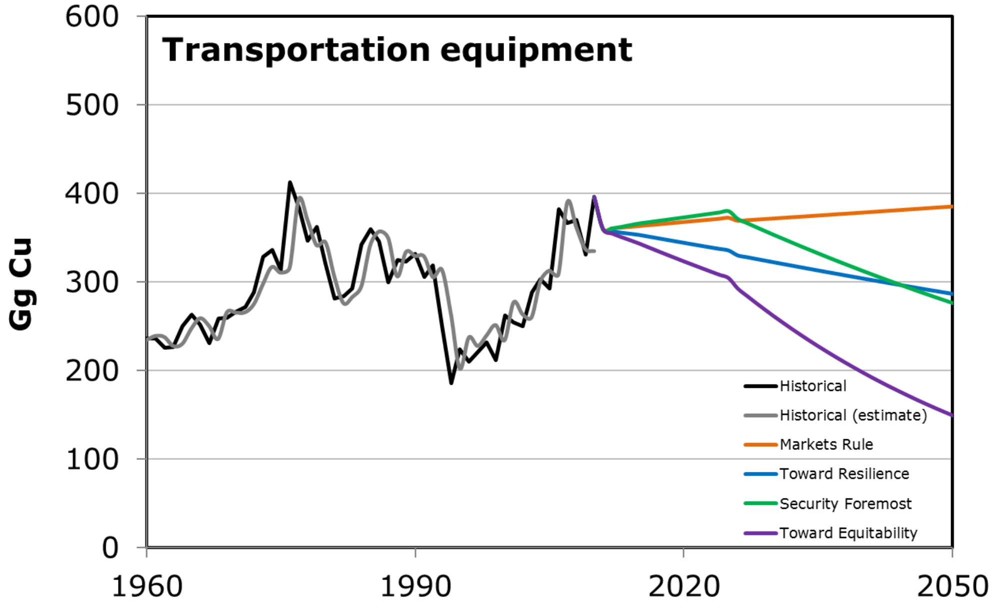

Figure S5. The European copper demand in transportation equipment for 1960-2010 (black line) compared with demands estimated by the regression model (grey line) and projections to 2050 as simulated by the MM scenarios (coloured lines).

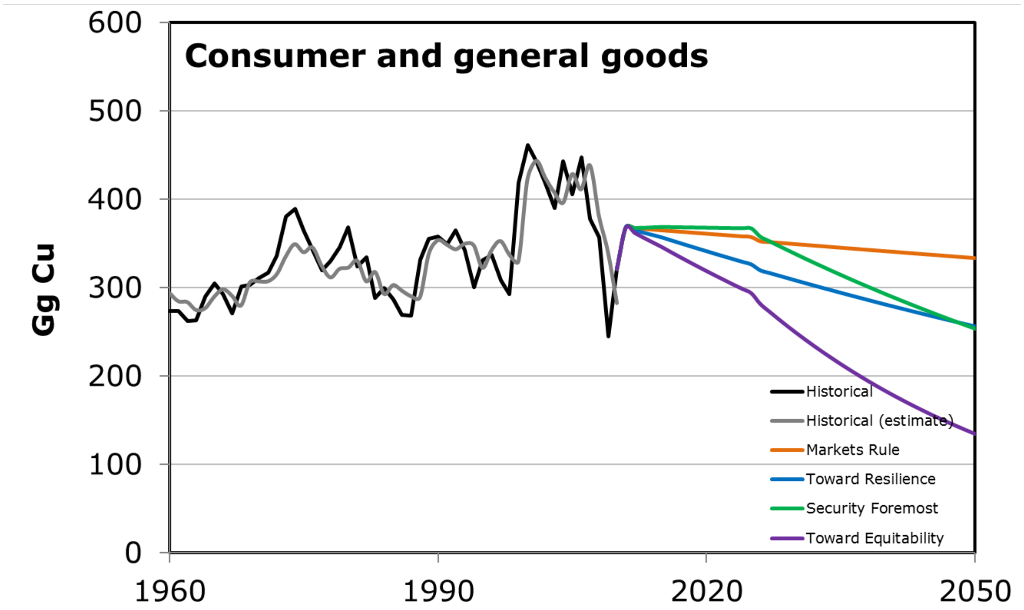

Figure S6. The European copper demand in consumer and general goods for 1960-2010 (black line) compared with demands estimated by the regression model (grey line) and projections to 2050 as simulated by the MM scenarios (coloured lines).

Table S2. Domestic copper demand and secondary supply at current recycling and near-perfect recycling conditions in 2010 and 2050.

			Mg Cu		
FLOW	**2010**	**MR**	**TR**	**SF**	**TE**
Demand	3556	4844	4153	3977	3146
Old scrap generated	2477	3650	3289	3441	2858
Current recycling *(as sum of)*	823	2190	1973	2065	1715
Direct melting	112	146	132	138	114
Secondary cathodes production	711	2044	1842	1927	1600
Near-perfect recycling *(as sum of)*	-	2957	2664	2787	2315
Direct melting	-	146	132	138	114
Secondary cathodes production	-	2811	2532	2650	2200

S4. Life cycle assessment

This section describes methods, data sources and results concerning the environmental implications (energy requirements, GHG emissions) related to the scenario effort. In compliance with the ISO 14040 and 14044 standards (ISO, 2016; ISO, 2018) for life cycle assessment (LCA), the "recycled content" approach was applied to account for the total environmental burdens as the sum of those resulting from primary and secondary copper production.

S4.1 Accounting for energy requirements

The amount of primary energy and final energy (i.e., electricity) required per unit of copper was determined for primary and secondary production at global and the EU-28 levels. From fabrication onwards, additional energy requirements are considered to be the same per unit of Cu for both primary and secondary sources. An overall conversion efficiency of 35% from primary energy to final energy generation was assumed in this study.

4.1.1 Current energy inputs

4.1.1.1 Primary Cu production

Global primary Cu production is estimated to require between 30 and 90 MJ/kg Cu, with common averages at 60 MJ/kg Cu (Elshkaki et al., 2016; Norgate and Haque, 2010). The ecoinvent process "*copper, primary, at refinery/GLO*" (Classen and et al., 2009) was used as a basis for the modelling of energy inputs to global primary copper production and utilized as a proxy for primary copper imported in Europe. This process allocates 90% of global copper production to the pyrometallurgical route and the remaining 10% to the solvent extraction-electrowinning route.

According to (Kulczycka et al., 2016), the average energy required for primary Cu production in Europe is lower than global averages because of a wider use of best available technologies (BATs) for Cu smelting than in regions in which older and more energy-consuming technologies are implemented. Data from literature show that about 70% of the total Cu produced in Europe uses energy-efficient furnaces (e.g., flash-smelting) such as those employed in the Outokumpu process, the INCO process, and the ISASMELT process that are considered to be BATs (Kulczycka et al., 2016; U.S. Geological Survey, 2019). The ecoinvent process "*copper, primary, at refinery/RER*" (Classen and et al., 2009), used in this study, lists the inventory of energy inputs required in primary Cu production in Europe, with refining distinguished according to the country specific mix of process alternatives (i.e., reverberatory furnace 6%, flash smelting furnace 76%, other pyrometallurgical processes 18%, solvent extraction and electrowinning 0%).

4.1.1.2 Secondary Cu production

The energy required for Cu recycling distinguishes between the contribution of direct melting and that of secondary smelting and refining. Secondary Cu cathodes production requires about 6.3 MJ/kg Cu (Bureau of International Recycling, 2008), while global average is 8.4 MJ/kg Cu (Elshkaki et al., 2016). However, these values likely refer only to the smelting and refining processing of Cu scrap, which results in potential energy savings of 84-88% (United Nations Environment Programme, 2013). In fact, collecting, transporting, and pre-processing of obsolete products at end-of-life, from which secondary Cu has to be separated and purified, require additional energy inputs that can erode a considerable part of the potential energy savings. Moreover, the quality of old Cu scrap influences the energy required to produce secondary cathodes and low Cu scrap is generally quite energy-intensive (Muchova et al., 2011).

The ecoinvent process "*copper, secondary, at refinery/RER*" (Classen and et al., 2009) provided a detailed estimate of the energy required in secondary Cu cathodes production, including energy inputs for the collection and handling of copper scrap, refining, and the processes for waste water treatment. This process models Cu old scrap at 89% of total the copper input to secondary production, with the remaining 11% being blister copper supplied from primary smelters (i.e., "*copper, blister-copper, at primary smelter/RER*").

For high quality scrap, direct melting gives the advantage of avoiding energy inputs for smelting and refining, leading to the greater energy savings. However, energy inputs are necessary to collect and recover Cu scrap from obsolete products at end-of-life as well as for melting processing. The ecoinvent process "*aluminium scrap, old, at plant/RER*" was used as a proxy for energy inputs for collection, sorting, and separation of obsolete products and waste containing Cu. Instead, the ecoinvent process "*bronze, at plant/CH*" was referred for modelling the energy requirements for direct melting of Cu scrap by fabricators.

Additional energy may be demanded for sweetening purposes. The presence of impurities and tramp elements may prevent the 100% utilization of Cu scrap for new products manufacturing, thus requiring inputs of virgin material for diluting old scrap. (Cullen and Allwood, 2013) We applied the same energy penalty of 11% used for secondary copper cathodes production.

S4.1.2 Scenario transition to 2050

4.1.2.1 Primary Cu production

The energy required for primary Cu production is demanded mainly in mining, beneficiation, and metal extraction. Depending on the metallurgical process (i.e., pyrometallurgy, hydrometallurgy) followed, the ore grade influences the energy required to produce Cu according to the relation previously described (Mudd et al., 2013; Schodde, 2010). In turn, the ore grade depends on a cumulative Cu production that increases in time and determines a decline in the global Cu deposits. Norgate and Jahanshashi anticipated the ore grade decrease as a function of the cumulative Cu production (Norgate and Jahanshahi, 2011). These authors distinguished the cumulative energy for Cu production between the contribution of mining and mineral processing versus metal extraction and refining for the two metallurgical routes (i.e., pyrometallurgy and hydrometallurgy). Based on those estimates, about 60% of total energy is required for mining and mineral processing. The largest fraction (~70%) of the energy required for mining and mineral processing is consumed in the form of primary energy for excavation, extraction, and comminution of the Cu ore. Final energy (i.e., electricity) is instead demanded for grinding the ore and feeding it to conveyors. According to the same authors, the ore grade decrease is not expected to influence the amount of grounding media per unit mass of ore treated.

Each MM scenario generates its own projection of the future global Cu demand (as dictated by storylines) and, consequently, of the cumulative production, ore grade, and associated energy inputs to mining and mineral processing that were quantified in (Elshkaki et al., 2016). For consistency purposes, the same energy requirements to produce 1 kg of Cu are used in this study, resulting in the coefficients listed in Table S3. The energy required for metal extraction and further processing is assumed to remain constant to 2050, as the declining ore grade is unlikely to affect smelting and refining processes (United Nations Environment Programme, 2013). Tables S3-S6 list the energy inputs by life cycle stage for primary Cu production in the world and in Europe.

In a second run of the assessment, the sensitivity of the model was tested by assuming an improvement in energy efficiency of 30% as the midpoint value among the potential energy savings in copper production resulting from best practices implementation (Norgate and Haque, 2010). The same assumption was also adopted in (Elshkaki et al., 2016).

Table S3. Coefficients applied to scale the current energy requirements for global copper mining and mineral processing to 2050. Multiplicative factors are based on estimates in (Elshkaki et al., 2016).

	MR	**TR**	**SF**	**TE**
Scaling coefficient	5.6	5.6	5.4	6.1

4.1.2.2 Secondary Cu production

The energy required for secondary Cu production depends on the difficulty required to collect, separate, and concentrate Cu forms from obsolete products at end-of-life, and by the quality of the Cu scrap. As a first approximation, the energy inputs associated with current Cu recycling are modelled to remain constant to 2050. It may be questioned if this assumption is reasonable, especially in case of aggressive recycling; as known, in fact, the more material recovery efficiency approaches 100%, the greater energy inputs are required (Norgate, 2004). However, the additional energy requirements needed to enhance Cu recovery could be partially or entirely offset by the adoption of design for resource efficiency practices (e.g., eco-design, design for recycling, for disassembly, and similar procedures) as well as by shifting from obsolete technologies for Cu scrap to BATs, in full harmony with the principles of the circular economy perspective discussed in this work. Implementation of BATs and design for resource efficiency practices are not discussed further here, but are assumed to occur similarly in all scenarios, as dictated by the storylines.

The total energy required for secondary Cu production depends upon scrap quality and the resulting partitioning between direct melting and secondary smelting of old Cu scrap. From the MFA results, the old Cu scrap utilized directly by fabricators has varied little in time, with new scrap being the main input to direct melting, and stabilized in the last 20 years at about 4% of the total old Cu scrap generated. We assumed that this ratio remains constant to 2050. The energy penalty of 11% for sweetening is also assumed to remain constant.

The remaining amount of old Cu scrap to input secondary cathode production is modelled both for the case of constant recycling performance and for aggressive recycling. For both options, such an increase in the amount of old Cu scrap processed domestically is modelled under a Euro-centric vision, which is hypothetical but useful to quantify the maximum environmental benefits achievable through closure of material flows in the EU-28. Tables S7-S8 list energy inputs for secondary Cu production in the EU-28.

S4.2 Accounting for GHG emissions

We provide a first-order estimate of the potential energy-related GHG emissions reduction. The contribution to climate change was quantified combining the energy requirements per unit of Cu processed with carbon intensity results per unit of energy required for primary and secondary Cu.

For primary energy, carbon intensity factors are listed in Table S4 and are assumed to remain constant to 2050. For final energy, the carbon intensity is expressed as a function of the electricity production mix both for the present situation and for its possible evolution. For the latter, the electricity mix projections of the International Energy Agency (IEA) scenarios (International Energy Agency, 2012) have been extrapolated to 2050. Table S5 lists the correspondence between the MM scenarios and IEA scenarios. The following tables report the electricity production mix and carbon intensity factors per unit of energy generated (Tables S6-S11), and per unit of copper produced (Tables S12-S13) at the global and the EU-28 levels.

Table S4. Carbon intensity values per unit of primary energy.

Primary energy source	Unit	Emission factor
Coal	gCO_2eq/MJ	96
Heavy oil	gCO_2eq/MJ	70
Natural gas	gCO_2eq/MJ	58
Diesel	gCO_2eq/MJ	93
Blasting	gCO_2eq/MJ	82

Table S5. Correspondence between MM scenarios and IEA scenarios.

MM scenario	IEA scenario
Market Rules (MR)	Current Policies Scenario
Toward Resilience (TR)	New Policies Scenario
Security Foremost (SF)	Current Policies Scenario
Toward Equitability (TE)	450 Scenario

Table S6. World averages for electricity production mix, emission factors, and the resulting carbon intensity as modelled for the Market Rules (MR) and Security Foremost (SF) scenarios.

MR/SF Scenarios	Production mix (%)		Carbon intensity per unit of energy generated (gCO_2eq/kWh)		Weighted carbon intensity (gCO_2eq/kWh)	
Source	**2010**	**2050**	**2010**	**2050**	**2010**	**2050**
Coal	41%	43%	1001	912	406	392
Oil	5%	1%	859	819	40	8
Gas	22%	23%	482	452	107	104
Nuclear	13%	8%	24	24	3	2
Hydro	16%	12%	11	11	2	1
Biomass & Waste	2%	4%	45	45	1	2
Wind	2%	7%	11	11	0	1

Geothermal	0%	1%	45	45	0	0
Solar PV	0%	1%	69	69	0	1
CSP	0%	0%	45	45	0	0
Marine	0%	0%	69	69	0	0
Total	**100%**	**100%**	**-**	**-**	**560**	**511**

Table S7. World averages for electricity production mix, emission factors, and the resulting carbon intensity as modelled for the Toward Resilience (TR) scenario.

TR Scenario	**Production mix (%)**		**Carbon intensity per unit of energy generated (gCO_2eq/kWh)**		**Weighted carbon intensity (gCO_2eq/kWh)**	
Source	**2010**	**2050**	**2010**	**2050**	**2010**	**2050**
Coal	41%	28%	1001	892	406	250
Oil	5%	1%	859	831	40	8
Gas	22%	24%	482	457	107	110
Nuclear	13%	12%	24	24	3	3
Hydro	16%	15%	11	11	2	2
Biomass & Waste	2%	5%	45	45	1	2
Wind	2%	10%	11	11	0	1
Geothermal	0%	1%	45	45	0	0
Solar PV	0%	3%	69	69	0	2
CSP	0%	1%	45	45	0	0
Marine	0%	0%	69	69	0	0
Total	**100%**	**100%**	**-**	**-**	**560**	**379**

Table S8. World averages for electricity production mix, emission factors, and the resulting carbon intensity as modelled for the Toward Equitability (TE) scenario.

TE Scenario	**Production mix (%)**		**Carbon intensity per unit of energy generated (gCO_2eq/kWh)**		**Weighted carbon intensity (gCO_2eq/kWh)**	
Source	**2010**	**2050**	**2010**	**2050**	**2010**	**2050**
Coal	41%	7%	1001	491	406	34
Oil	5%	0%	859	880	40	0
Gas	22%	11%	482	392	107	43
Nuclear	13%	22%	24	24	3	5
Hydro	16%	21%	11	11	2	2
Biomass & Waste	2%	10%	45	45	1	5

Wind	2%	18%	11	11	0	2
Geothermal	0%	1%	45	45	0	0
Solar PV	0%	7%	69	69	0	5
CSP	0%	3%	45	45	0	1
Marine	0%	0%	69	69	0	0
Total	**100%**	**100%**	**-**	**-**	**560**	**98**

Table S9. European electricity production mix, emission factors, and the resulting carbon intensity as modelled for the Market Rules (MR) and Security Foremost (SF) scenarios.

MR/SF Scenarios	**Production mix (%)**		**Carbon intensity per unit of energy generated (gCO_2eq/kWh)**		**Weighted carbon intensity (gCO_2eq/kWh)**	
Source	**2010**	**2050**	**2010**	**2050**	**2010**	**2050**
Coal	26%	10%	971	848	253	85
Oil	3%	0%	948	920	25	0
Gas	23%	38%	476	436	109	166
Nuclear	28%	6%	24	24	7	1
Hydro	11%	10%	11	11	1	1
Biomass & Waste	4%	7%	45	45	2	3
Wind	5%	21%	11	11	0	2
Geothermal	0%	1%	45	45	0	0
Solar PV	1%	5%	69	69	0	3
CSP	0%	1%	45	45	0	0
Marine	0%	1%	69	69	0	1
Total	**100%**	**100%**	**-**	**-**	**397**	**263**

Table S10. European electricity production mix, emission factors, and the resulting carbon intensity as modelled for the Toward Resilience (TR) scenario.

TR Scenario	**Production mix (%)**		**Carbon intensity per unit of energy generated (gCO_2eq/kWh)**		**Weighted carbon intensity (gCO_2eq/kWh)**	
Source	**2010**	**2050**	**2010**	**2050**	**2010**	**2050**
Coal	26%	4%	971	909	253	36
Oil	3%	0%	948	952	25	0
Gas	23%	28%	476	454	109	127
Nuclear	28%	20%	24	24	7	5
Hydro	11%	11%	11	11	1	1

Biomass & Waste	4%	8%	45	45	2	4
Wind	5%	20%	11	11	0	2
Geothermal	0%	1%	45	45	0	0
Solar PV	1%	7%	69	69	0	5
CSP	0%	2%	45	45	0	1
Marine	0%	1%	69	69	0	1
Total	**100%**	**100%**	-	-	**397**	**182**

Table S11. European electricity production mix, emission factors, and the resulting carbon intensity as modelled for the Toward Equitability (TE) scenario.

TE Scenario	**Production mix (%)**		**Carbon intensity per unit of energy generated (gCO$_2$eq/kWh)**		**Weighted carbon intensity (gCO$_2$eq/kWh)**	
Source	**2010**	**2050**	**2010**	**2050**	**2010**	**2050**
Coal	26%	2%	971	694	253	14
Oil	3%	0%	948	950	25	0
Gas	23%	2%	476	514	109	10
Nuclear	28%	27%	24	24	7	6
Hydro	11%	13%	11	11	1	1
Biomass & Waste	4%	12%	45	45	2	5
Wind	5%	30%	11	11	0	3
Geothermal	0%	1%	45	45	0	0
Solar PV	1%	10%	69	69	0	7
CSP	0%	3%	45	45	0	1
Marine	0%	1%	69	69	0	1
Total	**100%**	**100%**	-	-	**397**	**50**

Table S12. Energy requirements associated with copper production in 2010 and 2050.

	MJ/kg Cu				
	2010	**MR**	**TR**	**SF**	**TE**
Primary Cu production (World)	51.2	172.9	172.9	167.6	186.1
Primary Cu production (World)*	51.2	121.0	121.0	117.3	130.3
Primary Cu production (EU-28)	28.4	28.4	28.4	28.4	28.4
Secondary Cu production (Direct melting)	4.9	4.9	4.9	4.9	4.9
Secondary Cu production (Secondary cathodes)	22.9	22.9	22.9	22.9	22.9

*With energy efficiency improvements.

Table S13. GHG emissions associated with copper production in 2010 and 2050.

	kgCO$_2$eq/kg Cu				
	2010	MR	TR	SF	TE
Primary Cu production (World)	3.0	9.4	7.6	9.1	3.9
Primary Cu production (World)*	3.0	6.6	5.3	6.4	2.7
Primary Cu production (EU-28)	1.4	1.1	1.0	1.1	0.7
Secondary Cu production (Direct melting)	0.2	0.2	0.2	0.2	0.2
Secondary Cu production (Secondary cathodes)	1.4	1.2	1.1	1.2	0.9

*With energy efficiency improvements.

S4.3. Estimate of GHG emissions at 2000 levels

A reduction of 50% of GHG emissions below 2000 levels has been proposed as a target to help minimize the global average temperature increase. Applying the model developed to account for Cu demand and the associated energy requirements and GHG emissions, we estimated that about 4,800 Gg Cu entered the use phase in the EU-28 in 2000 supplied either from primary and secondary forms. Combining the MFA results with GWP of primary and secondary Cu forms, the total GHG emissions attributable to Cu demand in the EU-28 resulted in about 11.8 TgCO$_2$eq at 2000 levels (Table S14). This amount corresponds to a CO$_2$eq reduction target of about 5.9 TgCO$_2$eq. It is worth noting that the consumption-based accounting convention was preferred to estimate the embodied GHG emissions in copper flow into use in the EU-28. I.e., total CO$_2$eq emissions are computed as the sum of GHG emissions associated with primary and secondary copper supplied domestically (as dictated by MM scenarios), plus net-import of copper to meet the total demand. Therefore, the emissions estimated here will not be those occurring within the EU-28 boundaries (or the production-based accounting) and amounting to 4.5 TgCO$_2$eq in 2010 (Eurometaux, 2020).

GHG emission results for primary and secondary Cu supply in the EU-28 at current recycling rate and near-perfect recycling rate in 2050 are reported in Table S15. The effect of energy savings on these results is explored in Table S16. Lastly, Table S17 lists the GHG emissions gap embodied in copper demand in the EU-28 in 2050 as percent increase from the 50% cut target below 2000 levels with stationary global end-of-life recycling input rate included to model old Cu scrap as fraction of Cu demand in the net-import of Cu.

Table S14. Mass, carbon intensity, and total greenhouse gas (GHG) emissions estimated for primary and secondary copper flows in the EU-28 in 2000. Numbers may not match due to rounding.

	Mass	**Carbon intensity**	**GHG emissions**
Cu flow	**Gg Cu**	**GgCO$_2$eq/Gg Cu**	**TgCO$_2$eq**

Primary Cu	3.9	N/A	10.6
Domestic	0.8	1.5	1.1
Import	3.1	3.0	9.4
Secondary Cu	0.9	N/A	1.3
Direct melting	0.0	0.2	0.0
Secondary cathodes	0.9	1.4	1.3
Total	**4.8**	**N/A**	**11.8**

N/A – Not applicable.

Table S15. GHG emission results for primary Cu supply and secondary Cu supply in the EU-28 at current recycling rate and near-perfect recycling rate in 2050. Numbers may not match due to rounding.

			$TgCO_2eq$		
FLOW	**2010**	**MR**	**TR**	**SF**	**TE**
Current recycling (total)	**8.0**	**21.3**	**13.6**	**13.8**	**4.7**
Primary supply (*as sum of*)	*7.0*	*18.8*	*11.6*	*11.5*	*3.2*
Domestic extraction	1.0	0.8	0.7	0.8	0.6
Import	6.0	17.9	10.8	10.6	2.7
Secondary supply (*as sum of*)	*1.0*	*2.5*	*2.0*	*2.3*	*1.5*
Direct melting	0.0	0.0	0.0	0.0	0.0
Secondary cathodes production	1.0	2.5	2.0	2.3	1.5
Near-perfect recycling (total)	-	**14.9**	**9.1**	**8.1**	**2.9**
Primary supply (*as sum of*)	-	*11.6*	*6.3*	*4.9*	*0.9*
Domestic extraction	-	0.8	0.7	0.8	0.6
Import	-	10.7	5.6	4.0	0.3
Secondary supply (*as sum of*)	-	*3.4*	*2.8*	*3.2*	*2.1*
Direct melting	-	0.0	0.0	0.0	0.0
Secondary cathodes production	-	3.4	2.8	3.2	2.0

Table S16. GHG emission results for primary Cu supply and secondary Cu supply in the EU-28 at current recycling rate and near-perfect recycling rate with energy efficiency improvements. Numbers may not match due to rounding.

			$TgCO_2eq$		
FLOW	**2010**	**MR**	**TR**	**SF**	**TE**
Current recycling (total)	**8.0**	**15.9**	**10.3**	**10.6**	**3.9**
Primary supply (*as sum of*)	*7.0*	*13.4*	*8.3*	*8.3*	*2.4*
Domestic extraction	1.0	0.8	0.7	0.8	0.6
Import	6.0	12.5	7.6	7.4	1.9
Secondary supply (*as sum of*)	*1.0*	*2.5*	*2.0*	*2.3*	*1.5*
Direct melting	0.0	0.0	0.0	0.0	0.0
Secondary cathodes production	1.0	2.5	2.0	2.3	1.5

Near-perfect recycling (total)	-	**11.7**	**7.4**	**6.9**	**2.8**
Primary supply (*as sum of*)	-	*8.3*	*4.7*	*3.7*	*0.8*
Domestic extraction	-	0.8	0.7	0.8	0.6
Import	-	7.5	3.9	2.8	0.2
Secondary supply (*as sum of*)	-	*3.4*	*2.8*	*3.2*	*2.1*
Direct melting	-	0.0	0.0	0.0	0.0
Secondary cathodes production	-	3.4	2.8	3.2	2.0

Table S17. Greenhouse gas emissions gap embodied in copper demand in the EU-28 in 2050 as percent increase from the 50% cut target below 2000 levels. Stationary global end-of-life recycling input rate is included to model old Cu scrap as fraction of Cu demand in the net-import of Cu. MR – Market Rules; TR – Toward Resilience; SF – Security Foremost; TE – Toward Equitability.

	MR	**TR**	**SF**	**TE**
Current recycling	234%	116%	120%	-20%
Current recycling*	155%	69%	73%	-32%
Near-perfect recycling	141%	51%	36%	-47%
Near-perfect recycling*	94%	26%	18%	-48%

*With 30% energy savings in Cu production.

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