UNIVERSIDADE DE SÃO PAULO
FACULDADE DE ECONOMIA, ADMINISTRAÇÃO, CONTABILIDADE E ATUÁRIA
DEPARTAMENTO DE ADMINISTRAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM ADMINISTRAÇÃO

ALINE FERNANDA SOARES

Copper market in view of sustainable global trends: Demand forecast and systematic review of secondary sources

Mercado de cobre em vista das tendências globais sustentáveis: Previsão de demanda e revisão sistemática de fontes secundárias

São Paulo
2023

Prof. Dr. Carlos Gilberto Carlotti Júnior
Rector of University of São Paulo

Prof. Dr. Maria Dolores Montoya Diaz
Director of School of Economics, Business, Accounting and Actuary

Prof. Dr. João Maurício Gama Boaventura
Chief of the Business Department

Prof. Dr. Felipe Mendes Borini
Coordinator of the Post-Graduation Program in Business

Aline Fernanda Soares

Copper market in view of sustainable global trends: Demand forecast and systematic review of secondary sources

Mercado de cobre em vista das tendências globais sustentáveis: Previsão de demanda e revisão sistemática de fontes secundárias

Ph.D. thesis presented to the Business Post Graduation Program from the Business Department of the Economics, Business, Accounting and Actuary School of University of São Paulo as a partial requirement for obtaining the title of Doctor of Sciences.

Advisor: Prof. Dr. Renata Giovinazzo Spers

Corrected Version
(original version available at the Library of the Economics, Business, Accounting and Actuary School)

São Paulo
2023

Catalogação na Publicação (CIP)

Ficha Catalográfica com dados inseridos pelo autor

Soares, Aline Fernanda.
Copper market in view of sustainable global trends: Demand forecast and systematic review of secondary sources / Aline Fernanda Soares. - São Paulo, 2023.
112 p.

Tese (Doutorado) - Universidade de São Paulo, 2023.
Orientador: Renata Giovinazzo Spers.

1. Solar energy. 2. Wind energy. 3. Electric vehicles. 4. Recycling. I. Universidade de São Paulo. Faculdade de Economia, Administração, Contabilidade e Atuária. II. Título.

ACKNOWLEDGMENTS

I would like to thank the University of Sao Paulo, its professors, and staff. I did my undergraduate, master's and now Ph.D. at this university and I could not be more proud and thankful for all the support I have received.

I would like also to thank my advisor, Prof. Dr. Renata Spers, who helped in every stage of this journey and believed in my commitment to the doctorate. I am so glad that I have had the opportunity to work with a woman that has made a difference in the academic sector in Brazil.

I am grateful to have Professors Leandro Gilio, Nuno Martins, and Daniel Estima as members of the Ph.D. thesis committee. Prof. Dr. Leandro Gilio was a key asset in the development of this study, providing me with many insights and asking questions to challenge my way of thinking.

To my family, a special thanks for understanding the times I was absent while focusing on the doctorate and always being the main source of support.

A shout out to my friends that like my family, have been understanding and encouraging. Some of them are economists and helped me to clarify many doubts. Others may not be economists themselves, but they have experienced the challenges of being a Ph.D. student and understood the significance of any assistance offered. There are those friends who have simply been by my side, supporting me in this and other endeavors, providing unwavering encouragement every step of the way. To all of them, I extend my sincere gratitude for their unwavering support and camaraderie.

ABSTRACT

Soares, A. F. (2023). Copper market in view of sustainable global trends: Demand forecast and systematic review of secondary sources (Ph.D. Thesis). Economics, Business, Accounting and Actuary School, University of São Paulo, São Paulo.

Governments around the world have pursued alternatives to fight climate change in face of growing evidence of environmental risks. The transition to a low carbon energy matrix has received special attention, particularly with incentives to solar and wind energy and electric vehicles. These trends are intertwined with electricity, and the use of copper stands out following its property of high electrical conductivity. As emerging technologies, however, there are uncertainties regarding their evolution and how this will impact copper demand. On the other hand, copper supply is not as price elastic as other commodities, given that the time to discover a mineral deposit and develop a mining project is long. In this context, this study aimed to assess the possible paths of copper-intensive modern technologies, namely solar and wind energy and electric vehicles, and forecast global copper demand. Additionally, this study sought to understand the market dynamics of secondary sources of copper, which could be an option to the extraction of virgin ores. Growth in solar and wind energy technologies and electric vehicles has been consistent and robust, with solar and wind installed capacity rising annually 33.2% and 13.9%, respectively, from 2010 to 2021 and electric vehicles fleet increasing annually 86.6% in the same period, according to the International Energy Agency. However, comparing different scenarios for these trends from the same agency and adding the uncertainty regarding the copper content in these technologies, copper demand from solar and wind energy and electric vehicles can differ by approximately 3.5 million tonnes by 2030. Three autoregressive distributed lag models were tested to forecast copper demand and assess the impact of solar and wind energy and electric vehicles on the estimations. This analysis pointed to a difference of 5 million tonnes in copper consumption forecast for 2030 between the model with and without taking into account electric vehicles and renewable energies in the optimistic scenario. Conventional econometric models that include only explanatory variables related to economic activity and prices can underestimate the potential growth of copper demand, although the used methodology can overestimate the potential growth, given the short period of data for solar and wind energy and electric vehicles. Based on a selection of 42 articles from two databases, this study identified that the availability of secondary sources of copper depends on the in-use stock of copper, breakdown of the end-use sectors, product lifetime, scrap collection rate, recycling efficiency, copper prices, and trade barriers. They should be taken into consideration in an integrated way for the purpose of policy development, having in mind that good environmental and social recycling practices should be followed globally so that recycling has indeed an advantage over virgin materials and the energy transition is underpinned by low-carbon processes throughout the supply chain.

Keywords: Solar energy; Wind energy; Electric vehicles; Recycling

RESUMO

Soares, A. F. (2023). Mercado de cobre em vista das tendências globais sustentáveis: Previsão de demanda e revisão sistemática de fontes secundárias (Tese de doutorado). Faculdade de Economia, Administração e Contabilidade, Universidade de São Paulo, São Paulo.

Governos de todo o mundo têm buscado alternativas para combater as mudanças climáticas diante das crescentes evidências de riscos ambientais. A transição para uma matriz energética de baixo carbono tem recebido atenção especial, principalmente com incentivos para energia solar, eólica e veículos elétricos. Essas tendências estão interligadas com a eletricidade, e o uso do cobre se destaca por sua propriedade de alta condutividade elétrica. Como tecnologias emergentes, no entanto, existem incertezas quanto à sua evolução e como isso afetará a demanda de cobre. Por outro lado, a oferta de cobre não é tão elástica quanto as outras commodities, visto que o tempo para descobrir uma jazida mineral e desenvolver um projeto de mineração é longo. Neste contexto, este estudo teve como objetivo avaliar os possíveis caminhos das tecnologias modernas intensivas em cobre, nomeadamente energia solar e eólica e veículos elétricos, e prever a demanda global por cobre. Adicionalmente, este estudo buscou entender a dinâmica do mercado de fontes secundárias de cobre, que poderiam ser uma opção à extração de minérios virgens. O crescimento das tecnologias de energia solar e eólica e veículos elétricos tem sido consistente e robusto, com a capacidade instalada solar e eólica aumentando anualmente 33,2% e 13,9%, respectivamente, de 2010 a 2021 e a frota de veículos elétricos aumentando anualmente 86,6% no mesmo período, de acordo com à Agência Internacional de Energia. No entanto, comparando diferentes cenários para essas tendências da mesma agência e adicionando a incerteza sobre o conteúdo de cobre nessas tecnologias, a demanda de cobre da energia solar e eólica e de veículos elétricos pode diferir em aproximadamente 3,5 milhões de toneladas até 2030. Três modelos autorregressivos de defasagem distribuída foram testados para prever a demanda de cobre e avaliar o impacto da energia solar e eólica e dos veículos elétricos nas estimativas. Esta análise apontou uma diferença de 5 milhões de toneladas no consumo de cobre previsto para 2030 entre o modelo com e sem considerar veículos elétricos e energias renováveis no cenário otimista. Modelos econométricos convencionais que incluem apenas variáveis explicativas relacionadas à atividade econômica e preços podem subestimar o crescimento potencial da demanda de cobre, embora a metodologia usada possa superestimar o crescimento potencial dado o curto período de dados para energia solar e eólica e elétrica veículos. Com base em uma seleção de 42 artigos de dois bancos de dados, este estudo identificou que a disponibilidade de fontes secundárias de cobre depende do estoque de cobre em uso, divisão dos setores de uso final, vida útil do produto, taxa de coleta de sucata, eficiência de reciclagem, preços do cobre e barreiras comerciais. Eles devem ser levados em consideração de forma integrada para fins de desenvolvimento de políticas, tendo em mente que boas práticas ambientais e sociais de reciclagem devem ser seguidas globalmente para que a reciclagem tenha de fato uma vantagem sobre os materiais virgens e a transição energética seja sustentada por processos de baixo-carbono em toda a cadeia de abastecimento.

Palavras-chave: Energia solar; Energia eólica; Veículos elétricos; Reciclagem

INDEX

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Context

With growing evidence on global-scale environmental risks, such as ozone depletion, biodiversity loss and the alteration of the nitrogen cycle (Geissdoerfer, Savaget, Bocken and Hultink, 2017), governments around the world have developed strategies to fight climate change. Among alternatives, more electrification combined with renewable energy have been extensively explored.

Except for silver and gold, copper has the highest electrical conductivity of all metals, making it extremely important in an economic model where sustainability concerns are increasingly incorporated into the agendas of policy makers. The energy efficiency obtained from using copper provides benefits in multiple areas, including consumption savings and lower costs and emission of CO_2 (International Copper Association - ICA, 2022).

Copper is needed in a variety of sectors, with consumption divided into five broad segments: construction, electrical network, consumer products, transportation equipment, and industrial machinery. However, some technologies associated with the increasing environmental awareness of climate change are expected to leverage copper demand.

Copper is used in power cables, transformers, and switchgears among other components of solar panels and wind towers. In the energy storage, copper wiring and cabling connect renewable power generation with energy storage devices while in the switches of transformers, copper helps to deliver power at the right voltage. In electric vehicles, copper can be found in the battery, motor, inverters, and wiring, as well as in the infrastructure needed for their operation (ICA, 2022).

Support schemes for solar and wind energy and electric vehicles have been implemented around the world, although their development and adoption struggled in the 2000s. Negro, Alkemede, and Hekkert (2012) mention that market failures could explain the slow diffusion of solar panels and wind turbines, with the lack of stable institutions and their poor alignment with other stakeholders being key systemic problems.

This scenario has changed significantly with an increasing engagement of different actors, including consumers demanding more environmental-friendly products. As for solar and wind energies, they accounted for 21% of the global electrical installed capacity in 2021, from just 7% in 2012 (IEA, 2014, 2022b), whereas the compound average growth rate of electric vehicles sales reached 51% from 2015 to 2021 (IEA, 2022a).

Due to the key role of copper in these technologies, copper demand is expected to rise, although the development of new mining projects faces challenges due to increasing scrutiny over environmental, social, and governmental practices. Copper production and reserves are concentrated in few countries, with Chile being responsible for almost 27% of the copper production in the world in 2021 and for 23% of the reserves (USGS, 2022).

Declining ore grades have been observed in developed copper areas, such as in Chile (ICSG, 2022), and could be a source of negative impact on the environment and local community. In this scenario, a greater quantity of material needs to be moved and processed in order to yield an equivalent amount of finished metal, resulting in higher removal of rock waste, tailings generation, and disturbance of local habitats. To ensure their economic viability, mines tend to be larger in size to compensate for lower grades, which adds to the negative impact on the environment and community (Northey, Mohr, Mudd, Weng and Giurco, 2014).

Schipper et al. (2018) suggest that a potential solution to these challenges would be to reach a circular economy of copper, where the material and energy flow is maximized following a societal production-consumption system instead of a linear nature-society-nature system, according to Korhonen, Honkasalo, and Seppala (2018). Copper secondary production could be an alternative to offset the growing demand for this metal, as it accounts for one eighth of the total environmental impact generated by the primary copper production process (J. Chen et al., 2019).

Developed economies like the United States and Europe dominate the global copper secondary production due to their longer history of copper consumption, making them the primary suppliers of copper scrap. Recently, China has been the main consumer of copper scrap in the world and has imported material from developed countries. However, the copper secondary trade flow has been impacted since 2017 by a series of policies imposed by the Chinese government, which restricted imports of metallic scrap. The aim was to stop waste imports and develop domestic recycling of the accumulated copper in-use stock, after China's rapid economic growth and industrialization.

China's transition to a cleaner energy matrix and a low-emission transport sector is notably seen in its growing investments in renewable energy and incentives to electric vehicles and could be an additional source of copper scrap in the future. Compared to traditional energy sources, there is around 12 times more copper in some renewable energy systems (ICA, 2022) while battery electric vehicles require around 4 times more copper than conventional gasoline-powered vehicles (IdTechEx, 2017): This means that China has the potential to become a significant source of copper scrap in the future:

In this context, a thorough analysis of copper demand can be facilitated by evaluating potential pathways for modern copper-intensive technologies, such as renewable energies and electric vehicles, in conjunction with a comprehensive understanding of the copper scrap market.

1.2 Relevance and expected contributions

Studies on copper-intensive sustainable technologies, such as renewable energy and electric vehicles, have been previously conducted by Månberger and Stenqvist (2018), Schipper et al. (2018), Deetman, Pauliuk, Van Vuuren, Van Der Voet, and Tukker (2018), Watari et al. (2019), among others. The majority of these studies depict scenarios that encompass both conservative and aggressive growth rates for the evolution of these technologies. However, they have not addressed how copper demand could vary based on projections from well-known institutions on the energy transition topic, such as the International Energy Agency (IEA). Moreover, no studies have investigated the sensitivity of copper demand to different intensities of copper in wind and solar energy and in electric vehicles. This aspect is particularly pertinent due to the rapid evolution of technology in these sectors in terms of material composition. A study that examines both topics may fill the gap in the research field, contributing to a clearer understanding of the adoption of these trends and their impact on copper demand.

Analysis of the copper scrap market has mostly focused on China (Zhang, Yang, Cai, and Yuan, 2014; Zhang, Cai, Yang, Yuan and Chen, 2015; Wen, Zhang, Ji and Xue, 2015; Wang, Chen, Zhou and Li, 2017; Wang, Ju, Wang and Li., 2019; Dong, Tukker, and Van der Voet, 2019; Eheliyagoda et al., 2019; Hu, Wang, Lim and Chen, 2020; Hao et al., 2020; Dong et al., 2020) and to a lesser extent on the United States (Chen, Wang and Li, 2016; M. Wang et al., 2018, Mackey, Cardona and Reemeyer, 2019; Gorman and Dzombak, 2019). As the supply of copper scrap grows in other regions, including emerging markets, and its role in a circular economy increases, an updated and synthetic review may be important for policy makers, researchers, and companies.

The literature of copper demand is ample, with studies using top-down and bottom-up approaches (Schipper et al., 2018; Kwakkel, Auping and Pruyt, 2013; Stuermer, 2017; Fernandez, 2018; Elshkaki, Graedel, Ciacci and Reck, 2016), but few of them present forecasts (Elshkaki et al., 2016; Schipper et al., 2018). Watari, Nansai and Nakajima (2020) show that copper demand forecast for 2050 can differ from 27 million tonnes to 120 million tonnes, depending on the article. Therefore, this topic still requires further assessment, and this thesis aims to contribute to the literature.

1.3 Research questions

This thesis seeks to answer the following question: How will copper demand evolve given its role in a green energy transition world? The main objective is to propose a model for projecting the global demand for copper, by the growing necessity for this metal within the context of a sustainable framework. Specifically, this study assesses the future copper demand from renewable energies and electric vehicles. It also presents a qualitative and critical analysis of the scientific literature related to secondary sources of copper, using studies developed from 2010 to 2020. Finally, the study presents an econometric model of the global copper demand, seeking to project copper needs through 2030.

To this end, this thesis is organized in three complementary articles that help to address the main objective. Although the sequence contributes to the understanding of the main objective, the articles can be read independently. Therefore, eventual redundancies or repetitions of texts, quotes, motivations, or references are intended, notably in the introductory sections of the chapters.

The primary objective of the first article is to examine the potential rate of evolution for renewable energies, particularly solar and wind power, as well as electric vehicles. Furthermore, our objective is to quantify the global copper demand arising from solar energy, wind energy, electric vehicles, and electric buses. This will be accomplished by considering various scenarios for renewable energy and electric vehicles, while also accounting for different copper compositions within these technologies.

The main research questions addressed in this article are:

- How are renewable energies and electric vehicles expected to increase according to the scenarios from IEA?
- How much will renewable energies and electric vehicles incentivize copper demand according to the scenarios from IEA?
- How will copper demand respond to different copper content in solar and wind energy and electric vehicles?

The second article aims to conduct a systematic evaluation of existing literature on the market dynamics of secondary sources. Its objective is to identify common themes across published articles and the primary methodological approaches employed in this field. By doing so, the article seeks to characterize the key drivers influencing the supply of secondary copper sources.

The main research questions addressed in this article are:

- What is the available evidence in the scientific literature about the factors driving the supply of copper secondary sources?
- How were research questions formulated and how were the methodological resources employed?

The objective of the third article is to estimate the global copper demand using a combination of a top-down approach and an econometric model. Furthermore, it aims to project the global copper demand by the year 2030.

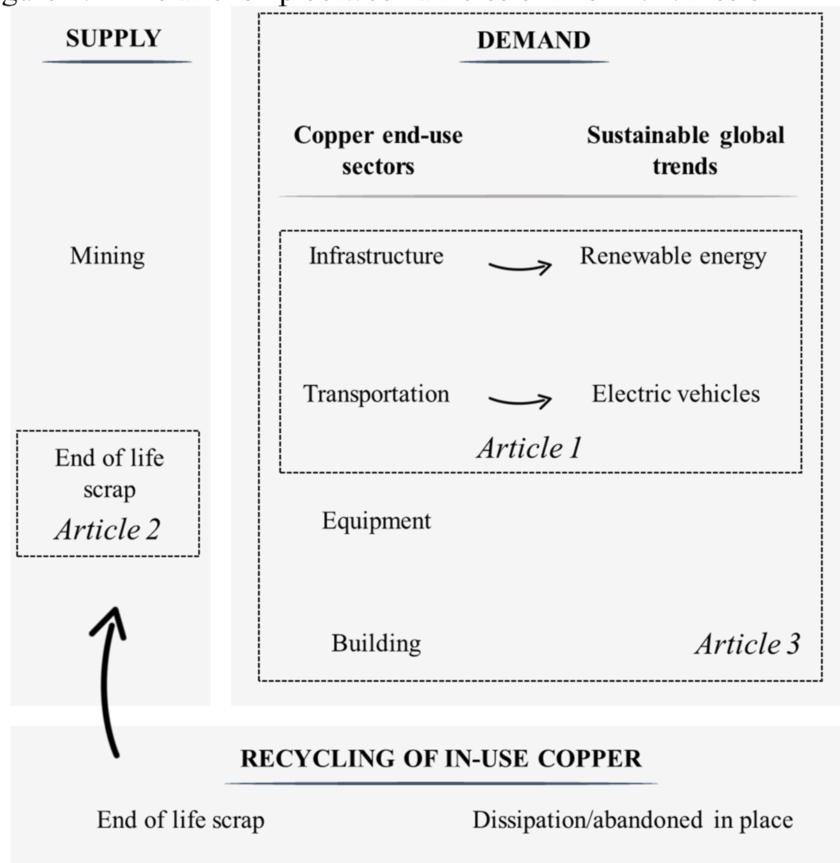
The main research questions addressed in this article are:

- What are the key variables that explain how copper demand evolved in the past?
- How much will global copper demand increase by 2030?

These articles intend to contribute to filling a gap in the scientific literature by addressing the uncertainty in the copper market from the green energy transition, understanding the debate around a critical raw material and providing insights to development of strategic policies for the public and private sectors.

The articles developed in this thesis are about the copper market and its relation is represented in the Figure 1.1.

Figure 1.1 - Relationship between articles of this Ph.D. thesis



Source: Developed by the author.

2. SCENARIOS OF COPPER REQUIREMENT IN RENEWABLE ENERGY AND ELECTRIC VEHICLES

Abstract

This article aims to present the status of solar and wind energy technologies and electric vehicles in the world and their potential expansion, quantifying the demand for copper from wind and solar energy, and electric cars and buses. Understanding how solar and wind energy and electric vehicles will impact copper demand is paramount to secure supply and enable the energy transition. Projections of solar panel and wind energy installation, and electric vehicle fleet originate from the International Energy Agency whereas the copper content in these technologies is taken from different papers. Growth in solar and wind energy technologies and electric vehicles has been consistent and robust, with solar and wind installed capacity rising annually 33.2% and 13.9%, respectively, from 2010 to 2021 and electric vehicle fleet increasing annually 86.6% in the same period. With projected continuous growth, solar photovoltaic panels and wind turbines are anticipated to need 2,661,122 and 1,309,828 tonnes of copper by 2050, respectively, based on the Announced Pledges Scenario and average intensity. By 2030, EVs are expected to be responsible for at least 1,875,490 tonnes of copper demand, considering the most pessimistic scenario in terms of adoption.
Keywords: Solar energy; Wind energy; Copper intensity

2.1 Introduction

Increasing concerns with the environment are a significant motivation for renewable energy (RE) and electric vehicles (EVs). At firm level, the turn towards environmental responsibility is driven by shareholder value and financial performance (Wirth, Kulczycka, Hausner and Koński, 2016), with companies taking a series of measures to reduce emissions and increase energy efficiency. For example, under the RE100 initiative, over 370 companies from telecommunications and retail to cement and automobile manufacturing have made a commitment to use 100% renewable electricity in the shortest possible timeline (by 2050 at the latest) (RE100, 2022) while copper mining companies have evolved in their corporate social responsibility policies (Wirth et al., 2016).

In view of the Sustainable Development Goals (SDGs), adopted by the United Nations General Assembly in 2015, governments are committed to renewables development in order to meet their established climate targets. Other sources of energy that present low or zero greenhouse gas emissions, such as nuclear power, lack public acceptance in several regions of the world, despite the reviving interest in these sources in face of growing energy needs (Gotzens, Heinrichs, Hake and Allelein, 2018; Whitfield Rosa, Dan and Dietz, 2009). Being committed to those climate targets, governments have the role to provide policy and regulatory frameworks that mobilize the market to invest (International Energy Agency - IEA, 2019d).

With transportation being one of the main sources of global greenhouse gas emissions (Intergovernmental Panel on Climate Change – IPCC, 2014)), EVs are an option to contribute to a better environment, promoting cleaner air, especially in large centers where car volume is high. In some countries, such as in the United States, the transportation sector generates the largest share of greenhouse gas emissions, with carbon dioxide (CO_2) corresponding to the majority of gas emitted by the sector. In addition, small amounts of methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbon (HFC) are released, according to the U.S. Environmental Protection Agency (EPA, 2019).

In cities such as Beijing (China), Oslo (Norway), Amsterdam (Netherlands) and San Francisco (United States), local governments have pursued a range of public policies to stimulate the EVs adoption, many of them with financial incentives. According to IEA (2018), five countries have announced that sales or registration of new gasoline or diesel cars will be banned by 2032.

Batteries are the main reason for the higher costs of electric vehicles compared to conventional technologies (Duffner, Wentker, Greenwood and Leker, 2020). Therefore, reduction in battery costs holds significant promise for the EVs segment. Metals are important components of batteries, with the lithium-ion technology being dominant in the market. In addition to the batteries, electric vehicles demand more electrical components, such as electric machines, power electronic converters, ultracapacitors, sensors and microcontrollers, with metals as major constituents.

The high conductivity of copper makes it an essential metal to enable the low carbon economy transition, with renewable energy and electric vehicles taking the lead in this movement. However, there is high uncertainty in forecasting the evolution of these trends since they still require public policies to encourage their adoption.

Given that, this article aims to present the status of solar and wind energy technologies and electric vehicles in the world and their potential expansion, quantifying the demand for copper from wind and solar energy, and electric cars and buses.

2.2 Literature review

The following sessions are composed of two parts. The first provides a detailed review of renewable energy with focus on solar and wind energy, while the second one describes electric vehicles. The aim of both parts is to present the main characteristics, advantages, and challenges of these technologies regarding their adoption.

2.2.1 Overview of solar and wind energy

Renewable energy, as defined by Twidell and Weir (2015), is the “energy obtained from natural and persistent flows of energy occurring in the immediate environment”, while a non-renewable energy is “obtained from static stores of energy that remain underground unless released by human interaction”. With appropriate technologies, the sun, the wind, water, the Earth’s heat, the tides, and plants can turn them into usable forms of energy.

Solar and wind energy are the most common form of renewable energy used in the world. In 2021, solar and wind energy accounted for 21% of the electrical installed capacity in the world, starting from just 2% in 2012 (IEA, 2014, 2022b).

Solar energy is used to produce heat, light and power passively or actively. The system is considered passive when the insolation is absorbed and utilized without significant mechanical pumping or blowing. The system is active if the solar heat is collected in a fluid, which is then moved by pumps or fans (Twidell; Weir, 2015).

The power produced by the solar energy system can be converted into electricity. One alternative is photovoltaic (PV) technology, which basically depends on modules that convert sunlight into direct current and inverters that convert the electricity into alternating current. Modules are formed by PV cells, which each produce electricity only enough for small devices, such as calculators and wristwatches. When modules are joined in PV panels or when PV panels form PV arrays, they can produce electricity for an entire house (Energy Information Administration - EIA, 2020). Batteries can store excess electricity produced by the system (Tromly, 2001; Twidell; Weir, 2015).

Another alternative to convert solar energy into electricity are the solar thermal electric systems, which turn the sun’s heat into electricity using concentrating solar power technologies. The main components of these technologies are mirrors that capture and focus sunlight onto a receiver, which then transfers the heat to a conventional engine-generator that generates electricity. As the required infrastructure is big, solar thermal electric systems are generally used in large-scale power plants for powering cities and communities (Tromly, 2001).

Wind energy has been an important source of electricity, traditionally used to generate mechanical power, such as for pumping water. Wind results from expansion and convection of air as solar radiation is absorbed on Earth and is able to spin turbine blades or air foils around a central hub connected to a shaft, which powers a generator to make electricity (Tromly, 2001; Twidell, Weir, 2015).

Turbines below 50kW are considered to have a small scale in terms of electricity generation, while large projects can have hundreds of turbines, forming wind power plants or wind farms (Tromly, 2001). The largest wind turbines in operation have electricity generating capacities of up to 10,000 kW (EIA, 2020), but the growing market of wind energy has led to increasing investments in research and development of larger turbines. In 2020, a company launched a wind turbine with a normative capacity of 14,000 kW, shortly after another company had launched a 12,000-kW machine (Mathis, 2020).

Turbines can be placed onshore or offshore in the shallow water near a coastline. In 2021, 93% of the wind energy capacity installed was onshore, but lack of land availability can be a driver of offshore farms (International Renewable Energy agency - IRENA, 2022).

Solar and wind are available only when the sun shines or the wind blows and they are not dispatchable if not associated with a storage capability, which generally increases electricity costs substantially (Zhou, Wang, Zhou, Clarke and Edmonds, 2018). Liu (2018) investigated the economic and political barriers of solar energy development and concluded that the most important global limitations are climate, technical constraints, and unwillingness to make investments.

In a study focused on China, Zhou et al. (2018) estimated the impact of intermittency on future deployment of wind and solar energy by using an integrated assessment model called the Global Change Assessment Model. The authors took into consideration the fact that wind and solar energy requires growing quantities of backup power from reservoir hydropower, pumped hydro storage, and natural gas generation. Coal can also be used as a backup power, but this source loses efficiency as the number of ramp-up/-down procedures grows, so there is efficiency penalty related to coal. The results indicated that by 2050 the shares of wind and solar energy in China's power sector would decline by more than 10% compared to the case without consideration of intermittency. Moreover, wind and solar share in the electricity generation could be 20% in 2050 in a scenario where an economy-wide carbon price was imposed on greenhouse gas emissions in all time periods.

Gotzens et al. (2018) analyzed how expected future decreases in investment costs for photovoltaics, concentrated solar power, wind onshore, and wind offshore may affect the European and national electricity systems. Although the results showed that the assumed cost reductions lead to an especially pronounced increase of PV distributed unevenly across

Europe by 2050, the higher shares of VRE affect the electricity exchange patterns throughout Europe, reducing cost benefits for traditional electricity exporter economies. This might generate a lack of agreement among countries and hinder the exploitation of cost synergies or even slow down variable renewable energy expansion on a European scale.

The challenges associated with solar and wind energy adoption may result in different projections of their penetration in the energy matrix. In addition to these challenges, electricity demand models generally use GDP, population, and energy services price (Zhou et al., 2018), which can be another source of variability.

2.2.2 Overview of electric vehicles

A battery electric vehicle (BEV) is an electric vehicle (EV) that uses energy stored in rechargeable batteries. Electric vehicles have electric motors instead of or in addition to internal combustion engines (ICEs). Vehicles using electric motors and ICEs are called hybrid vehicles (HEVs) and are generally not considered pure BEVs. Hybrid vehicles with batteries that can be charged and run without their ICE are called plug-in hybrid vehicles (PHEVs) and are pure BEVs while they are not burning fuel (Opitz, Badami, Shen, Vignarooban and Kannan, 2017).

HEVs are more fuel efficient given the optimization of the engine operation and recovery of kinetic energy during braking compared to conventional vehicles (Chan, 2007). When PHEVs are charged from an electric power grid based on renewable sources, emissions are exceptionally low. These characteristics make the adoption of EVs appealing for governments to meet their climate targets.

Customers also value some characteristics when choosing between an ICE and an EV. Liao, Molin, and van Wee (2017) showed that the impact of financial, technical and infrastructure attributes of EV is significant to explain consumer preferences. These attributes include the purchase and operating costs, driving range, charging duration, vehicle performance, density of charging stations, and brand diversity on the market. To some extent, these attributes are conflicting. Once larger batteries will enable longer range, it tends to increase vehicle price and to change charging patterns and requirements for charging infrastructure.

The reduction in the purchase and operating cost largely depends on batteries, which are the most expensive component of EVs. The lithium-ion battery (LIB), the main technology used in the market, basically consists of a positive electrode (cathode) and a negative electrode (anode), which exchange lithium ions through an electrolyte. There is also a separator to prevent short circuits and current collectors to assist in electron transfer. Most modern LIBs use copper sheets as current collectors (Duffner et al., 2020).

The advantages of LIBs are the provision of the highest energy and power densities, a longer life cycle, and the ability to incorporate smart battery management systems, despite being more expensive compared to other cell chemistries (Opitz et al., 2017). Nykvist, Sprei and Nilsson (2019) analyzed BEVs running with LIBs and found that the price percentile, where the price of a BEV is comparable to conventional cars, changes in a nonlinear way when battery pack costs fall below 200–250 USD/kWh. In 2021, a LIB costed 132 USD/kWh (IEA, 2022b), below the 150 USD/kWh mark that implies cost competitiveness between a BEV with a 200-mile range and almost 50% of the US car market segments, in accordance with Nykvist et al. (2019).

In addition to reductions in LIBs costs, driving range, charging duration, and vehicle performance have improved. A relatively short driving range is one of the biggest barriers to the widespread adoption of EV (F. Liao et al., 2017). On brand diversity on the market, more compelling models have hit the market and car manufacturers are increasing their commitments to electrification (Pereirinha et al., 2018).

The driving range and charging duration issues are partially addressed by the density of charging stations and the increasing number of fast charging outlets. Aaldering, Leker and Song (2019) observed, based on the study of Dimitropoulos, Rietveld, and Van Ommeren (2013), that preference for range may be sensitive to charging station density and charging time.

The adoption of EVs is still dependent on government incentives, however. The review of F. Liao et al. (2017) pointed out that tax reduction is most likely effective, while there is not yet evidence supporting the effectiveness of other usage cost reduction such as free parking and toll reduction. Hardman, Chandan, Tal, and Turrentine (2017), by reviewing papers about financial purchase incentives directed to BEVs and PHEVs, showed that the premature removal of incentives could negatively affect their adoption, concluding that incentives should be designed with longevity in mind.

Like electric vehicles, electric buses (EBs) also operate by different degrees of electrification. The Battery Electric Bus (BEB) runs purely with battery and the Hybrid Electric Bus (HEB) uses electric motors and ICE. The Plug-in Hybrid Electric Bus (PHEB) follows series hybrid settings with an additional feature that allows the on-board battery to be recharged with an external electric source. The Fuel Cell Electric Bus (FCEB) powers the electric motor with electricity generated from fossil fuel (Mahmoud, Garnett, Ferguson and Kanaroglou, 2016).

2.3 Methodology

The methodology is composed of two parts. The first one shows how we estimated copper demand from renewables and electric vehicles. The second part describes the potential scenarios with projections of renewables and electric vehicles. In the following sessions, renewables can be understood as solar and wind energy, unless otherwise specified.

2.3.1 Calculation of copper demand

Following Dong et al. (2019), we used a bottom-up approach, where variations in in-use stock caused by changes in demographics, economic welfare, and government policies were linked to the end-of-life replacement of products, in accordance with the following formulae:

$$CS_{I,t} = \sum_{i=1}^{I} (P_{i,t} \times m_{i,t}) \quad (1)$$

$$CF_{i,t-l}^{in} = F_{i,t-l}^{in} \times m_{i,t-l} \quad (2)$$

$$CF_{I,t}^{out} = \sum_{i=1}^{I} CF_{i,t-l}^{in} \quad (3)$$

$$CD_{I,t} = \left(CS_{I,t} - CS_{I,t-1}\right) + CF_{l,t}^{out} \quad (4)$$

Where i represents product categories, I is the total number of product categories, which refers to offshore wind energy, onshore wind energy, solar energy, BEV, PHEV, and electric buses. t is the time in years. CS_t is the total copper stock in all products. $P_{i,t}$ is the physical quantity of each product in-use, such as the fleet size of BEV in a certain year t. $m_{i,t}$ is the copper intensity of each product. $CF_{I,t}^{out}$ is the outflow of discarded or obsolete products in year t, which equals to the sum of $CF_{i,t-l}^{in}$, the inflow of products i used in the year $t - l$, where l is the average lifetime of each product i. $CS_{I,t}$ and $CS_{I,t-1}$ are the total in-use stocks of copper from EVs in year t and year $t - 1$, respectively. $CD_{I,t}$ is the total copper demand of all products I.

The data series starts in 2015 and projections go up to 2030 for electric vehicles while the data range is from 2000 to 2050 for renewables. Both segments were basically inexistent in the energy and automotive markets before the starting year of the data series.

The intensity of material usage in solar energy has varied over the years and across technologies. Carrara, Alves Dias, Plazzotta and Pavel (2020) analyzed the copper usage intensity in four PV technologies, that are Crystalline Silicon (c-Si), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), and Amorphous Silicon (a-Si). Copper, together with concrete, steel, plastic, glass, aluminum, is a general material used in the structural and electric components of the PV power plants and are common to all technologies. CIGS panels are intensive in copper, although this segment represented less than 2% of the market share of PV technologies in 2017 and the additional copper intensity is lower than the copper used in the electric system, according to Carrara et al. (2020). We adopted a median value of 4.1 t/MW as the copper usage intensity figure in this study (Table 2.1).

In the case of wind energy, the intensity of material usage differs significantly within the same technology. We adopted the copper usage intensity median of 10.0 t/MW and of 3.5 t/MW for the onshore and offshore wind installations, respectively (Table 2.1). The most common models in the wind turbine segment are Direct Drive with Electrically Excited Synchronous Generator (DD-EESG), Direct Drive with Permanent Magnet Synchronous Generator (DD-PMSG), Gearbox with Permanent Magnet Synchronous Generator (GB-PMSG), Gearbox with Double-Fed Induction Generator (GB-DFIG), and Gearbox with Squirrel Cage Induction Generator (GB-SCIG). In 2018, the GB-DFIG technology was estimated to account for approximately 50% of the onshore wind in the global market, followed by the DD-PMSG and the GB-PMSG, which in combination had a nearly 30% share. In the case of the offshore wind, the DD-PMSG was responsible for 50% of the global market, followed by the GB-PMSG and the GB-SCIG, which had a share of roughly 40% together (Carrara et al., 2020).

Table 2.1 - Copper content in solar and wind energy

	Solar panel (t/MW)	Wind turbine Offshore (t/MW)	Wind turbine Onshore (t/MW)
Copper Development Association (2022)	5.50	9.60	3.50
Carrara et al. (2020)	4.60		
Beylot, Guyonnet, Muller, Vaxelaire, and Villeneuve (2019)	3.60		
Valero et al. (2018)	3.55		
Valero, Valero, Calvo, and Ortego (2018)		14.08	3.78
García-Olivares et al. (2012)		10.00	2.00
Minimum	3.55	9.60	2.00
Maximum	5.50	14.08	3.78
Deviation	55%	47%	89%
Maximum deviation	34%	41%	8%
Minimum deviation	-13%	-4%	-43%
Average	4.31	11.23	3.09
Median	4.10	10.00	3.50
Count	4	3	3

Source: Developed by the author based on Copper Development Association (2022), Carrara et al. (2020), Beylot et al. (2019), Valero et al. (2018), Valero, Valero, Calvo and Ortego (2018), García-Olivares et al. (2012).

The copper use between onshore and offshore installations differs considerably. Because of that, we separated historical wind installed capacity by onshore and offshore technologies based on IRENA data (2022). For projections, however, we applied the share from 2021, that was 93% for onshore installed capacity.

Table 2.2 presents the copper content of electric vehicles and buses while Table 2.3 shows the average lifetime of renewables and electric vehicles. Nguyen, Eggert, Severson, and Anderson (2020) presented an estimate for EV battery lifetime of 8 years, based on a study from 2012, Deetman et al. (2018) used a lifetime of 9.1 years, based on Weibull distribution parameters of a study from 2013. Dong et al. (2019) considered the lifespan from a more recent study from 2016.

Table 2.2 - Copper content by vehicle type

Vehicle type	Copper content (kg per vehicle)
PHEV	60
BEV	83
PHEB	89
BEB	297

Source: IdTechEx (2017).

Table 2.3 - Life span of technologies

Technologies	Life span (years)	Source
Solar PV	25	Carrara et al. (2020)
Onshore wind	25	Carrara et al. (2020)
Offshore wind	30	Carrara et al. (2020)
PHEV	13	Dong et al. (2019)
BEV	13	Dong et al. (2019)
PHEB	13	Dong et al. (2019)
BEB	13	Dong et al. (2019)

Source: Carrara et al. (2020) and Dong et al. (2019).

2.3.2 Estimates for solar and wind energy and electric vehicles

IEA (2022b) designs three scenarios for the path the energy system can follow: Announced Pledges Scenario (APS), Stated Policies Scenario (STEPS), and Net Zero Emissions by 2050 (NZE). The first considers all the climate commitments made by governments around the world, including Nationally Determined Contributions as well as longer term net zero targets, and assumes that they will be met completely and on time while the STEPS considers that governments will not reach all announced goals. The NZE sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050 and is designed to meet key energy-related United Nations SDGs (IEA, 2022b).

All scenarios are available for installed capacity of wind and solar energy in the world, while for EVs, the scenarios used are STEPS and APS, containing the fleet size for battery and plug-in hybrid passenger light-duty vehicles (PLDVs) and buses. The NZE scenario is discussed in the Global Energy Outlook Report, but the entire dataset related to it is not publicly available.

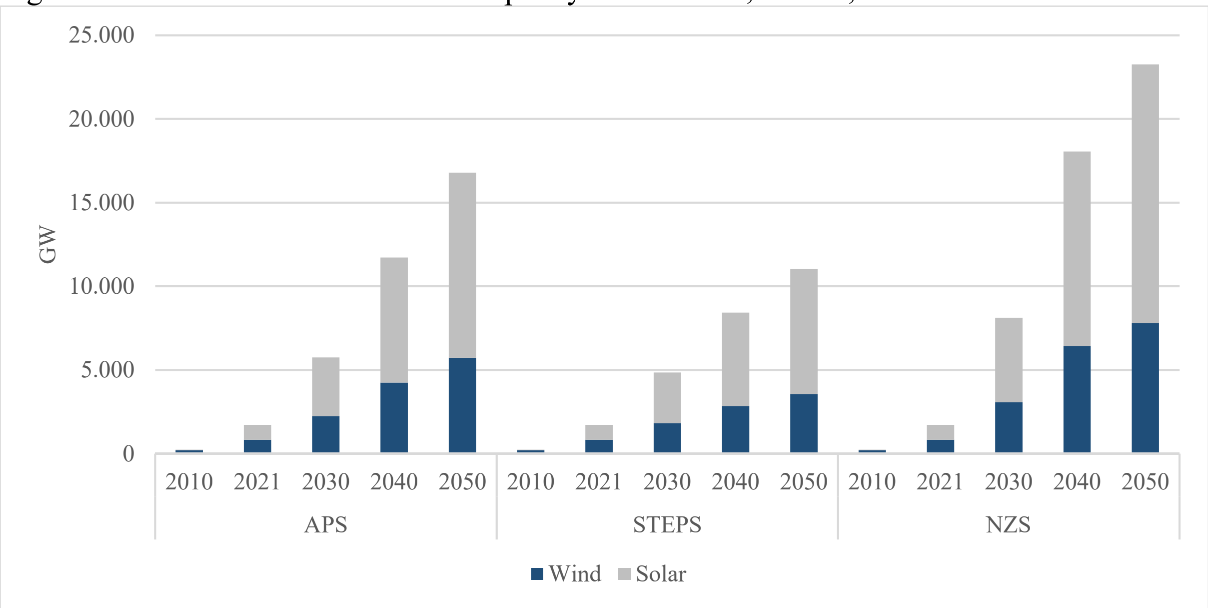
IEA (2022b) does not provide projections for the entire year but for specific years. In the case of renewables, there are projections for 2030, 2040, and 2050 while for electric vehicles, IEA (2022a) provides forecasts for 2025 and 2030. We considered a linear growth between these time ranges.

2.4 Discussion of results

2.4.1 Copper demand from solar and wind energy

Global installed capacity of solar energy increased 33.2% annually from 2010 to 2021 while wind energy presented a rise of 13.9% annually in the same period (Figure 2.1). The drastic reduction in costs of solar and wind has been driven by improved technologies, economies of scale, supply chain competitiveness, and knowledge accumulation. Newly installed renewable power capacity increasingly costs less than the cheapest power generation options based on fossil fuels, and new solar and wind projects are undercutting the cheapest existing coal-fired plants (IRENA, 2020). Despite that, falling oil prices and weak macroeconomic aspects can delay the adoption of renewable energy (Shah, Hiles and Morley, 2018).

Figure 2.1 - Solar and wind installed capacity in the world, in GW, 2010 - 2050



Source: IEA (2012, 2022a).

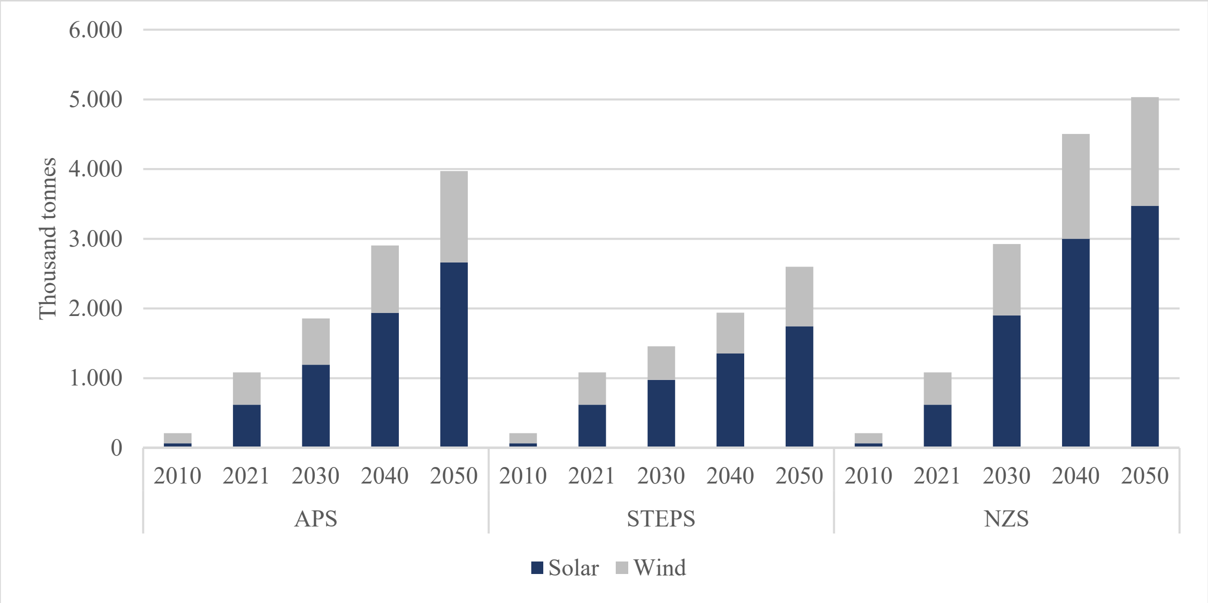
The scenarios APS, STEPS, and NZE project a rise of 9.1%, 7.6%, and 10.3% annually of solar installed capacity from 2021 to 2050, respectively. For wind installed capacity, these figures are 6.9% for APS, 5.1% for STEPS, and 8.0% for NZE over 2021-2050 (Figure 2.1). Government incentives and continued cost reduction will likely contribute to the expansion of renewables, although the gap between these scenarios reflects the uncertainty that surrounds the multiple options that need to be combined to reduce CO_2 emissions and the challenges associated with solar and wind adoption, such as the variability and intermittency inherent to variable renewable energy.

Increases in solar and wind energy installation have spurred copper demand. In 2021, solar PV panels used around 619,100 tonnes of copper while wind turbines were responsible for approximately 463,851 tonnes, with both representing a share of 4.3% in global refined copper demand of 25,264,000 tonnes, according to data from the International Copper Study Group (ICSG) (2022). However, the copper intensity in these technologies depends on their size and model. Based on the minimum copper intensity in renewables from selected articles (Table 2.1), demand from solar and wind could have been of nearly 880,000 tonnes in 2021. The maximum copper intensity suggests a demand of almost 1,400,000 tonnes in 2021. Although this difference is small considering the size of the copper market, it tends to increase as these technologies become more prominent in their segments.

Copper demand from solar and wind is expected to present a significant growth by 2050 in all scenarios. Solar PV panels and wind turbines are projected to need 2,661,122 and 1,309,828 tonnes of copper by 2050, respectively, based on the APS scenario and average intensity. The STEPS scenario shows copper demand growing to 1,745,137 tonnes from solar PV and 854,416 tonnes from wind turbines by 2050 while the NZE scenario points to a demand of 3,473,196 tonnes from solar and 1,560,537 tonnes from wind (Figure 2.2).

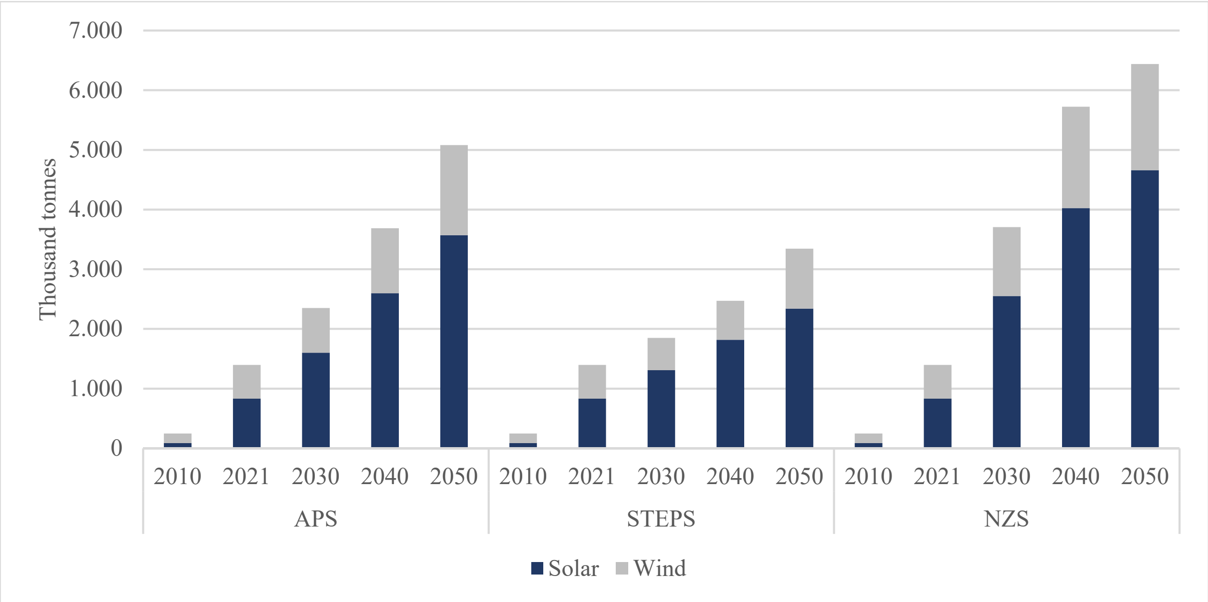
In the scenario where the maximum figure of copper intensity is assumed, solar PV panels and wind turbines are projected to need 3,569,798 tonnes and 1,511,459 tonnes of copper by 2050, respectively, based on the APS scenario (Figure 2.3). On the other hand, solar panels and wind turbines demand 2,304,143 tonnes and 864,911 tonnes of copper by 2050, respectively, in the scenario based on the minimum figure of copper intensity (Figure 2.4). Therefore, under the same installed capacity growth of the APS scenario, copper demand from renewables and EVs can differ by nearly 1,912,203 tonnes. Comparing, however, the scenarios NZE with maximum copper intensity and SDS with minimum copper intensity, the difference is above 4,000,000 tonnes.

Figure 2.2 - Copper demand from solar and wind, average intensity scenario, in thousand tonnes, 2010 - 2050



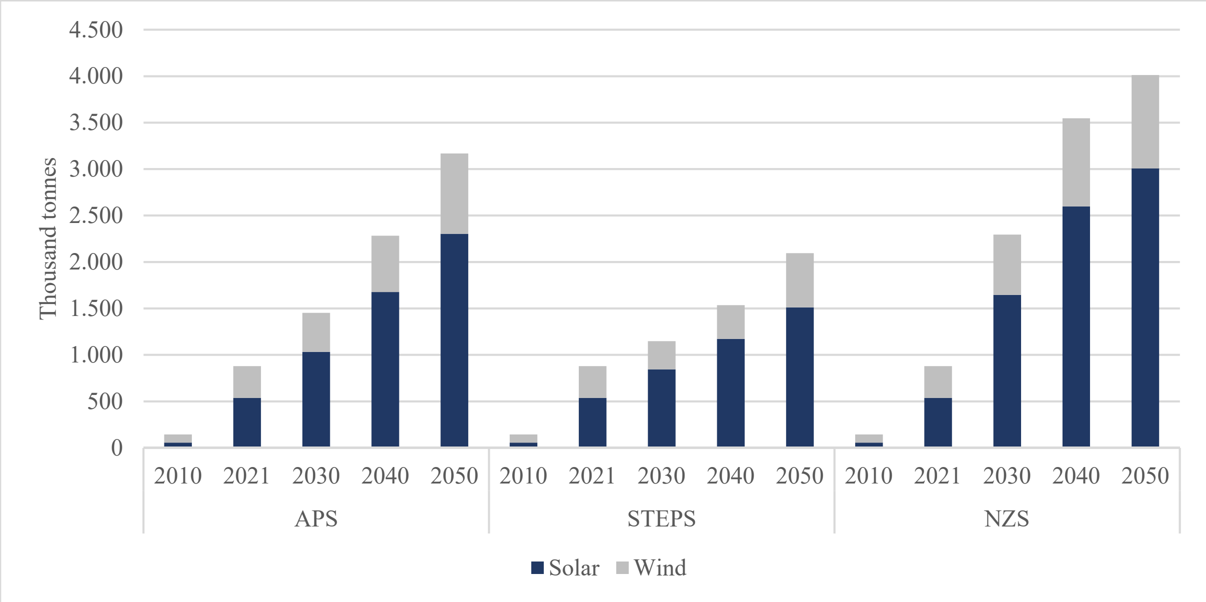
Source: Original research data.

Figure 2.3 - Copper demand from solar and wind, maximum intensity scenario, in thousand tonnes, 2010 - 2050



Source: Original research data.

Figure 2.4 - Copper demand from solar and wind, minimum intensity scenario, in thousand tonnes, 2010 - 2050



Source: Original research data.

2.4.2 Copper demand from electric vehicles and Ebus

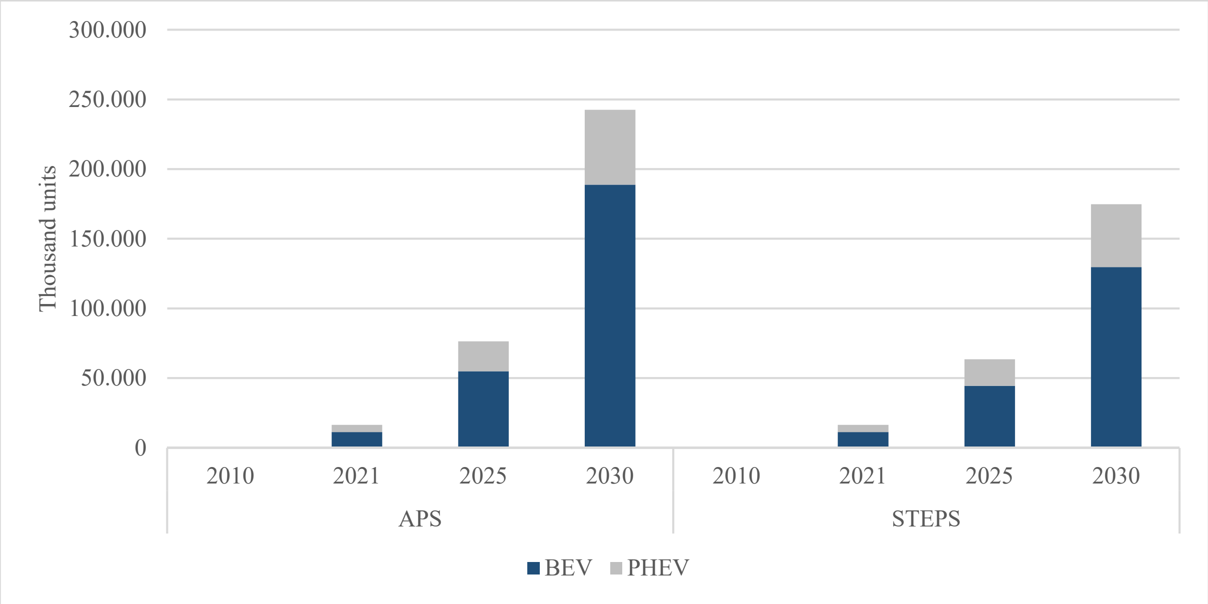
The share of electric vehicles in the global fleet has increased over the years and reached 1.4% in 2021, following the compound average growth rate of electric vehicles sales of 51.1% from 2015 to 2021 (Figure 2.5). China has the largest annual sales of battery electric vehicle (including plug-in hybrid vehicles) in the world and its electric fleet totaled over 7.8 million cars in 2021, followed by the United States with 2.1 million cars in that same year (IEA, 2022a).

The growing adoption of EVs has been driven by improvement of EVs attributes that are valued by customers. Factors such as cost reduction in LIBs, increasing penetration of EVs, cumulative knowledge on this battery technology, and possibility of recombining innovations at low switching costs for automotive applications may benefit LIBs optimization and potentially further reduce costs (Aaldering et al. 2019).

Yet the cost gap between electric and conventional vehicles has reduced, the uptake of electric mobility still depends on public policies, such as fiscal incentives, regulatory measures (e.g., lower toll or parking fees) and development of charging infrastructure in cities and highways (IEA, 2019c). In 2021, the number of public charging points was nearly 1.8 million, with 32.2% corresponding to fast charging points (IEA, 2022a). Most public charging connectors were in China, which is the country with the highest number of EVs in the fleet. This demonstrates the importance of charging infrastructure development in promoting EV.

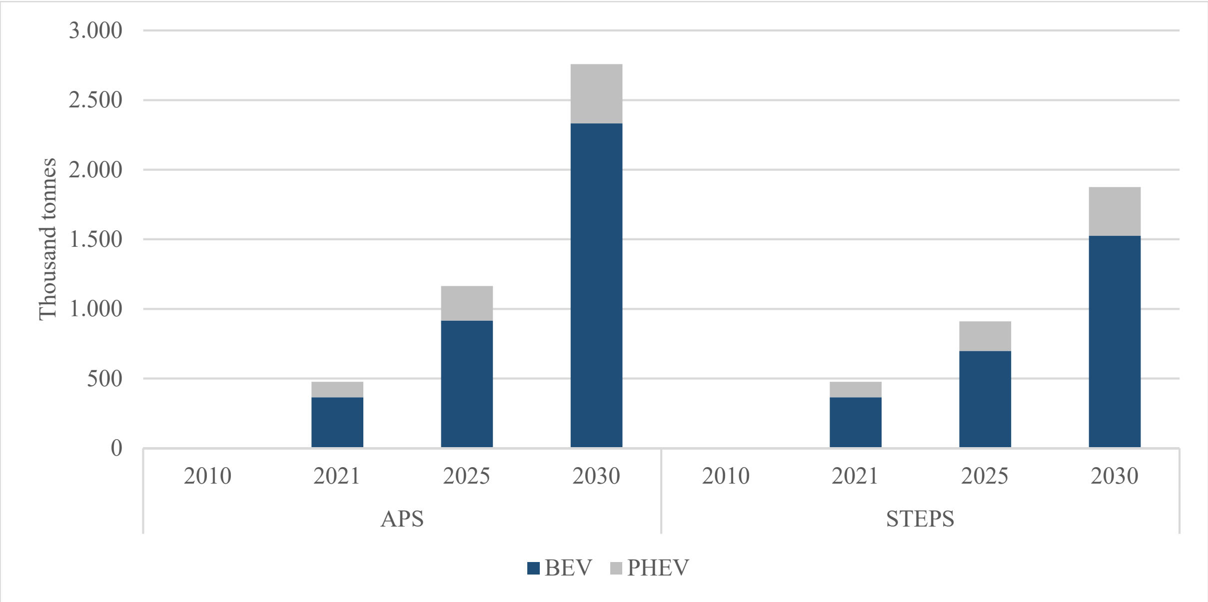
In 2021, EVs consumed 476,533 tonnes of copper, accounting for 1.9% in global copper demand, according to data from ICSG (2022). By 2030, EVs are expected to be responsible for 2,758,252 and 1,875,490 tonnes of copper demand in the APS and STEPS scenarios, respectively (Figure 2.6).

Figure 2.5 - Electric vehicle fleet (BEV and PHEV) in the world, in thousand units, 2010 - 2030



Source: IEA (2022a).

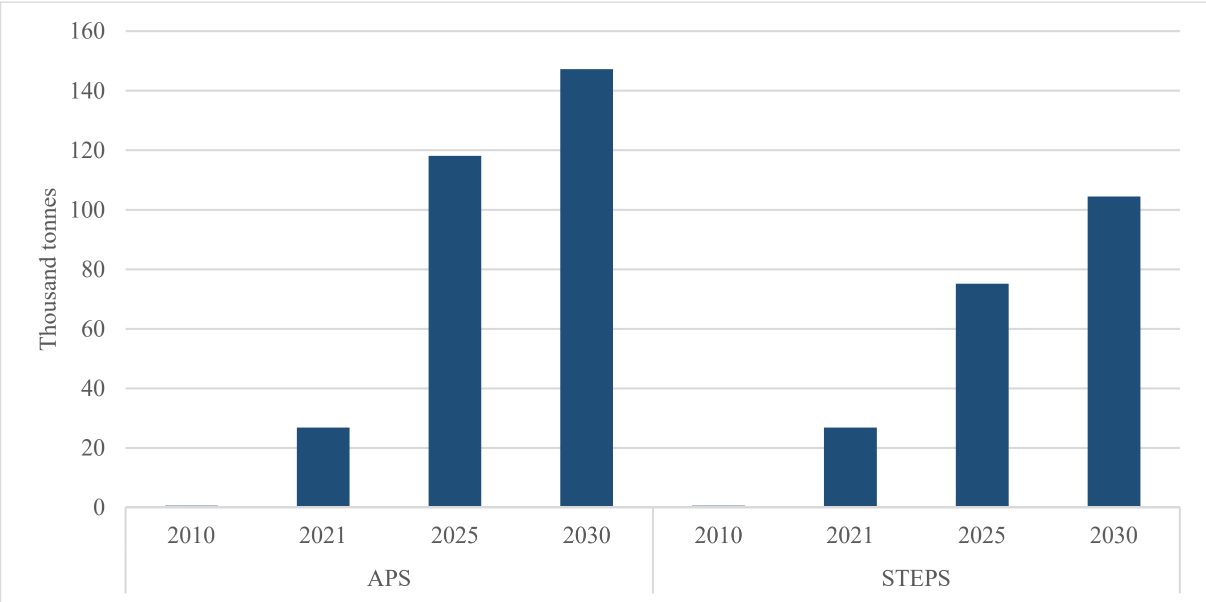
Figure 2.6 - Copper demand from BEV and PHEV in the world, in thousand tonnes, 2010 - 2030



Source: Original research data.

Electric buses have gained share in the market, with the global electric bus stock at 673,000 units in 2021, representing about 4% of the global fleet for buses (IEA, 2022a). China is the leading market in terms of number of units sold and fleet size, with the highest share of EBs in the bus fleet. By 2030, electric buses are expected to demand 147,251 tonnes of copper from 26,863 tonnes in 2021 in the APS scenario. In STEPS, copper demand is projected to be of 104,450 tonnes by 2030 (Figure 2.7).

Figure 2.7 - Copper demand from electric buses (BEB and PHEB) in the world, in thousand tonnes, 2010 - 2030



Source: Original research data.

2.5 Conclusions

Growth in solar and wind energy technologies and electric vehicles has been consistent and robust, with solar and wind installed capacity rising annually 33.2% and 13.9%, respectively, from 2010 to 2021 and electric vehicles fleet increasing annually 86.6% in the same period.

However, the forecasts of these trends are influenced by multiple factors and stakeholders. The willingness and capacity of governments to provide incentives for these sectors, driven by the overarching goal of combating climate change, play a crucial role. Additionally, the evolution of solar and wind energy and electric vehicles is influenced not only by environmental factors but also by other considerations, such as a country's dependence on energy imports.

Companies also have a significant role to play in this landscape. They can contribute by enhancing existing technologies to make them more appealing to consumers. Simultaneously, investments in research and development can lead to the discovery of new technologies that further advance the progress in these fields.

The selected scenarios for solar and wind energy and electric vehicles result in a large difference in terms of copper demand. But if we add the uncertainty regarding the copper content in these technologies, the difference widens and can reach more than 4,000,000 tonnes by 2050.

Assessing and anticipating the future demand for copper is crucial for avoiding supply shortages and disruptions in the transition towards sustainable energy sources. Moreover, it plays a vital role in supporting essential aspects such as infrastructure development, resource allocation, and research and development efforts.

Copper supply is not as elastic as other commodities, meaning that supply cannot change in a short period of time despite price incentives. Considering the limited elasticity of copper supply, exploring strategies to enhance copper recycling and promoting sustainable mining practices are essential to address the potential challenges associated with meeting the surging demand.

3. SYSTEMATIC REVIEW OF THE MARKET DYNAMICS OF SECONDARY SOURCES OF COPPER

Abstract

This study systematically evaluates the literature on the market dynamics of secondary sources of copper, based on a selection of 42 articles from two databases. There is an increasing number of articles addressing this topic, which shows the growing importance of secondary sources from a circular economy and demand perspectives. Despite the rising number of articles, most part of the research is focused on few regions, namely China, United States, and Europe. While they are the major players in the recycling sector, the global recycling industry and its legal framework should work in a collaborative way to guarantee best environmental, social, and governance practices in the recycling process. We identify several factors that explain the dynamics of the copper scrap market, including copper in-use stock, product lifetime, scrap collection rate, recycling efficiency, copper prices, and trade barriers. The identification of these factors could help policy makers and stakeholders to make more assertive decisions to promote the copper recycling industry, helping countries to achieve a circular economy.

Keywords: Scrap; Recycling; Circular economy; China

3.1 Introduction

The high electrical conductivity of copper makes it an essential metal in the mitigation of climate-change through the adoption of green technologies, such as wind and solar energy and electric vehicles. Increasing primary copper supply, however, is challenging amid growing environmental, social, and governance scrutiny and an empowerment of non-state actors.

Another concern is related to resource scarcity, although the discovery of additional deposits has exceeded consumption for many non-renewable resources over many time periods so that reserves have risen (Krautkraemer, 1998). The idea that mineral production cannot meet the material aspirations of future generations dates back to the Eighteenth century, when Thomas Malthus studied demography and resources. With an estimated population of 9.7 billion in 2050 and the least developed countries among the fastest growing in the world in this period, there is an emerging pressure regarding resources use and the achievement of the Sustainable Development Goals amid this scenario (United Nations, 2022).

Some argue that many of the minerals that the population demands exist in practically inexhaustible amounts but mining them comes with direct or accumulative environmental consequences that can pose serious threats to ecosystems and human health (Wagner, Sullivan and Sznopek, 2002). Declining ore grades is already observed in the copper mining industry, either due to a change in the type of mined deposit, with a rise in the share of relatively low-grade porphyry deposits, or the ageing of many mines (Crowson, 2012). Mining low-grade ore deposits can impact the environment through higher waste rock removal, tailings generation, and disturbance to local habitat (Northey et al., 2014).

The inequality in the distribution of geological resources could also limit the availability of raw materials between countries, as it is the case with cobalt, oil, and rare earth elements (Habib, Hamelin and Wenzel, 2016). In 2020, Chile accounted for almost a third of world copper mine production with mine output of 5.7 million tonnes in copper content, followed by Peru with 10% (ICSG, 2022). Other copper mining regions face political instability, such as the Democratic Republic of Congo, where the ability of the government to formulate policies and implement regulations that create conditions for attracting investment is low, according to the governance indicators from 2019 of the World Bank (2022).

A circular economy is constructed from societal production-consumption systems that maximize the service produced from the linear nature-society-nature material and energy flow, according to the definition from Korhonen et al. (2018). The adoption of a circular economy could be an alternative to deal with challenges of the primary copper industry and contribute to the economic, environmental, and social dimensions of sustainable development.

Secondary sources of copper, commonly called scrap, could reduce or eliminate the need for primary copper extraction in the long term. China has been the main consumer of copper scrap in the world, while developed economies such as the United States and Europe have been the major suppliers, because they have consumed copper for longer.

Understanding the market dynamics and characteristics of secondary sources of copper is important from the perspective of the sustainable development paradigm and of the mining industry with the purpose of strategic planning and capital allocation. Based on this brief overview, the present study systematically evaluates the literature on the market dynamics of secondary sources of copper. It seeks to identify converging themes in published articles and the main methodological resources used in the area, so that it is possible to characterize the main supply drivers of secondary sources of copper. This study will provide an updated and synthetic review for future studies.

3.2 Methodology

A systematic review locates and selects existing studies, evaluates contributions, analyzes and synthesizes data, and reports the evidence, allowing reasonably clear conclusions to be reached about what is and is not known (Denyer and Tranfield, 2009). This methodology helps to identify the main research practices in a specific topic or area in different periods of time and the deficiencies and trends that can contribute to future research.

Systematic reviews have been widely adopted in health science, where an evidence-based approach is carried out as part of clinical decision making. In management, systematic reviews may be used to provide solid conclusions and support decision making in different contexts. This requires defining a clearly specified question, usually derived from a policy or practical problem, using existing studies (Denyer and Tranfield, 2009).

Considering the increasing need of copper and the challenges associated with rising its supply, secondary sources of copper is expected to play a key role in the future. Hence, the guiding question of this study is: What is the available evidence in the scientific literature about the factors that drive the supply of secondary sources of copper? The aim is to verify how questions have been formulated and how the methodological resources have been employed in such a way that the results can be analyzed, and conclusions could help to underpin through which channel copper scrap market could be stimulated. In case that knowledge gaps and inconsistencies are found, questions for future research could be raised.

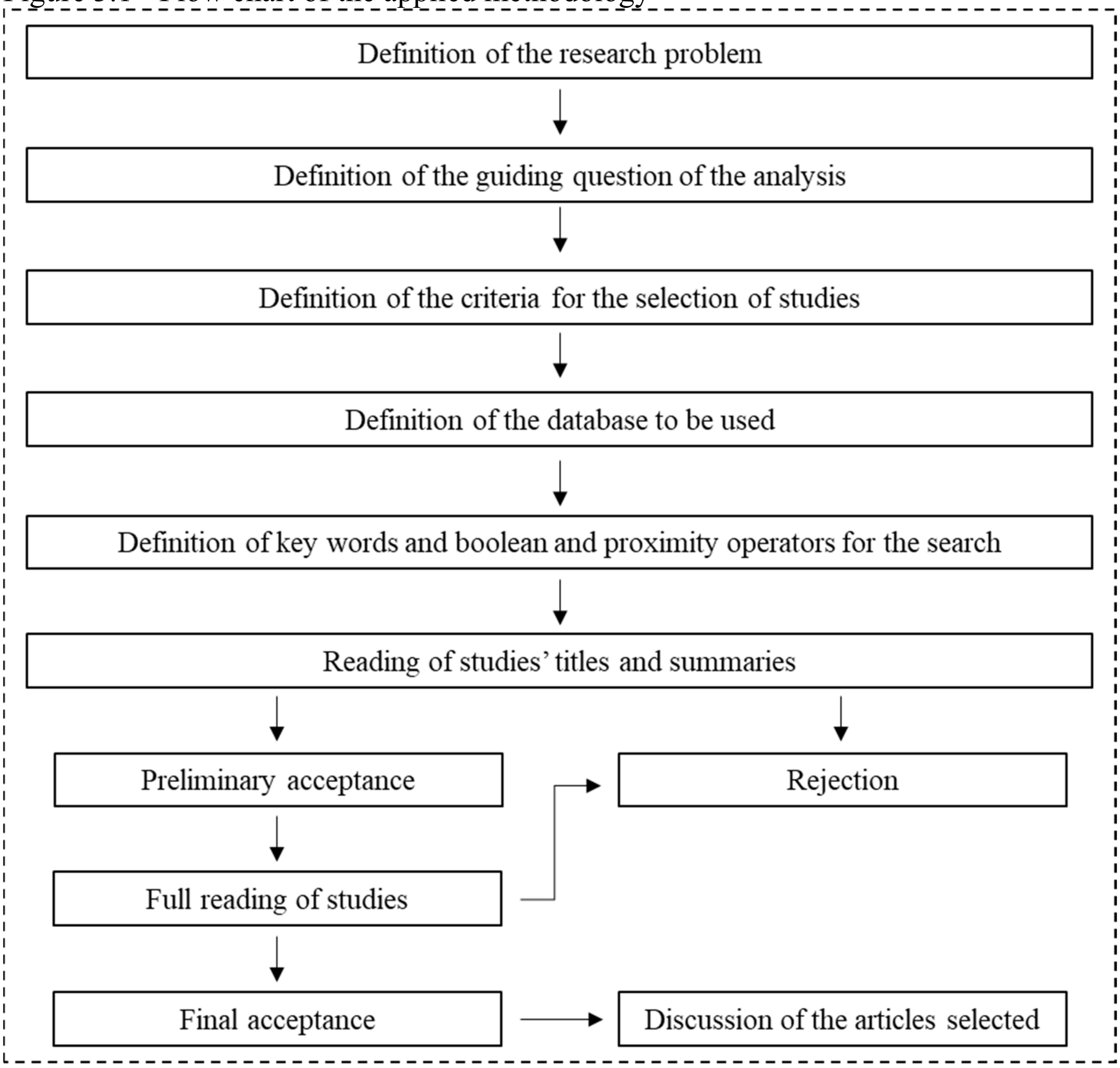
The bibliographic search was carried out in December 2020, through electronic search of scientific articles indexed in the following databases: Elsevier Scopus and University of Sao Paulo Integrated Search Portal (PBi, in Portuguese). The use of more than one database aims to avoid biased results, since databases can favor some field, country, and language, among other factors (Harzing, Alakangas, 2016; Mongeon, Paul-Hus, 2016).

Related to criteria for the selection of studies: (i) published from 2010 to 2020; (ii) articles written fully in English; (iii) original studies related to the fields of management, economy, business, social science, environment, and energy; (iv) related to the guiding question, focusing on the factors associated to the copper scrap supply throughout the study and not only addressing the topic superficially.

The initial selection was based on results from a search where a combination of specific terms was used related to the guiding question. In the case of Scopus, this combination of terms was possible using proximity operator “W/n” and Boolean operators “AND” and “OR”. The proximity operator “W/n” means that a certain term must occur within n words of another term. For instance, in the case of “copper W/30 scrap”, the word copper must occur within 30 words of scrap, regardless the sequence of the words. This approach seeks to bring more relevant results to the search. The PBi does not allow for proximity operators, therefore quotation marks were used to collect more relevant results. The words should be in the title, summary, and/or keywords. The search code used in Scopus and PBi is in the Appendix A.

We read the summaries of the articles that resulted from the initial selection and applied the criteria mentioned above to select or exclude them. Following this procedure, we analyzed the selected articles completely and applied the criteria of selection and exclusion again. This last step resulted in the articles whose findings were discussed in the systematic review. Figure 3.1 provides a schematic flow of the method and its steps.

Figure 3.1 - Flow chart of the applied methodology



Source: Developed by the author.

3.3 Systematic review of selected studies

The initial selection resulted in 145 and 621 studies from Scopus database and the Integrated Search Portal from USP, respectively. The large number of articles in the Integrated Search Portal is driven by the fact that it does not allow for proximity operators. Consequently, the Integrated Search Portal showed 388 studies from Scopus, while Scopus itself showed 145, where the proximity operator “w/n” was used with Boolean operators.

Although the specific search terms and all other required criteria were fulfilled, most studies were related to engineering and chemistry. After reading the titles and summaries, the combined number of selected studies from the two databases was 42, with 13 focusing on the Chinese copper scrap market.

3.3.1 Studies focused on the Chinese market

For each study of the 13 studies that focused on the Chinese copper scrap market, Table 3.1 shows the name of the authors and the year of publication and a symbol to identify them in tables and graphs presented in the next sessions, where we discuss methodologies, and key results of the selected studies.

Table 3.1 - Identification of studies focused on the Chinese market

Authors	Article symbol
Zhang, L., Yuan, Z. & Bi, J. (2012)	CH.1
Zhang, L., Yang, J., Cai, Z. & Yuan, Z. (2014)	CH.2
Wen, Z., Zhang, C., Ji, X. & Xue, Y. (2015)	CH.3
Zhang, L., Cai, Z., Yang, J., Yuan, Z. & Chen, Y. (2015)	CH.4
Wang, M., Chen, W., Zhou, Y. & Li, X. (2017)	CH.5
Soulier, M., Pfaff, M., Goldmann, D., Walz, R., Geng, Y., Zhang, L. & Espinoza, L. A. T. (2018)	CH.6
Dong, D., Tukker, A. & Van der Voet, E. (2019)	CH.7
Eheliyagoda, D., Wei, F., Shan, G., Albalghiti, E., Zeng, X. & Li, J. (2019)	CH.8
Wang, J., Ju, Y., Wang, M. & Li, X. (2019)	CH.9
Dong, D., Espinoza, L. A. T., Loibl, A., Pfaff, M., Tukker, A. & Van der Voet, E. (2020)	CH.10
Hao, M., Wang, P., Song, L., Dai, M., Ren, Y. & Chen, W. Q. (2020)	CH.11
Liu, S., Zhang, Y., Su, Z., Lu, M., Gu, F., Liu, J. & Jiang, T. (2020)	CH.12
Zeng, X., Ali, S. H., Tian, J. & Li, J. (2020)	CH.13

Source: Developed by the author.

3.3.2.1 Objective of the studies

China is the largest importer of copper ores, refined copper, and copper scrap, as domestic copper mine production is not enough to meet its demand. The share of imported copper scrap in total supply of recycled copper scrap in China exceeded 50% almost every year from 1990 to 2016, despite the increasing relevance of domestic material (J. Wang et al., 2019). However, environmental problems triggered by poor technology and equipment for dismantling and recycling copper scrap have prompted the Chinese government to restrict the imports of certain low-quality copper material (Dong et al., 2020).

A stricter import policy, however, does not suggest that China will see a shortage of copper scrap supply, because the Chinese domestic copper scrap availability is expected to surge in the following years, reducing its dependence on imported material. China has been the largest copper consumer in the world since 2002 and has accumulated a remarkable amount of copper in goods and infrastructure used by society, which will eventually reach their end of life and be available for recycling (Dong et al., 2019). Additionally, Chinese copper demand is projected to continue to increase, driven by an increasing population, income, and urbanization.

In this context, several studies have explored alternatives and suggested policies to meet China's copper demand in the future, with scrap being one of the main topics addressed. The general research objective of the 13 studies was to assess the Chinese copper in-use stock to subsequently estimate the supply of recycled copper and its potential to meet a growing demand in China (Table 3.2).

Table 3.2 - Objectives of studies focused on the Chinese market

Article symbol	Study's objective
CH.1	Estimate copper in-use stocks in Nanjing - China in the year of 2009 using a bottom-up approach
CH.2	Illustrate how copper utilization pattern has changed in the anthroposphere of China from 1975 to 2010 to understand the utilization pattern of copper resource, including natural resources exploitation, recycling situation, and trade situation
CH.3	Explore the trends of urban mine reserves from 2010 to 2050, assess the potential for secondary metal resources replacing primary metal resources, and discuss practical strategic measures to achieve the proposed scenarios
CH.4	Assess the possible future trend of copper in-use stocks from 2013 to 2080 based on the copper flows and stocks from 1949 to 2012
CH.5	Model copper metabolism by 2022 based on refined copper consumption from 1949 to 2013, exploring the temporal delay from copper products to copper scrap through society
CH.6	Present a dynamic analysis of the Chinese copper cycle for the time frame between 1990 and 2015 based on highly disaggregated industry and trade data, capturing the entire value chain from mining to recycling
CH.7	Analyze copper demand in China from 2005 to 2050 based on government and related sectoral policies
CH.8	Determine the annual historical demand and supply, the annual prospective demand, and the carrying capacity and future sustainability of copper resources in China
CH.9	Assess the in-use stock of refined copper from 1990 to 2035 to estimate the potential supply of recycled copper in China
CH.10	Explore the questions of whether China should continue to import scrap copper and how the country should meet its future copper demand
CH.11	Quantify the location, amount, and category of copper in-use stocks by building the copper in-use stocks database, which compiles 74 types of copper-containing products from 1978 to 2016 by using the bottom-up method
CH.12	Forecast the supply and demand of China's future copper
CH.13	Map the generation of anthropogenic mineral and 23 types of the capsulated materials by targeting their evolution from 2010 to 2050

Source: Developed by the author.

3.3.1.2 Methodology of the studies

There were 12 studies that used flow analysis to define the copper cycle, with some of them classifying their methodologies as a material flow analysis (Wen et al., 2015; Soulier et al., 2018; Dong et al., 2019; J. Wang et al., 2019; Dong et al., 2020; Hao et al., 2020; Zeng, Ali, Tian and Li, 2020) and others as a substance flow analysis (Zhang, Yuan and Bi, 2012; Zhang et al., 2014; Zhang et al., 2015; M. Wang et al., 2017; Eheliyagoda et al., 2019). According to the Organization for Economic Cooperation and Development (OECD, 2008), material flow analysis monitors flows of selected raw materials or semi-finished products at various levels of detail and applications and considers life-cycle-wide inputs and output. Substance flow analysis monitors flows of individual substances that raise concerns related to the environmental and health risks associated with their production and consumption. OECD (2008) explains that the term 'materials' designates the usable materials or substances extracted from natural resources, such as metal ores and metals. By substances, the term refers to 'pure' chemical elements or compounds, such as CO_2 and heavy metals, that raise environmental concerns. Despite this difference in the classification of material and substance flow analysis, the selected studies used different terminologies to analyze the process at which a raw material becomes a finished product that is used during a time, and after it is discarded.

Only Zhang, Yuan and Bi (2012) and Zhang et al. (2014) assessed the copper system in specific years, providing a static picture of the flow while most of the studies carried out a dynamic assessment, describing the behavior of a system over a time interval. A dynamic assessment provides an understanding on the in-use stock of materials over time and determines the potential of the secondary resource supply in the future combined with a lifetime distribution (J. Wang et al., 2019). Studies reliant on dynamic assessment, however, do not necessarily forecast copper flows. Soulier et al. (2018) and Hao et al. (2020) applied a dynamic model for the periods 1990 – 2015 and 1978 – 2016, respectively, but did not project how the in-use stocks would evolve.

The copper flow analysis tends to be complex, as its value chain involves many steps, which are generally split into mining, refining, fabrication, manufacturing, use, and waste management and recycling. Zhang et al. (2015) explain that copper ore is firstly mined, crushed, and ground to separate metal-bearing mineral from the gangue, having concentrates and tailings as final products of these processes. Copper concentrate then feeds into a smelter, which in turn produces blister copper and slag, with the first been further refined into high-purity copper. The subsequent process is the conversion of high-purity copper into semi-finished products to finally manufacture and assemble more complex intermediate products and final products.

Copper products enter the society use stage and will provide service for some years, with their lifetime varying among the end-use categories. The amount of copper been used by society is referred to as copper in-use stocks and the discarded annual outflow of obsolete products from the in-use stocks eventually becomes part of the waste management and recycling flow.

In addition to the recycling from the worn out, discarded or obsolete copper content in end-use sectors, two other sources of scrap are generated at the semi-finished and final production steps and re-enter into the copper system, such as clippings, trimmings, stampings, borings, and turnings. At the semi-finished production step, Zhang et al. (2014) mention that scrap can return to the refinery or, according to Soulier et al. (2018), is usually re-melted immediately without material losses. At the final production step, scrap normally goes back to copper semis fabricators for direct remelting, although Soulier et al. (2018) point out that Chinese end-use fabricators often run their own furnaces, where new scrap is recycled and thus not recorded as a new scrap flow.

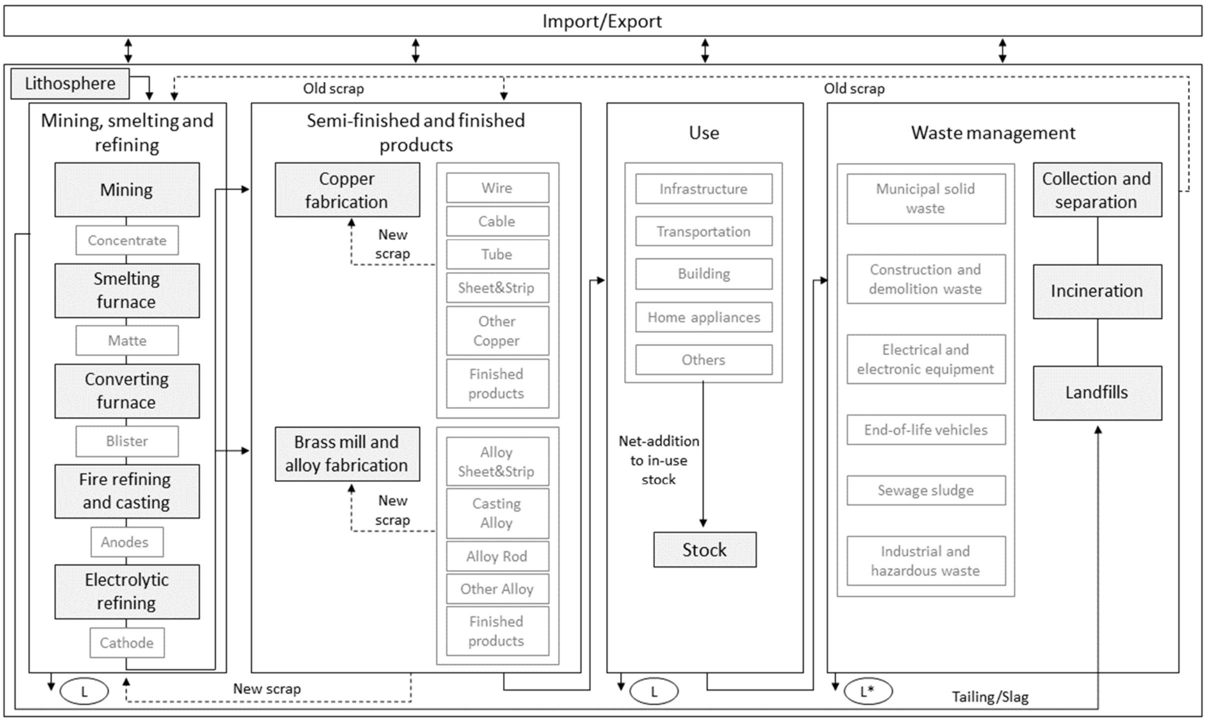
According to Dong et al. (2020), scraps generated at the production stage is dependent on the fabrication efficiency, related to the equipment and technological adoption, and the collection efficiency, which J. Wang et al. (2019) state to be relatively high, as very few of these two sources of scrap will fail to be recycled and become losses to the biosphere.

Scrap that comes from semis and final production is known as new scrap or pre-consumer scrap once it has not reached consumers and is in the processing stage. Copper scrap that comes from worn out, discarded or obsolete products is known as old, end-of-life (EOL), post-consumer scrap, as the copper-bearing material has reached consumers and has been discarded (Soulier et al., 2018; Eheliyagoda et al., 2019).

As China is highly dependent on imported copper in different forms, international trade is generally observed in all the stages of the copper life cycle, summarized in Figure 3.2.

Zhang et al. (2014) and Zhang et al. (2015) considered the scrap generated from the semi-finished and final production stages and from worn out, discarded or obsolete copper products, while some studies simplified the flow analysis by not considering these three sources of copper scrap. According to Soulier et al., (2018), Eheliyagoda et al. (2019), and Dong et al. (2020), scrap comes from the production stage and old scrap while the remaining studies focused on old scrap originated from national and international origins.

Figure 3.2 - Copper life cycle in an open economy



Source: Developed by the author
Note: L refers to losses to the biosphere; * in addition to losses to the biosphere, it includes abandoned material.

Zhang et al. (2014) and Zhang et al. (2015) state that scrap from the semi-finished manufacturing was based on the apparent consumption of refined copper multiplied by a coefficient from the literature. Scrap from the final production stage of final goods was calculated based on the production of semis, including copper semis and copper alloy semis multiplied by a coefficient from the literature. Dong et al. (2020) applied a dissipation rate to estimate new copper scrap generated during the fabrication of copper products and to reflect a certain amount of dissipation or abandoned copper in place and a loss rate of separation. The fabrication efficiency assumed was the 2016's figure of 89%, with a collection efficiency of 95%.

Figure 3.2 shows that old scrap is highly dependent on past consumption of copper and the service time of copper-bearing materials. However, the calculation of old scrap generation differs among studies. Only few studies adopted a bottom-up approach, such as Zhang, Yuan and Bi (2012), Dong et al. (2019) and Hao et al. (2020), where flows and stocks are quantified based on the number of copper products in use within a defined boundary and their respective copper intensity. On the other hand, the top-down approach applies the end-use sector shares into total copper demand and then multiply the copper demand for each end-use sector by its corresponding average product lifespan.

Copper usage is generally segmented into infrastructure, transportation, equipment, and building (Zhang, Yuan and Bi, 2012, Zhang et al., 2014, Zhang et al., 2015, M. Wang et al., 2017 and Hao et al., 2020), while some studies split equipment into industrial and other equipment (Eheliyagoda et al., 2019) and others are able to breakdown home appliances and electronic appliances (J. Wang et al., 2019) or consumer products, commercial products, and agricultural and industrial durables (Dong et al., 2019). One study segmented copper end-use sector into electrical and electronic equipment, vehicle and wiring and cable (Zeng et al., 2020).

Studies employed the Weibull distribution, Normal distribution, or average lifespan to estimate the lifespan of copper-containing products. Dong et al. (2019) compared these methods and found out no great impact on values when long time series were involved.

Zhang et al. (2014), Zhang et al. (2015), M. Wang et al. (2017), Soulier et al. (2018), Hao et al. (2020) and Zeng et al. (2020) estimated the available old scrap by combining copper inflows into society use by end-use sector with the lifetime of copper containing products. Zhang et al. (2014), Zhang et al. (2015) and Soulier et al. (2018) explored the stages related to the collection recycling efficiency of copper scrap.

Zhang et al. (2014), Zhang et al. (2015) considered that 10% until 1980 of the total waste are released in landfill and dispersed into the environment, being 5% after that period. The recycled waste, the sum of available old scrap plus net imports of recycled waste minus landfill and dispersion to environment, is sent to the refining and manufacturing stages. The waste that goes to the refining stage is the secondary copper that comes from the literature statistics, discounted of recovery losses minus the new scrap directed to the semis production stage while the waste that goes to the manufacturing stage is the difference between the recycled waste and the refining stage waste.

Soulier et al. (2018) calculated the amount of collected copper scrap needed to meet reported copper production which cannot be completely satisfied by primary material. The collection rate is the result of the ratio between the collected scrap and the available scrap. After collection, scrap is processed and the EOL processing rate is a weighted average of the technical recycling efficiencies. The end-of-life recycling rate is the combined efficiency of collection and processing of old scrap measuring the performance of the EOL recycling system in total.

Eheliyagoda et al. (2019) combined recycling rate scenarios with lifespan and primary demand scenarios to assess the sustainability of copper in China. To this end, they calculated the primary copper demand in certain year net of the quantity of copper that is recoverable from recycling, based on a recycling rate applied to the outflow of the EOL scrap plus the new scrap that is generated in that same year. The EOL scrap was dependent on the copper domestic consumption of each sector from t-k years ago, where k is the average life span of each end-use group, taken from the literature. New scrap was obtained through a linear regression, where the independent variable was the copper primary demand. Recycling rates of 20, 35, 50, 70, 80, and 90% were analyzed.

Dong et al. (2020) considered the generation of EOL scrap, its collection rate, dissipation rate, and loss rate of separation to estimate the amount of EOL scrap. The imported copper scrap was divided into categories that reflect different copper grades (Category 6 and Category 7). Estimates of future imports and exports of Category 6 were based on the historical relationship between GDP and the volume of imports and exports of copper scrap. Category 7 scrap has not been allowed to enter in China since 2019, as it includes material with copper content lower than 70%.

In Wen et al. (2015), the copper stock is dependent on the per capita resource capacity, population, intrinsic growth rate parameter, and resource recovery, which is at approximately 80% in the base case scenario. The theoretical scrap, meaning scrap available for recycling, but not necessarily collected and recycled, is the sum of the metal resource demand from previous years, which is obtained from the difference in the stocks and multiplied by the lifetime distribution function.

J. Wang et al. (2019) estimated the stock of copper scrap as the total consumption of copper-containing products in previous years multiplied by the rate of scrap generation in the current year. Additionally, J. Wang et al. (2019) estimated the consumption, in-use stock, and recycled amount of refined copper until 2035 under different scenarios of scrap import regulation standards and rates of recycling efficiency, knowing that these rates have increased dramatically after 2008 and reached 48.5% in 2014, followed by a slight decline to 45.1% in 2016.

Dong et al. (2019) calculated the outflow of discarded or obsolete products in year t as the sum of the inflow of products utilized in the year $t - l$, with l being the average lifetime of each product and the inflow being dependent on physical quantity of each product multiplied by their copper content. They also used recovery rates varying from 25% to 89% for the various waste categories in different years.

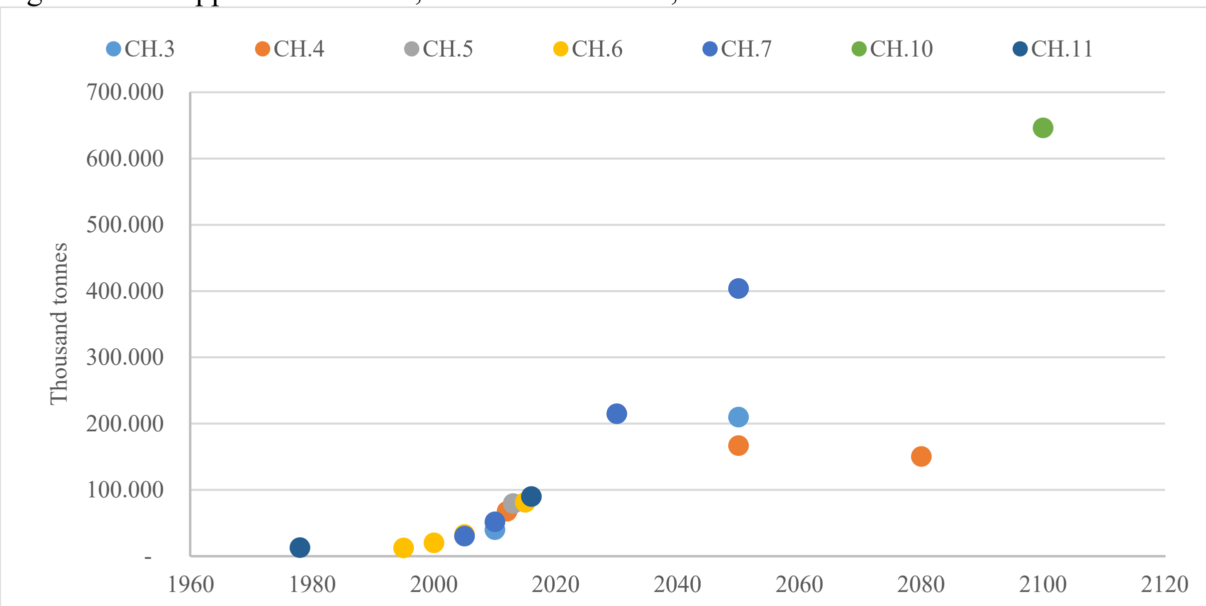
While 12 studies adopted a flow analysis method, Liu et al. (2020) adopted a quali-quantitative approach, whose results will be discussed in the following session.

3.3.1.3 Results of the studies

M. Wang et al. (2017) showed that almost 95 million tonnes of refined copper were put into Chinese society from 1949 to 2013, with about 70% of this amount being consumed from 2000 to 2013 and making part of the in-use stock. The growing consumption of copper over the years led to a consistent rise in the in-use stock (Figure 3.3), making it around four times higher than China's copper ore reserves, based on 2016 data from Hao et al. (2020) and a major recycling target due to its value, as Zeng et al. (2020) highlighted. Although Chinese population significantly increased from 1978 to 2016, per-capita copper in-use stocks also rose, changing from 14 kg in 1978 to 75 kg in 2016, despite large regional disparity across the whole country (Hao et al., 2016).

Copper in-use stocks projections, however, present different trends in terms of copper content, which could be associated with distinct estimates for demand and product service time, which are generally based on an average for an entire end-use sector and the breakdown of the copper end-use sector.

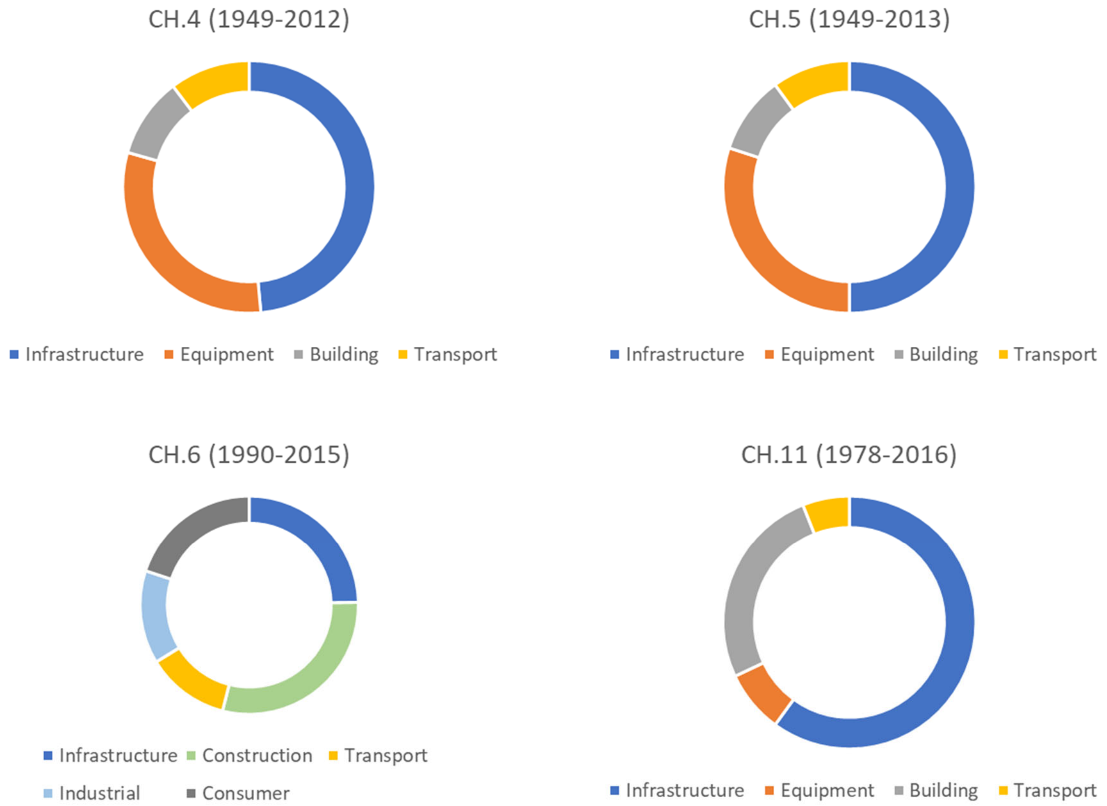
Figure 3.3 - Copper in-use stock, in thousand tonnes, 1978 - 2100



Source: Developed by the author.
Note: the starting date to account for the in-use stock can differ by study.

The end-use sectors of copper have slightly different breakdowns, depending on the study (Figure 3.4). Generally, infrastructure has the largest share in copper in-use stocks given the longer service time of this segment.

Figure 3.4 - Breakdown of copper end-use sectors in copper in-use stocks



Source: Developed by the author.
Note: years within parentheses indicate the period of in-use stock accumulation.

According to M. Wang et al. (2017), equipment was intensively consumed before 1980s driven by the government efforts to develop the Chinese industry, while infrastructure became dominant following the Chinese economy reform and its opening in 1980, which resulted in economic development and urbanization. Symbols of material success in China elucidates how the economy evolved. According to Zeng et al. (2020), bicycle, radio, wristwatch, and sewing machine were symbols of material success in the 1970s. These were replaced by washing machine, refrigerator, black-white television, and audio recorder one decade later, while air conditioner, audio electronics, color television and video recorder dominated the success symbols in the 1990s and apartment, mobile phone, car and deposit were the symbols of 2000s.

J. Wang et al. (2019), having a more granular split of the copper end-use sectors, showed that the power infrastructure sector occupied approximately half of the total consumption in 1992, 2000, 2008, and 2016, supported by the expansion of the Chinese power grid. The construction sector was responsible for roughly 10% of total consumption in the same years, which is a small share compared to developed countries.

With some end-use sectors having a longer service time, the scrap generation by end-use sector tends to be different than the end-use sector shares in in-use stock. According to M. Wang et al. (2017), despite the importance of infrastructure as the main copper end-use sector, the cumulative scrap in infrastructure from 1949 to 2013 was smaller than equipment, mostly due to the shorter life span of the latter. J. Wang et al. (2019) mentioned this because of the larger lifetime span of power infrastructure and buildings, their contribution to scrap generation will take more time to happen, while home appliances have played a major role in continuously supplying the Chinese scrap market.

In M. Wang et al. (2017), the shorter life span of equipment combined with strong demand in the past makes it the main source of scrap availability, with the cumulative amount calculated to be 10.1 million tonnes from 1949 to 2013 and estimates to reach 9.9 million tonnes from 2014 to 2022. In the case of transportation, although the cumulative scrap generation was lower than 2 million tonnes before 2013, the flow is expected to roughly double from 2014 to 2022. The cumulative building scrap generation is even smaller than the transportation sector, but the flow is also expected to increase.

The longer service time of the major copper end-use sector, combined with growing Chinese copper demand, led China to import copper in different forms. Net imports of copper scrap went from zero in 1975 to 1.3 million tonnes in 2010 (Zhang et al., 2014). In J. Wang et al. (2019), imported copper scrap exceeded 50% of recycled copper in China during the period of 2000 and 2016.

The reliance on imports is expected to reduce in the future, since copper flows have accumulated into China's anthroposphere mainly from 1995 onwards and copper-bearing products will eventually retire. Wen et al. (2015) showed that the copper regeneration will exceed the imports in 2030 and become the main source of the domestic supply in the business-as-usual scenario. Zhang et al. (2015) showed that outflows of copper in obsolete products will rise continuously until around 2070, with the peak value ranging from 7.8 to 8.2 million tonnes/year, and then moderately decreasing to approximately 7.5 million tonnes/year till 2080. By 2050, transportation and infrastructure will be the main reason for waste generation while new energy vehicles make up the larger contribution within the subcategories of these sectors (Dong et al., 2019).

The supply of secondary copper is believed to increase, based on the expected retirement of copper materials. However, rising the recycling industry efficiency in terms of collection, disassembling, and processing is a key factor to enhance the availability of secondary material. According to Soulier et al. (2018), China's end-of-life collection rate for copper scrap was around 57% between 1990 and 1999, increasing significantly to 83% in 2010-2015. After collection, scrap is processed with individual efficiencies which averaged between 63% and 64% in 1990-2015. The end-of-life recycling rate started with values of 30%-40% in 1990-2009 and increased to the range of 50%-55% in 2010-2015.

According to Eheliyagoda et al. (2019), recycling rates between 70 and 90% would be ideal to reduce the primary demand needs, although these rates are unlikely to be achieved, as they would require an improvement on product designs to facilitate recycling, among other initiatives in the short term.

While increasing recycling rates is an alternative to reduce primary demand, the service life of products and the demand growth pace are important variables to consider. Eheliyagoda et al. (2019) showed that the predicted increase in primary demand surpasses the projected Chinese reserve base before 2040 even under ideal recycling rates of 70-90% and medium and long lifespans. This occurs because longer products service time combined with a growing demand leads to a higher need of primary ore, but this could be a sustainable alternative for the long term. Dong et al. (2020) found out that effective measures to prolong product lifetime could lead to a significant reduction in copper demand through the year 2100.

According to Dong et al. (2020), a change in a product lifetime would require an adaptation at the product design stage, when product structure and material selection are defined. This, however, generally takes time, as it involves research and development for new materials and, eventually, new production processes, and industry and market acceptance. Dong et al. (2020) also mentioned as alternatives the repair and reuse products that would otherwise be scrapped.

M. Wang et al. (2017) discussed the environmental problems that can be raised in face of increasing scrap generation and the recycling industry. For that, research focusing on the potential environmental and human health impacts from recycling copper scrap is needed, combined with regulation of enterprises and technology and innovation adoption. Although the use of scrap to meet the copper demand in China is the main alternative being discussed in the literature, Dong et al. (2020) mentioned that production based solely on secondary sources could cause negative environmental impacts.

The Chinese government has developed policies focused on the recycling sector, underpinned by the 13th Five Year Plan for the years 2016-2020, when sustainability was a key topic (Liu et al., 2020). The Reform and Implementation Plan to Enhance Solid Waste Import Management System by Prohibiting the Entry of Foreign Waste, issued in 2017, sought to completely prohibit the importation of solid waste with major environmental hazards and intense public reaction by the end of 2017; and by the end of 2019, gradually halt the importation of solid waste that can be replaced with domestic resources. Following this announcement, the Chinese government changed the regulation on imports of copper scrap (Table 3.3).

Table 3.3 - Main policies and regulations on the imports of Chinese copper scrap

Material	Classification on imports	Effective date
Cu-bearing slags and residues	Prohibited solid waste	December 31, 2017
WEEE*	Restricted solid waste	December 31, 2017
Other copper waste and scrap	Unrestricted imported solid waste	December 31, 2017
WEEE*	Prohibited solid waste	December 31, 2018
Copper waste and scrap	Restricted solid waste	July 1, 2019

Source: Liu et al. (2020); General Administration of Customs of the People's Republic of China; Ministry of Ecology and Environment of the People's Republic of China
Note: * WEEE includes waste motor, wire, cable, hardware, and electrical appliances)

3.3.2 Studies focused on the global market (excluding China)

For each study of the 29 studies that focused on the global copper scrap market, Table 3.4 shows the name of the authors and the year of publication and a symbol to identify them in tables and graphs presented in the next sessions, where we discuss methodologies and key results of the selected studies.

Table 3.4 - Studies focused on the global market (excluding China)

Authors	Article symbol
Agrawal, A. & Sahu, K. K. (2010)	ROW.1
Tanimoto, A. H., Durany, X. G., Villalba, G. & Pires, A. C. (2010)	ROW.2
Sahni, S. & Gutowski, T. G. (2011)	ROW.3
Bader, H. P., Scheidegger, R., Wittmer, D. & Lichtensteiger, T. (2011)	ROW.4
Inoue, Y., Kishita, Y., Fukushige, S., Kobayashi, H. & Umeda, Y. (2012)	ROW.5
Jain, P. K. (2012)	ROW.6
Wellmer, F. W. & Dalheimer, M. (2012)	ROW.7
Bonnin, M., Azzaro-Pantel, C., Pibouleau, L., Domenech, S. & Villeneuve, J. (2013)	ROW.8
Poulton, M. M., Jagers, S. C., Linde, S., Van Zyl, D., Danielson, L. J. & Matti, S. (2013)	ROW.9
Higashida, K. & Managi, S. (2014)	ROW.10
Sverdrup, H. U., Ragnarsdottir, K. V. & Koca, D. (2014)	ROW.11
Chen, W., Wang, M. & Li, X. (2016)	ROW.12
Knapp, F. L. (2016)	ROW.13
Ciacci, L., Vassura, I. & Passarini, F. (2017)	ROW.14
Maung, K. N., Hashimoto, S., Mizukami, M., Morozumi, M. & Lwin, C. M. (2017)	ROW.15
Tokimatsu, K., Murakami, S., Adachi, T., Ii, R., Yasuoka, R. & Nishio, M. (2017)	ROW.16
Fu, X., Ueland, S. M. & Olivetti, E. (2017)	ROW.17
Pfaff, M., Glöser-Chahoud, S., Chrubasik, L. & Walz, R. (2018)	ROW.18
Emel'yanov, A. A., Voronov, D. S., Dolzhenko, R. A. & Dushin, A. V. (2018)	ROW.19
Wang, M., Liang, Y., Yuan, M., Cui, X., Yang, Y. & Li, X. (2018)	ROW.20
Mackey, P. J., Cardona, V. N. & Reemeyer, L. (2019)	ROW.21
Gorman, M. R. & Dzombak, D. A. (2019)	ROW.22
Sverdrup, H. U., Olafsdottir, A. H. & Ragnarsdottir, K. V. (2019)	ROW.23
Liao, M. I., Shih, X. H. & Ma, H. W. (2019)	ROW.24
Ciacci, L., Fishman, T., Elshkaki, A., Graedel, T. E., Vassura, I. & Passarini, F. (2020)	ROW.25
Henckens, M. L. C. M. & Worrell, E. (2020)	ROW.26
Seck, G. S., Hache, E., Bonnet, C., Simoën, M. & Carcanague, S. (2020)	ROW.27
Hu, X., Wang, C., Lim, M. K. & Chen, W. Q. (2020)	ROW.28
Wang, C., Huang, X., Lim, M. K., Tseng, M. L. & Ghadimi, P. (2020)	ROW.29

Source: Developed by the author.

3.3.2.1 Objective of the studies

The old copper scrap market has distinct features in the global market, as recycling involves an international network where material usually flows from developed countries to competitive manufacturing countries (Sahni and Gutowski, 2011; Higashida and Managi, 2014, Wang, Huang, Lim, Tseng, and Ghadimi, 2020). However, there are increasing efforts from governments to promote a circular economy within their territory, such as the European Union (Ciacci et al., 2020).

The high amount of copper scrap in developed regions is driven by strong copper consumption, after copper having amounted to in-use stocks for many years, while the importance of developing countries in the global imports of copper scrap has increased following a greater demand for secondary materials and often cheaper labor costs (Sahni and Gutowski, 2011).

China is the largest importer of copper scrap, but other countries, such as India, is considered a long-term potential market for exporters (C. Wang et al., 2020). While there are many studies focused on the Chinese copper cycle, the literature is limited for other developing markets, with the systematic review resulting in two articles for India (Agrawal and Sahu, 2010; Jain, 2012) and one for Brazil (Tanimoto, Durany, Villalba and Pires, 2010).

For the developed regions, the academic literature turned the attention mostly to European countries and the United States. The remaining studies were about the global trade flow of copper scrap, although they ended up focusing on China, the United States, Europe, and Japan, given their importance in the international copper scrap market.

3.3.2.2 Methodology of the studies

Studies that focused on the copper scrap market outside China or on a global level have more diverse methodologies, with 9 studies relying on material or substance flow analysis (Tanimoto et al., 2010; Bader, Scheidegger, Wittmer and Lichtensteiger, 2011; Bonnin, Azzaro-Pantel, Pibouleau, Domenech and Villeneuve, 2013; W. Chen et al., 2016; Ciacci, Vassura and Passarini, 2017; Pfaff, Glöser-Chahoud, Chrubasik and Walz, 2018; M. Wang et al., 2018; Ciacci et al., 2020), while some authors linked this method with other approaches, such as linear programming to minimize discounted sum of overall system cost of the resources (Tokimatsu et al., 2017). Although a material flow analysis has a quantitative nature, there were other 8 studies that followed a quantitative approach while not adopting a flow analysis methodology in full (Inoue, Kishita, Fukushige, Kobayashi and Umeda, 2012; Maung, Hashimoto, Mizukami, Morozumi and Lwin, 2017; Fu, Ueland and Olivetti, 2017; Emel'yanov, Voronov, Dolzhenko and Dushin, 2018; Gorman and Dzombak, 2019; Liao, Shih and Ma, 2019; Henckens and Worrell, 2020; Seck, Hache, Bonnet, Simoën and Carcanague, 2020). There were 6 studies that followed qualitative or quali-quantitative approaches (Agrawal and Sahu, 2010; Jain, 2012; Wellmer and Dalheimer, 2012; Poulton et al., 2013; Knapp, 2016; Mackey et al., 2019). There were 4 studies that focused on the international trade of copper scrap, relying on international trade theories, such as gravity model and complex network theory (Higashida and Managi, 2014; Hu et al., 2020; C. Wang et al., 2020) or using a life cycle applied to collected scrap materials (Sahni and Gutowski, 2011). The remaining 2 studies adopted system dynamics (Sverdrup, Ragnarsdottir and Koca, 2014; Sverdrup, Olafsdottir and Ragnarsdottir, 2019).

Related to the material flow studies, Tanimoto et al. (2010) and W. Chen et al. (2016) followed a static approach, assessing the copper system for Brazil for 2005 and for the U.S. for 1975, 1986, 1995, 2005, 2010 and 2012, respectively, while the remaining studies adopted a dynamic approach.

Other differences were found among the studies that applied material flow analysis, mainly led by data availability and the structure of the copper industry, as some countries do not have a developed copper mining industry, relying on the imports of copper concentrate and semi-finished and finished products. In Tanimoto et al. (2020), the old scrap generation depends on the collection and separation rates of the segments municipal solid waste (MSW), construction and demolition waste (C&D), waste from electrical and electronic equipment (WEEE), sludge and sewage waste (SS), end of life vehicle waste (ELV), hazardous and industrial waste (HIW), and non-hazardous industrial waste (NH&IW). In Bonnin et al. (2013), the segments are similar, except for the fact that there is only one category to account for HIW and NH&IW.

In the other 7 flow analysis studies, old scrap generation was obtained by applying lifespan distribution models or average into the flow of major copper uses. Some, such as Bader et al. (2011) and Ciacci, Vassura and Passarini (2017), considered in-use dissipation losses, which, according to Ciacci et al. (2015), are the flows of materials from the anthroposphere to the biosphere in a manner that makes their future recovery extremely difficult, if not impossible. The lifespan distribution models were based on the Weibull and Normal, but lifetime average was also applied.

While copper scrap is generated at three stages - semi-finished products, finished products and after products EOL –, Bonnin et al. (2013) focused only on the old scrap as, according to them, almost all scrap produced during the fabrication and manufacturing steps are recycled as new scrap. Bader et al. (2011) also concentrated on the flow of old scrap, having based on an inventory stock analysis of more than 300 items from copper end-use segments. While mobile is directly recycled, the building and infrastructure materials are firstly dismantled, whose process potentially results in additional copper losses. Copper-bearing products from these segments that are not recycled are disposed at landfills.

The remaining flow analysis studies focused on old scrap and new scrap. In Tanimoto et al. (2010), new scrap is the material that returns to the production process of the only refinery in Brazil and is estimated at 15% of the copper production. The old scrap generation depends on the copper content in the waste after collection and separation. Some segments, such as MSW, follows the incineration process and a share of the copper contained in incinerated waste is assumed to be destined to landfill sites, although these sites also receive copper-bearing material that has not been incinerated. The difference between the waste flows and their final destination was considered to be lost to the biosphere.

In Pfaff et al. (2018), high grade EOL scrap and new scrap occurring during manufacturing are directly remelted in semis mills or by ingot makers which supply the semis fabricators, while low grade scrap is reintroduced to the converter or anode furnace and subsequent electrolytic refining gives secondary material the same quality as primary refined copper. Following this logic, the authors considered that the total amount of new scrap enters the semis production stage and is calculated based on assumptions regarding processing efficiency by application, ranging between 75% to 95% depending on the end-use sector.

In W. Chen et al. (2016), Ciacci, Vassura and Passarini (2017), Ciacci et al. (2020), both new and old scraps can be processed through smelting and refining or directly processed at a fire refinery to produce refined copper, depending on the scrap quality. In other words, the smelting, semi-finished and finished production stages can receive new and old scraps. Ciacci, Vassura and Passarini (2017) and Ciacci et al. (2020) calculated the amount of new scrap generated in a given year based on the fabrication and manufacturing recovery efficiency rates of around 76%-90%, depending on the end-use sector, multiplied by copper finished products input. After that, 90% of the new scrap was assumed directly melted and the remaining 10% entered the old scrap market. Annual amounts of new scrap utilized by fabricators were subtracted to historic statistics of total copper directly melted in the EU-28 to enable an estimate of the amount of copper deriving from old scrap sources. Annual copper flows out of use generated from each application sector were aggregated into five waste type categories to enable a representative modeling of the regional waste management while collection and preprocessing rates were applied to compute the amount of old scrap domestically recovered for recycling in a given year. The remaining amount of old scrap not processed directly by fabricators was modeled to enter secondary smelting plants and this flow was further increased by the amount of new scrap not directly recycled by fabricators in the same year.

Ciacci et al. (2020) followed similar methodology adopted by Ciacci, Vassura and Passarini (2017), but modelled four development paths for copper demand and, consequently, copper scrap generation, by applying time-series regression analysis 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) and the urbanization rate (defined as the percentage of total population living in urban areas).

Pfaff et al. (2018) also modeled several scenarios (changes of lifetime extension, EOL collection rate, increase in secondary copper, reduction of copper intensity, fabrication efficiency, absolute demand reduction) to assess the impact on primary copper demand or the supply of secondary copper.

Tokimatsu et al. (2017) applied linear programming to estimate copper supply from 2010 to 2150 and modelled copper demand following sectoral relationships among intensity of use, final product demand expressed by GDP and/or population, and the exogenously given from the IPCC scenario for future GDP and population. The supply model is based on the optimization of the objective function that minimizes the discounted sum of the overall supply-side cost for the entire life cycle, including recycling, subject to some constraint equations.

In the other quantitative approaches, Emel'yanov et al. (2018), who assessed and projected the copper scrap resource in Russia from 1937 to 2014, projecting it to 2035, calculated the theoretical amount of scrap in function of past consumption and average lifespan of the copper-bearing products, not discounting for the collection and recovery rates. Copper production from scrap comes from the literature and the ratio between scrap used in production and theoretical scrap generation gives the recycling efficiency rate.

Gorman and Dzombak (2019) employed regression analysis to forecast old collected scrap, new scrap, net scrap exports and losses to landfill, while available scrap was obtained following a mass balance formula. Historical data ranges from 1970 to 2015, with forecast going to 2030. The explanatory variables were socio-economic demand drivers (GDP, population, and urbanization), material specific drivers (copper price), and materials use indicators to represent dematerialization and decoupling (domestic materials consumption and manufacturing as a percentage of GDP).

As estimates of in-use stock can give an indication of the potential of copper scrap availability, Maung et al. (2017) applied a classification framework of secondary resources to copper to assess the secondary copper reserves and resources of China, Germany, Italy, Japan, Korean Republic, Spain, and the United States from 1960 to 2010. The framework related the level of knowledge about the secondary resource with profitability of recovering it. Basically, there is more knowledge on the amount of "final products in/after use" stocked in society than on the "wastes in managed landfill sites" or "dissipated material", as well as more knowledge on the wastes or secondary resources that are likely to emerge in a year than on the "final products in/after use" stocked in society. Similarly, the reuse of secondary resources depends on the degree of profitability, split into economic, marginally economic, subeconomic, and other conditions at the time of the estimation. Secondary resources need to be economic and marginally economic profitable while the knowledge stage needs to be final product in/after use.

Sverdrup, Ragnarsdottir and Koca (2014) combined mining, trade markets, price mechanisms, population dynamics, use in society and waste as well as recycling into a global systems dynamics model. Recycled copper was modelled using a regression with copper price been the explanatory variable. Sverdrup, Olafsdottir and Ragnarsdottir (2019) also modelled copper scrap using a regression with copper price been the explanatory variable, while additional effects were included to estimate recycling as a percentage of the total supply. The scrap loss was split into physically loss by dropping it where it is not likely to be found or retrieved (at random and in landfills) and by corrosion. The idea behind the model is that the scrapping process for stock-in-use in society is driven by price, and from that the infrastructure where it is incorporated has become obsolete or worn out. Once the metal is available as scrap not in service, the recycling from scrap is driven by profits. After the metal has arrived at the scrap heap, the metal price will have a promotion effect in causing somebody to recover it.

M. Liao et al. (2019) built a secondary copper waste input-output model that identifies the relationship between waste flows and the economic activities of the production and waste treatment industry sectors for Taiwan. Seven treatment sectors were specified for copper-related waste, including five reuse processes (shredding and sorting, thermal treatment, smelting, electrolytic refining, and leaching) and two non-reuse processes (solidification and landfill).

Henckens and Worrell (2020) investigated whether and at which conditions a sustainable production rate of copper can be combined with an increase in copper consumption for the entire future world population to the same level as in developed countries in 2020, which was around 11 kg/capita/year. The authors considered three ambition levels regarding a sustainable production rate for copper: 1000 years, 500 years and 200 years.

Seck et al. (2020) applied linear programming into a bottom-up long-term energy model through to 2050 with an endogenous copper supply chain from the resources to the end-use sectors, the availability constraints on resources and the trade balances. Copper demand from the sectors not represented in detail technologically - Electrical and Telecom networks, Consumer, Industry sector, Building and Other Road Transport sectors, are exogenous and calculated according to the GDP per capita while copper demand in power plants and the road transport sector was based on an endogenous technological evolution, satisfying electricity needs and mobility demand.

3.3.2.3 Results of the studies

The factors that determine the recycling potential are the amount of material in actively used products, in scrap that is accessible and in landfills, the amount dissipated through use, the purity, geographic distribution of stocks and the lifetime of the material in use (Poulton et al., 2013).

The lifetime of the material in use is becoming shorter and the recycling process is getting more difficult and expensive, with technology development having to keep pace with more complex and fast-evolving products (Wellmer and Dalheimer, 2012). The products complexity is driven by the use of different elements that occasionally do not occur together in nature and the element dispersion in the final product (Poulton et al., 2013; Wellmer and Dalheimer, 2012; Knapp, 2016). According to Ciacci, Vassura and Passarini (2017), the variety of alloys in number and composition hinders efficient sorting and separation and, ultimately, functional recycling.

The challenges associated with recycling become more evident in developing regions. In India, the collection, finance, technology, and environmental parameters are very unorganized, dominated by small and medium enterprises (Agrawal and Sahu, 2010; Jain, 2012). More recent studies, however, could draw a different picture for the Indian copper scrap sector, although our systematic research that comprehended the period from 2010 to 2020 resulted in two articles whose last date of publication was 2012.

In India, the copper scrap supply is needed to meet the country's copper deficit, as mined production is not enough to meet the country's copper demand. India and the Association of Southeast Asian Nations (ASEAN) signed a free trade agreement in 2009, which promoted scrap copper trade between India and ASEAN. India has also maintained good trade relations with countries in Africa, especially South Africa. Exporters appear to regard India as another long-term potential market to deleverage and limit dependence on a single market such as China (C. Wang et al., 2020).

The copper scrap market in India is supplied by old and new scrap while the manufacture of brass products by small scale handicrafts and utensil making units is the biggest user of copper and copper alloy scrap. Old scrap, responsible for approximately 60% of copper scrap generation, is mainly generated from large scale ship breaking activities, insulated cables/wires, mixed old scrap by Indian Railways, brass ash, dross, copper alloys durables collected from households by individual scrap merchants, imports, among others, while new scrap comes from fabrication and manufacturing units without a melting facility, whose scrap is either sold in the scrap market or returned to the raw material supplier (Agrawal and Sahu, 2010).

Although the use of copper scrap meets approximately 40% of the total copper demand in India, there are few specific policies for the recycling sector (Agrawal and Sahu, 2010), with the market been driven by the economics of copper scrap, mainly prices for scrap and primary copper. Copper scrap is generally not stockpiled in India, which could bring high volatility to the price and reduce the incentives to use it as a raw material given the uncertainty related to its supply. According to Jain (2012), the profit margin gets squeezed when the price of primary copper declines, as consumer prefers virgin metal to secondary one.

Wellmer and Dalheimer (2012) explain that the secondary market follows the same pattern as the primary one, with scrap prices rising when there is a shortage of copper scrap in a market economy. Higher prices lead to increased production by improving recycling rates, reprocessing of lower-grade scrap which becomes profitable with improved prices and reducing downgrading to optimize the use from the Technosphere. Ciacci, Vassura and Passarini (2017) clarify that low quality copper, which constitutes the greatest input of copper scrap to secondary smelting production, is mostly influenced by changes in the refined copper market and, consequently, refined copper prices. High quality copper scrap, however, has less sensitivity to global copper demand, and seems to be driven by scrap availability more than copper prices.

Brazil is a net importer of copper both in concentrate and refined metal, which means that copper scrap is also needed to meet the country's demand. Tanimoto et al. (2010) estimated the Brazilian per capita annual waste generation at 1411 kg/capita/year, which is comparable with that of Europe at 1856 kg/capita/year, while relatively lower purchasing power of Brazilian population and lower rate of technological development led to a smaller amount of discarded product in some segments, such as WEEE, ELV and I&HW. In terms of copper concentration, the amount of copper contained in wastes was estimated at 170,600 t/year or 0.926 kg Cu/capita/year in 2005, with WEEE and ELV representing less than 1% of the total waste generated, yet together they contain almost 38% of copper released into the atmosphere.

The Brazilian recycling rate is only around 25%, which could be partially associated with poor availability of data, as Tanimoto et al. (2010) mention that there is an informal economy dominating the recycling sector in Brazil. The recycling rate is much lower than other countries, such as Russia (Emel'yanov et al., 2018) and China (Zhang et al., 2015; J. Wang et al., 2019). The main final destination of the waste flows are landfill sites, with industrial landfill sites receiving 37% of this material, which, according to Tanimoto et al. (2010), make them a potential source of copper in the future since they are fewer in number and involve an operational structure that is well suited for exploitation (logistics, technological resources, utilities and the potential for private investment).

While India and Brazil have a mining activity within the countries' boundaries, the copper cycle in Germany, Switzerland and France is based on imported material.

The German in-use stocks are stagnating at around 240 kg/capita (Pfaff et al., 2018), which is significantly above estimations for the EU average stock of around 180 kg/capita (Ciacci, Vassura and Passarini, 2017), driven by the comparatively high level of industrialization in Germany and well-established infrastructure. The authors also found out that a scenario where product service time is extended leads to a considerable reduction in the EOL scrap. In contrast, the increase in the EOL collection rate leads to a corresponding increase in the amount of collected EOL scrap.

According to Sahni and Gutowski (2011), 30% of the scrap collected in Germany is retained domestically while the rest is lost amongst several countries, mainly the EU member states. Available copper scrap refers to states where material is available for future use and has potential to flow to the next phase and lost copper scrap refers to states from where material usually is not recovered, like landfills or other dissipations. For Sahni and Gutowski (2011), when comparing how Germany performs in the international trade of copper scrap with the case where the country would follow a closed-economy, they found out that the results for closed and open-economy forms are almost similar in its ability to extract more use out of the collected German scrap because most of the countries that have imported German scrap have reported similar recycling efficiencies.

In Switzerland, Bader et al. (2011) estimated stocks from buildings, infrastructure, and mobiles at around 222 kg/capita in 2000 and recycling volume of 4.2 kg/capita in the same year, driven by a high base of copper consumption, calculated at about 8 kg/capita in 2000. The accumulated copper consumption provides an important stock of copper scrap for the future. Bader et al. (2011) found out that the electrification of households and the improvements in building technologies (roofs, gutters, installations) around 1920–1940 led buildings and mobiles to present strong logistic growth. The electrification age and a large growth of infrastructure (power stations, new grids, and telecommunication systems) resulted in a two-step logistic growth in the infrastructure sector, with the peak recorded in 1910-1920 and 1960-1990, respectively.

The estimated fraction of recycling in the total waste is about 70%, yet there is a loss of about 2 kg/capita/year from 2000 to 2060, with some 98% of this amount deposited in landfills and the rest distributed diffusely to the soil and aquatic compartments through abrasion/corrosion/fertilisers. Based on a sensitive analysis, the authors concluded that while increasing the recycling reduces losses to landfill, only copper substitution can reduce the different losses to the environment, although with a time delay of the order of a lifetime.

In France, copper wastes collected in 2000-2008 was around 280,000 tonnes but most of it was exported because there is a lack of first transformation industry for recycling low-grade scrap (Bonnin et al., 2013). From 2000 to 2009, Bonnin et al. (2013) show that scrap production is quite stable, as consumption in France has reached a steady state. As recycling however mostly depends on imports, recycling in France reduced in 2000-2009 following a downward trend in waste imports. In fact, the utilization rate of secondary copper as a fraction of total copper refined in France is 25% in average, while this share has historically fluctuated between 20% and 40% in the region in the European Union (EU-28), resulting in a median value of 30%. If the amount of secondary copper directly melted by fabricators is included, the median value increases to 36% as percentage of the total fabrication input (Ciacci, Vassura and Passarini, 2017).

The drop in copper scrap imports is also observed in the European Union countries, where net-import of copper scrap has shrunk from the 2000s, resulting in net-exports of copper scrap from Europe to third countries. Refined production of secondary copper, however, remained stable around 800 Gg/year.

Europe has accumulated a significant amount of copper in their in-use after years of strong consumption that promoted the development of infrastructure, building and other segments. From 1960 to 2014, about 91 million metric tonnes of copper were accumulated in the European in-use stock, which corresponds to an average of 180 kg copper/capita. Building, construction, and electrical and electronic products have increased notably, and they covered more than 70% of the regional in-use stock in 2014 (Ciacci, Vassura and Passarini, 2017). Ciacci et al. (2020) show that the use of copper in construction activities covers about half of the total demand projected by 2050, followed by electrical and electronic products, industrial machinery and equipment, transportation equipment, consumer, and general goods. Given the elevated lifetime of construction materials, stock in use will likely continue to be dominated by this segment.

About 60% of the total amount of scrap generated in Europe is recovered nationally or exported, but Ciacci, Vassura and Passarini (2017) and Ciacci et al. (2020) highlight that the European Commission is putting great emphasis on circular economy, aiming at turning waste into valuable resources while securing access to raw materials strategic to its development, such as directives on ELV and WEEE and the Circular Economy Action Plan. Ciacci, Vassura and Passarini (2017) comment that current European recycling initiatives do not commonly cover C&D, which has a relatively high quality of copper scrap and an ease of separation. Frace, Bonnin et al. (2013) comment that selective collection has made significant progress in recent years, especially regarding small electric and electronic equipment that contains most of the copper found in MSW.

Despite increasing concern with recycling, European countries saw a reduction of secondary production capacity in the last decades, triggered by technological innovations in the copper industry and the enforcement of environmental legislations that resulted in the closure of several secondary copper smelters based on obsolete technologies. Conversely, the expansion of the Asian copper recycling industry has increased competitiveness in the scrap market (Ciacci, Vassura and Passarini, 2017).

There are ways to promote a circular economy in the region, although the difficulties are significant, as it depends on a combination of efforts, such as reducing copper demand, improving recycling rates and enhancing technology of the recycling industry. Ciacci et al. (2020) showed that under one scenario, where copper demand starts to fall from mid-2020, the secondary copper flows will gradually approach the expected demand by 2050, which is further advanced if the EOL recycling rate is increased from 60% to 80%.

In Russia, the copper scrap market has a different picture. Until the 1990s, before the Soviet Union dissolution, Russia was a net exporter of copper scrap, with the main source of scrap generation been from the defense industry. Following the dissolution, the restoration of Russian copper production led to a reduction in the exports of copper scrap and the defense industry share in copper consumption reduced at the expense of industrial products (Emel'yanov et al., 2018). The recycling efficiency rate has increased from 38% in 1968-1999 to 62% in 2000-2014, which is similar to the European level, according to Emel'yanov et al. (2018).

Despite growth in the efficiency rate, the Russian copper scrap market is expected to see a lack of material in the future, as the current base of scrap generation is formed based on copper consumed in 1990–2000, when economic problems and the related reduction of fixed capital investments reduced internal consumption and likely prevented old industrial equipment to be released and maintained the old age of active industrial assets. Emel'yanov et al. (2018) estimate that the scrap copper extraction from industrial products may reduce to 213,000 tonnes/year by 2030, reduction of 85,000 tonnes from the level of 2014. The end of life of consumer products imported during the period of peak private consumption in 2000–2014 could partially offset the reduction in copper scrap supply as well as the extraction of copper bearing-material discarded in 1968-1999, but not recycled given the low recycling efficiency rate observed in that period.

In Russia, the increasing role of consumer goods as a source of scrap generation could raise the need for changing the technology used to recycle scrap, as their composition is different from large-scale industrial machines, and the government policies to incentivize the correct disposal and collection of consumer goods.

In the U.S., the copper industry has shifted their focus to the production of semi-finished and finished products. W. Chen et al. (2016) commented that this is the result of competition with cheap primary production, substitution by plastic and aluminum, and tighter environmental regulations, increasing the costs for the development of secondary smelter. Added to that, M. Wang et al. (2018) mentioned increasing exports of scrap combined with higher imports of refined copper and lower copper content of old copper scrap compared to new scrap and refined copper while Mackey et al. (2019) noted that economics on domestic recycling and international trade in scrap all influence the extent of recycling.

Meanwhile, apparent consumption in the U.S. increased from 1975 to 2002, peaking at 2600 Gg in 2002 and reducing to 1760Gg in 2010 and 2012. According to data from M. Wang et al. (2018), the consumption of copper in the U.S. was 1665 Gg in 2016. Comparing the factors that impact copper consumption and collection of copper scrap, Gorman and Dzombak (2019) found out that a decrease in copper consumption will not result in reduced scrap availability through 2016-2030.

Building and construction is the major reservoir of copper, with a share of 45% in 2012, followed by electrical & electronic products, according to W. Chen et al. (2016). M. Wang et al. (2018) presented similar numbers, with building and construction averaging 48% in the 2000-2016 period and electrical & electronic products averaging 21% in the same period. From 1900 to 1999, the share of end use sectors remained basically the same, except for building and construction and industrial machinery and equipment, with the first gaining share since the 80s and the latter presenting a downward trend, representing 9% in 2000-2016 of the U.S. copper used.

Although building and construction is the largest consumer of refined copper, the theoretical generation of copper scrap has been dominated by electrical & electronic products since 2016, given its shorter service life of 10-25 years compared to building and construction of 30-80 years (M. Wang et al., 2018).

With the build-up of in-use stock following strong demand and reduced demand for old scrap, the output of secondary refined copper (which goes to smelter + refinery) shrank 90% from 1986 to 2012, stabilizing below 50 Gg in 2010 and 2012 while the U.S. started to export old copper scrap, with the total exported old scrap increasing 8.13 times in 2012 compared to that of 1975, which was 130.829 Gg (W. Chen et al., 2016).

According to Sahni and Gutowski (2011), international trade has apparently helped increase the amount of service derived per unit of copper scrap collected in the U.S. The closed economy structure means that all scrap collected was repeatedly recycled in the same country without any international trade. In terms of material savings, international trade helps displace 40% more virgin material through the flows compared to the closed economy recycling structure. In terms of final distribution of the material, close to 50% of the US collected scrap ends up in China, and only 15% is lost within the U.S.

According to Wang et al. (2018), the amount of scrap generation has continued to increase until 2016, when reached 2118 Gg. The efficiency with which old scrap from EOL products is recovered remained relatively high, been at 53% from 1931 to 2016, although it oscillated from 60 to 70% in 2011-2016.

But the American copper industry relies on the use of new scrap, however. In 2011, about 81% of the total amount of recycled copper comes from the purchase of new scrap and only 19% of the old scrap obtained from used products was recycled for domestic consumption. Since 2004, the U.S. scrap used less than 200 Gg of copper from old scrap, which has been floated around 150 Gg, at the same time, this rate has been declined, from 46.1% in 1979 to just 7.1% in 2016 (M. Wang et al., 2018).

The percentage of new scrap is approximately 30% of the refined copper consumption during the period from 1975 to 2012, although the percentage of new scrap in the refinery or manufacturing stage fluctuated during this period, being 23.71% and 76.29%, respectively, in 1975 and 2.94% and 97.06%, respectively, in 2012. This occurs because new scrap is easy to determine the components of scrap and it's very easy to separate scrap of different grades, often clean and uncontaminated, without organic coatings (W. Chen et al., 2016).

In Mackey et al. (2019), the authors concluded that enhanced copper recycling from secondary materials would be beneficial to the U.S., but an upgrading in skills and technology is required to enable metal scrap to be efficiently treated in the U.S.

Gorman and Dzombak (2019) found out, however, that collected EOL scrap and landfilled material are impacted by mostly the same variables in the U.S., which suggests that policies to promote a circular economy must be well elaborated to avoid increasing the amount of copper ending up in landfills. Collected EOL scrap and landfilled material are positively driven by time linearity and copper prices, and negatively affected by an increase in GDP. Landfilled material has also a negative correlation with population. The impact of GDP and price on collection is consistent with a hypothesis that a wealthier society would invest less in expensive and laborious disassembly, sorting and recycling activities without very high economic incentive for collected materials from these efforts.

On a global scale, Fu et al. (2017) had different results from Gorman and Dzombak (2019) that focused on the U.S. They found out that both industrial activity and world GDP correlate with global scrap supply (direct melt plus refined scrap), with limited dependence on copper price.

Sverdrup, Ragnarsdottir and Koca (2014) explained that the scrap generation from stock-in-use in society is not strongly driven by price, but rather from the objects containing copper becoming obsolete in some way while, after the copper has hit the scrap heap, the copper price will have a promotive effect in recovering it there.

Taiwan, although it has an annual copper consumption around 30e39 kg per person, which could be an important source of copper as the copper-bearing materials retire, the country lacks the technological capacity to produce high-grade electrolytic copper, which means the waste treatment plants can only recycle secondary copper resources and conduct preliminary processing (M. Liao et al., 2019). As a result, copper scrap is transported to other countries that have refined copper smelters for further recycling and refining, while higher grade copper must be imported.

Results from M. Liao et al. (2019) showed that it could be beneficial from the resource and economic aspects to build domestic refinery plants that recover and refine the copper from the waste, depending on the importing price. The scenario developed by the authors included a leaching plant, but the production cost of leaching revealed the difficulty of achieving economies of scale in leaching. If the country develops its own industry, international copper flows could be impacted.

Globally, the copper stock in society was estimated to be about 46 kg per person in 2010-2011 and consumption was 2.4 kg primary extracted copper per person per year, corresponding to a demand of about 17.5 million tonnes of primary produced copper per year. In 2017, the market was supplied with about 30 million to copper metal, the excess over primary supplied coming from recycled copper (13 million tonnes per year, or about 43% of the total supply), which corresponds to a demand for copper of about 4.1 kg copper per person and year (Sverdrup, Olafsdottir and Ragnarsdottir, 2019).

Globally, the yearly copper consumption increases with the growing GDP per capita and will vary from around 27 million tonnes in 2015 to around 86 million tonnes and 102 million tonnes in 2050 depending on the scenario, respectively. These values would result in an average consumption of copper per inhabitant per year of 3.6 kg/capita/year in 2015 and 8.9 and 10.5 kg/capita/year in 2050, depending on the scenario, respectively (Seck et al., 2020).

Results from Inoue et al. (2012) pointed to an annual copper demand varying from 66 to 71 million tonnes in 2050, depending on the scenario, with the first scenario having a supply of recycled copper of 18 and the latter of 19 million tonnes in 2050, which means that recycled copper contributes more than 25% of copper demand in both scenarios.

Simulations from Sverdrup, Olafsdottir and Ragnarsdottir (2019) suggest that total copper supply to society peaks at about 60 million tonnes of copper per year in 2050, when recycling represents 50% of total supply, and stay at that level until about 2160, when the supply declines and, recycling share is about 80% of total supply. The stock-in-use in society reaches a maximum in 2090 at 1,600 million tonnes of copper according to the calculations. Secondary extraction, a by-product of the production of other metals is also substantial, and it will also become larger than primary mining, but less than recycling.

Tokimatsu et al. (2017) found similar results to Sverdrup, Olafsdottir, and Ragnarsdottir (2019), with the amount of recycled copper representing 60% of the amount of material consumed in 2060 while the amount of recycled copper over scrap generated (before collection) estimated to reach 90% in the same period and keep around this level until 2150.

Results from Henckens and Worrell (2020) showed that the required EOL recycling rate for achieving a sustainability level of 1000 years of sufficient copper supply to the world population is respectively 93%, 89% and 55% with available copper resources of respectively 6 Gt, 10 Gt and 40 Gt. However, in practice, it will be difficult to realize an EOL copper recycling rate of more than 85%. With an EOL recycling rate of 85%, the required available copper resources must be minimum 14 Gt to be sufficient for supplying a world population of 10 billion for 1000 years.

As the share of secondary copper in total copper demand varies over time because the dynamic speed of the copper demand and the available scrap copper stock used for recycling are different, countries where strong economic growth is expected, such as Africa, need to develop an efficient upstream copper recycling sector to reduce import dependency. Europe, Japan, U.S., and South Korea, due to their moderate expected economic growth, can maintain relatively stable secondary production share over time after 2030 (Seck et al., 2020).

Maung et al. (2017) showed that the United States (44 million tonnes) and China (33 million tonnes) have the largest secondary copper reserves. Germany, Italy, and Japan have similar secondary reserves (∼15 million tonnes) in 2010. On a global level, secondary copper reserves were estimated at ∼175 million tonnes. In terms of resource – including reserve - Italy, Japan, and the United States, respectively, have secondary copper resources of about 25.9 million tonnes, 37.5 million tonnes, and 101.5 million tonnes and on a global level, ~550 million tonnes of copper has been extracted at the global level while about 130.0 million tonnes (24%) are in landfill sites and 175.0 million tonnes (32%) will be disposed of, dissipated, or lost in mixed metals.

The United States has a large amount (23.0 million tonnes) of secondary copper deposited as waste in landfill sites. Japan has similarly large amounts of such resources in landfill sites (10.9 million tonnes). These deposits represent potential targets for the future extraction of secondary copper through landfill mining.

With copper in-use stock increasing over the years, recycling could lead to a disarticulation from geophysical processes and, by extension, mining country geopolitics, although it still depends on capitalist commodity production, consumption, and prior extraction to exist (Knapp, 2016). In fact, copper scrap international trading is a significant market and Higashida and Managi (2013) found out that the greater the market scale - measured in terms of GDP or population size - of an importing country, the more recyclable waste it imports.

Normative requirements and governing principles are important to shape the recycling industry, as recycling can generate negative externality costs for waste-importing countries. These externalities could arise from the use of unskilled labor, environmental pollution, lack of awareness of the toxicity of waste materials, dumping into landfills of waste-importing countries, including illegal dumping, etc (Higashida and Managi, 2013). In Higashida and Managi, they commented that wages can affect the trade volume of recyclable waste positively or negatively. Recycling in early-stage developing countries might be labor intensive, and negative externalities of importing waste from developed countries will likely overshadow gains from trade. If a higher wage country imports more recyclable waste, it implies that import volumes will increase along with industry expansion.

These concerns have also restricted the international flow of copper scrap, despite copper scrap have brought more flexibility in terms of geographic distribution. China, which has been the world's largest importer of scrap copper since 2000, imposed some restrictive policies on scrap imports (C. Wang et al., 2020). In 2013, the Green Fence Operation was enacted by China Customs to strengthen the supervision of solid waste imports, and in 2018, China imposed a ban on the import of certain kinds of solid waste (Hu et al., 2020).

Hu et al. (2020) showed that CWS export share to China shifted from Europe and the Americas to Asia from 2010 to 2017, which suggests that countries in Southeast Asia seem to serve as hubs for the offshore purification business, and then the purified CWS is shipped to China. According to Higashida and Managi (2013), the gains from importing recyclable waste dominate externality losses depends on the economic conditions in each developing country.

New importing guidelines will likely alter the international flow of copper scrap, reason why countries need to diversify trade connections with countries and blocks to reduce dependence on a single economy. Hu et al. (2020) found out that when decreasing CWS imports, countries will prioritize maintaining good trade connections with their major trade partners but will be less extreme compared to those under the trade country preference scenario. Additionally, the CRM trade network is highly related with the CWS trade network, and a shock in the CWS trade network will spread to the CRM trade network.

Other factors that could impact the international flow of copper scrap are the small number of countries involved in the redistribution of scrap copper, which can negatively affect scrap copper network connectivity and increase China's scrap copper import vulnerability. Trade frictions, such as the China-US trade friction that escalated in 2020, war and intracountry strife among suppliers, disasters and supply chain disruption could hamper the trade flow of copper scrap (C. Wang et al., 2020).

According to Hu et al. (2020), highly CRM import-dependent countries, such as China, the U.S., and Germany, must promote infrastructure investment in scrap metal collection and recycling, encourage domestic recyclers to upgrade innovative technologies, and develop close trade relationships with trading countries to ensure the security of copper resources.

3.4 Discussion of results

Demand for copper in the form of metal is driven by expenditure, rate of urbanization, size of population, copper prices, among other variables that measure the pace of the economic activity (Stuermer, 2017; Fernandez, 2018; Elshkaki et al., 2016). On the other hand, the discovery and exploration of a copper deposit is a time and capital-demanding process, depending on factors that go from technical viability to local community acceptance. Once a project is in place, it is also very costly to adjust extractive capacity in response to a change in the resource price path (Krautkraemer, 1998). In a certain period, such as a year, demand and supply may not match, leading to an unbalanced market, which reflects in prices. In the case of secondary sources of copper, this dynamic is slightly different.

Factors that impact the availability of copper scrap and its demand could vary subject its quality and to the stage - smelter and refinery stages or semis and final manufacturing - that it will enter in the production process. But comparing to primary copper, copper scrap is expected to be more elastic to economic incentives.

Smelter and refinery are generally fed by low grade copper scrap while semis and final manufacturing receives high grade copper scrap. New scrap tends to be cleaner than old scrap, therefore it is the main copper source in the manufacturing stage. New scrap depends basically on the manufacturing activity level, which in turn, is related to the economic activity growth. As it is generated at production facilities, new scrap collection is high, and the recycling process is facilitated. Based on these characteristics, new scrap does not rely heavily on refined copper price.

Old scrap has a slightly different dynamics, because its availability depends on past copper consumption and the service time of products. Copper consumption could be calculated following a bottom-up or a top-down approach, with bottom-up approaches requiring a vast amount of data while top-down methods rely on the breakdown of end-use sectors and generally a bottom-up calculation for at least a short period. Both approaches require assumptions of copper content in copper-bearing materials, which changes over time with technology development and consumer lifestyle. The analyzed studies have not considered this nuance.

The service time of products could differ by country and within the country when it faces a change in the income level. In developing regions, durable goods tend to be used longer and it is generally sold in the second-hand market before retiring, which raises a significant challenge as statistics for the second-hand market are generally poor. Under projections of increasing economic development, the service time of products could be reduced.

The available copper scrap needs to be collected and the factors involved in this process range from geographic material and scrap yard center dispersion, ease of collection, price incentive, and trade agreements. Few studies have included the economic incentives as a driver of old scrap collection or a factor that incentivize higher processing rates at smelter and refinery facilities.

The collected copper scrap is then recycled, but technology adoption, process knowledge, among other factors could affect this process. The recycled material is also a function of the total refined demand and few studies looked at recycled copper scrap from the demand perspective.

Copper scrap that is not recycled is disposed at landfills and incinerators or lost into the environment. Landfills account for a significant amount of copper, while there are few discussions and policies towards this topic.

The geographic distribution of studies is very limited, been mainly focused on either developed regions or China. While this happens because high income countries are the main supplier of copper scrap and China has been the major consumer, some low and medium-income regions have been developed followed the Chinese economic boom since the 2000s and their copper in-use stocks have been growing. Additionally, with nascent trade barriers in the trade flow of copper scrap, these regions could start receiving lower quality copper scrap with the aim to disassemble it and reexport it to industrial countries. Policies should be developed taking into consideration the global recycling industry and the negative externalities that disorganized and unregulated recycling could generate.

Copper supply and demand is influenced by many variables, which are sometimes related to each other, making the development of any policy aimed at the recycling sector very complex.

There are several channels to expand the recycling industry, including the support of advanced technology and equipment to treat and recover wastes of copper-containing materials (M. Wang et al., 2017; J. Wang et al., 2019; Eheliyagoda et al., 2019), improvement of corporate responsibility (Liu et al., 2020), development of a treatment-based strategy of waste recycling and urban mining demonstration bases and elimination of backward enterprises (Wen et al., 2015) and education and public awareness (Tanimoto et al., 2010). Other possibilities are the design oriented towards sorting, disassembling, and recycling, with labelling of copper containing products and establishing separate collection and selective dismantling of copper containing products (Henckens and Worrell, 2020).

Although the recycling industry could be expanded by several ways, the development of policies amid an emerging recycling landscape is compelling and should take into consideration the fragmentation and articulation of this industry.

With copper recycling been a global industry, the lack of organization and regulation in some recycling markets should be addressed to avoid negative externalities that the recycling process could generate. The right design of policies could increase the number of players in the market, promote modernization and technology adoption, increase tax collection, and reduce environment liabilities, especially in developing regions, such as India (Agrawal and Sahu, 2010; Jain, 2012). Moreover, changes in the recycling import policies, initiated by China, could become a common movement in the industry, meaning that each country will need to handle more of its own scrap metal.

3.4 Conclusions

This study provides a comprehensive analysis of the supply of secondary sources of copper. Notably, the number of publications on this topic has shown a steady increase from 2010 to 2020. This rise in publications can be attributed to the growing recognition of the significance of secondary sources in the context of a circular economy. However, there are gaps in scientific literature, particularly in terms of regional coverage, suggesting areas where further investigation is needed.

As the demand for copper continues to rise mainly due to the increasing adoption of renewable energy technologies, electric vehicles and the associated infrastructure, understanding secondary sources is key for ensuring a secure and sustainable supply chain.

We identified several supply drivers of copper scrap, one of which is the in-use stock. Obtaining reliable data on the amount of copper already in circulation is important for understanding the potential supply of copper scrap. However, determining the accurate estimation of the existing copper in-use stock is challenging due to various factors such as undocumented or hidden stock and limited data availability.

Moreover, different sectors consume copper at varying rates, and their recycling patterns differ as well. Analyzing the end-use sector breakdown helps in identifying sectors with the highest potential for copper scrap generation. However, obtaining comprehensive data on end-use sector breakdowns can be difficult, particularly in regions with fragmented or unregulated recycling systems, which tend to occur in low-income countries.

The lifespan of copper-containing products also impacts the availability of copper scrap. Longer lifecycles can delay the flow of copper into the recycling stream, affecting the overall supply of copper scrap. Accurately estimating product lifetimes across different industries and regions is essential but can be complex due to variations in product usage and durability.

Increasing the collection rate of copper scrap is crucial for boosting the supply of recycled copper. However, obstacles arise in developing efficient collection systems, particularly in regions where recycling infrastructure is underdeveloped or lacking. Improving collection rates requires initiatives such as awareness campaigns and improved recycling infrastructure.

The efficiency of recycling also plays a role in the availability of copper. Enhancing the efficiency of copper recycling processes maximizes the yield of usable copper from scrap. However, achieving high recycling efficiency can be challenging due to technological limitations, impurities in the scrap, and variations in recycling practices across different regions. Advancements in recycling technologies and standardization of recycling processes can help overcome these challenges.

Fluctuations in copper prices can also influence the willingness of individuals and businesses to recycle copper. When prices are low, the economic incentive to recycle may diminish, resulting in reduced copper scrap supply. Maintaining stable and favorable copper price conditions can encourage consistent recycling behaviors. On a global basis, trade barriers, including tariffs, quotas, and restrictions, can impact copper prices and the global flow of copper scrap. These barriers can disrupt the availability of copper scrap in certain regions, affecting the overall supply chain. Harmonizing trade policies and minimizing trade barriers can help facilitate the efficient movement of copper scrap across borders.

By collaboratively addressing the factors that influence the supply of copper scrap, policymakers and stakeholders can make informed decisions to actively support the copper recycling industry, thus facilitating the transition towards a circular economy.

4. PROJECTION OF GLOBAL COPPER DEMAND IN THE CONTEXT OF ENERGY TRANSITION

Abstract

Copper is used in a variety of sectors, but technologies with an important role in a low carbon future are also copper-intensive, with wind turbines, solar panels and electric vehicles been key elements in this transition. This article seeks to estimate the global copper demand and forecast it up to 2030. The methodology applied is an autoregressive distributed lag model, where copper consumption per capita was explained by the real gross domestic product per capita, by the real price of copper and by the lagged values of these variables. A second model that included aluminum price is presented, and a third model where copper consumption per capita from solar and wind energy and electric vehicles (EVs) are subtracted from copper consumption per capita. Using the three models to forecast copper demand, there is an insignificant difference between Model 1 and Model 2. In Model 3, copper consumption forecast for 2030 could be almost 5,000 thousand tonnes different from models 1 and 2, in a more optimistic scenario for solar and wind energy and EVs. As these technologies are expected to receive growing incentives due to their low and sometimes zero-carbon emission nature, conventional top-down models that include only explanatory variables related to economic activity and prices can underestimate the potential growth of copper demand.
Keywords: Electric vehicles; Renewables; Aluminum; ARDL

4.1 Introduction

Being needed in a variety of sectors, the demand for copper increased at a compound annual growth rate of 2.6% from 2000 to 2019 (ICSG, 2022), mostly driven by the economic growth of China, combined with the development of its basic infrastructure following a rising urbanization rate (Dong et al., 2019).

Longer term, technologies with an important role in a low carbon future are copper-intensive, with wind turbines, solar panels and electric vehicles been key elements in this transition. Moreover, world gross domestic product (GDP) is forecast to nearly quadruple by 2050 compared to 2010 and the world population is estimated to grow to 9.2 billion in the same period, with approximately 70% living in urban areas where housing, electricity, transport among other traditional copper end-sectors will need to be developed (OECD, 2012).

On the other hand, deficiencies in the copper market - consisting of supply shortage, regulatory constraints, environmental issues, and price volatility - could trigger a substitution process, with copper being replaced by other materials, new technologies or production process. Aluminum is the main substitute for copper as a conductor for electrical products, but other materials have emerged, such as optical fibre in telecommunications and plastic in pumbling. Product miniaturization, however, could favor copper in some applications.

Copper supply depends on the exploitation of primary ore and recycling of secondary source of copper. The development of new projects faces, however, significant hurdles to move forward, driven by environmental and social pressure. Copper deposits with low ore grades can result in higher use of energy, waste generation and disturbance in the local environment (Northey et al., 2014). Furthermore, the primary copper production process generates nearly eight times more environmental impact than recycling (J. Chen et al., 2019).

The rigid extractive capacity structure of the mining industry combined with the challenges associated with new project development could exacerbate the volatility of copper prices (Krautkraemer, 1998). This has consequences on the economies of importer and exporter countries through potential spillover effects to output, exchange rates, inflation, and interest rates. Hegerty (2016) found that Chile, the biggest copper producer in the world, is influenced by – and influences – copper prices, with fluctuations affecting all macroeconomic variables of the country.

A quantitative analysis on copper demand could bring paramount information for stakeholders in the copper value chain. In this context, this article seeks to estimate the global copper demand and project it up to 2030.

4.2 Literature review

The literature review is split into two sessions, the first being related to studies that estimated copper demand, focusing particularly on the econometric modelling and the explanatory variables used. The second session explores substitute materials for copper and their performance as a substitute.

4.2.1 Econometric regression of copper demand

Copper demand could be estimated using a bottom-up or a top-down approach, with the first method building copper demand from the various types of usages to the overall demand and the latter estimating copper demand at a high level of aggregation as a function of other variables. While the bottom-up analysis could provide more detailed results, the top-down approach requires limited data and a smaller number of assumptions (Schipper et al., 2018).

Both approaches have been found in the scientific literature, occasionally in the same article (Kwakkel et al., 2013; Schipper et al., 2018). Several studies have adopted a top-down method (Inoue et al., 2012; Elshkaki et al., 2016; Stuemer, 2017; Gorman and Dzombak, 2019; Ciacci et al., 2020) and relied on regressions analysis to estimate copper demand, with the log-linear demand function been the most common method adopted (Table 4.1).

Table 4.1 - Methodologies applied to estimate copper demand

Study	Method	Explanatory variable	Region	Date range (real / projection)
Inoue et al., 2012	Linear demand function	GDP per capita	World	1960-2010 / 2050
Kwakkel, Auping, and Pruyt, 2013	Dynamic scenario discovery using time series clustering	GDP per capita, GDP, population, Cu price	World	-
Elshkaki et al., 2016	Linear demand function	GDP per capita*, urbanization, time	World	1980-2010 / 2050
Stuermer, 2017	Auto-regressive distributed lag model of a log-linear demand function, applied into a panel data set	Value added in manufacturing per capita*, Cu price*, lagged values of Cu demand per capita	Fifteen countries	1840-2010
Schipper et al., 2018	Log-linear demand function	GDP per capita and population	World	1950-2010 / 2100
Gorman and Dzombak, 2019	Log-linear demand function	Urbanization, Cu price, manufacturing contribution to GDP, domestic materials consumption, time	United States	1970-2015 / 2030
Ciacci et al., 2020	Log-linear demand function, including an autoregression error term	GDP per capita*, population, urbanization	Europe (EU-28)	1960-2010 / 2050

Source: Developed by the author based on Inoue et al. (2012), Kwakkel et al. (2013), Elshkaki et al. (2016), Stuermer (2017), Schipper et al. (2018), Gorman and Dzombak (2019), Ciacci et al. (2020).
Note: GDP refers to Gross Domestic Product and Cu refers to copper. * Indicates the variable is in constant value (adjusted for inflation).

Elshkaki et al. (2016) carried out an analysis of total and sectoral demand for copper and found out that the explanatory variables are significant when used individually, with per capita GDP been the most significant variable in explaining the total demand for copper and its demand in different sectors on a global level. Almost all models were a function of per capita GDP and time. Using the Fourth Global Environmental Outlook (GEO-4) set of scenarios of the United Nations Environment Program, Elshkaki et al. (2016) estimated that copper demand could be between 40 million tonnes and 70 million tonnes by 2050, depending on the scenario.

Schipper et al. (2018) applied logarithms into a multiplicative demand function to obtain an additive regression model. The explanatory variables were slightly different from Elshkaki et al. (2016), as Schipper et al. (2018) relied on an established model where population and a measure of wealth – per capita GDP as selected by the authors – were used to explain copper demand. Projections were based on the five Shared Socio-economic Pathways scenarios from O'Neill et al. (2014). Results show that there could be a 3 to 21-fold copper demand increase for the year 2100 with respect to the production of the year 2012, depending on the scenario. Copper demand is mainly driven by GDP growth, which weigh more on demand than population growth (Schipper et al., 2018).

Elshkaki et al. (2016) and Schipper et al. (2018) did not include copper prices as explanatory variable, while Stuermer (2017) found out that the estimated long-run copper demand elasticity to real prices of copper is inelastic and significant. Stuermer (2017) analyzed how industrialization affects demand for mineral commodities, based on an autoregressive distributed lag model of a log-linear demand function. They also found out that the long-run demand elasticity to manufacturing output for lead, tin, and zinc are far below 1 while for copper is close to unity. The estimated long-run demand elasticity to manufacturing for aluminum is higher than copper, implying that the demand for aluminum increases at a higher rate than manufacturing output.

Although Gorman and Dzombak (2019) focused on the United States, their results showed that U.S. copper price affects consumption negatively, which suggests that consumption decreases as price marginally grows, according to the authors. Other variables that impact copper demand are urbanization, contribution from the manufacturing sector to GDP, and domestic materials consumption, but these variables have a positive correlation with consumption, suggesting that when they marginally increase, copper demand tends to rise. According to Gorman and Dzombak (2019), contribution from the manufacturing sector to GDP and domestic materials consumption were included in the analysis as proxies for economic activities.

Ciacci et al. (2020) adopted a log-linear function to estimate European copper demand and included an autoregression error term to correct for serial correlation. When working with time series, this term ensures that the interpretation of the explanatory variable coefficients is unconditional on the value of previous values of copper demand. Although time-series data is often subject to serial correlation of the disturbances across periods (Greene, 2012), most studies did not discuss the possibility of autocorrelation, such as Elshkaki et al. (2016), Schipper et al. (2018) and Gorman and Dzombak (2019).

Inoeu et al. (2012) did not include an autoregression error term but differently from other studies, they considered the impact that the diffusion of new products and that substitution could have on demand. Inoue et al. (2012) estimated copper demand considering two combined models. One was a regression analysis that calculated metal demand in function of per capita GDP and the other was an equation to account for the diffusion of electric vehicle and photovoltaic systems and substitution. The effect of electric vehicles and photovoltaic systems on metal consumption did not emerge in past statistics given their recent adoption but might affect projections, according to the authors.

The different methods applied to estimate copper demand led to a notable divergence in copper demand estimates. Watari et al. (2020) provided a systematic review of studies published between 1998 and June 2019, exploring the projected long-term demand of various critical materials through 2030 and 2050. Based on some selection criteria, with one of them being the inclusion of energy technology-driven scenarios rather than simple relationships between economic activities and metal demand, three studies were found to project copper demand. Copper demand for 2050, was forecast between 27 million tonnes and 120 million tonnes, according to the range from these studies.

The literature of copper demand still needs to be further explored aiming to reduce uncertainty and raise comprehension in specific issues.

4.2.2 Risk of copper substitution

The microeconomic theory states that the demand for a certain good is a function of the good's price and income. When a good can be replaced by another one, its demand also depends on the price of this substitute good. However, the availability of a substitute does not guarantee that the substitution process will occur, as different factors other than relative prices may be considered in a production system, which can speed the substitution process up or down.

According to Tilton (1984), material substitution may result from shifts in the composition or quality of final goods or from the introduction of a new technology. Material substitution also refers to changes in the mix of factor inputs, such as labor, capital, and energy, or changes in the mix of goods used to meet a particular function or to satisfy a given need, although not altering the manufacturing processes and the use of materials in the production of individual goods. Schlabach (1984) described four types of substitution that are similar to Tilton’s view and pointed out that the kinds of substitution are closely related in that a substitution of one type may well cause others.

The evolutionary school of economic thought says that the use of materials relies on the products, technologies, and technological systems of which they are part. The knowledge about a product tends to enhance over time with corrections of small product flaws and incremental innovations, leading to the consolidation of the whole product concept. The material composition is generally the result of extensive research and development, followed by the employment of specific technologies, system, and a cooperation network with different actors of the supply chain (Messner, 2002). Therefore, short-term substitution in face of supply shortage, regulatory constraints, environmental issues, strategic concerns, and price volatility could be challenging.

Some empirical studies showed that the pace that substitution occurs depends on several factors. Smith and Eggert (2018) applied a survey to analyze the industry responses to the 2010/2011 rare-earth price spike taken by manufacturers of permanent magnet and wind turbine. Doing nothing and passing costs through were the easiest and immediate response while substitutions involving the adoption of pre-existing processes or methods already under development occurred rather quickly. Although more significant improvements took longer and might have been more significant had prices remained high for a longer period, Smith and Eggert (2018) showed that a small number of actual technological breakthroughs reduced rare-earth use in wind turbines. This corroborates with Tilton’s view that prices may influence material substitution most by inducing technological change, with the relationship between price and material demand being discrete and irreversible. This suggest that the demand lost when a material’s price increases cannot be completely recaptured when the price returns to its original level.

Messner (2002) modelled the relative material use of copper and aluminum in the production of conductor materials and products in function of variables that seek to reflect the driving forces that influence the process of material use and substitution. The author calls the tendency to maintain the material composition of established products or technologies as path dependency. For Germany and the U.S., Messner (2002) concluded that path dependence in copper use and relative prices are important factors influencing the relative material use between copper and aluminum, mainly in the long run. For Japan, results suggested that there is a learning trend in favor of aluminum, although the coefficient is not statistically significant.

Guzmán, Nishiyama, and Tilton (2005) found out that new copper-saving technologies and other time-related variables had a negative impact on Japanese copper use intensity between 1960 and 2000, measured as copper demand over GDP. The negative impact was larger enough to offset the positive effects that growing per capita income had on copper use intensity.

Copper and aluminum stand out as a conductor for electrical products due to their low resistance and high conductivity, being possible substitutes in some applications. The first notable time that aluminum became a threat to copper was following the World War II, when its large-scale industry was already set up and copper prices skyrocketed (Messner, 2002).

Differences in their physical and mechanical properties, however, make aluminum or copper more suitable to be used. In electrical conductor materials, Messner (2002) showed that aluminum was able to replace copper in the segment of long-distance power transmission lines for high-voltage capacity of more than 100 kV, when industrialized nations started to build up high-voltage transmission systems and aluminum was able to enter this market since the beginning given its low-density adequacy for the overhead lines combined with price advantage. In power transmission lines and cables for medium and low-voltage (1–60 kV), technical advances in the use of aluminum contributed to the substitution process, although copper had an advantage for both overhead lines and underground cables due to the lower cable diameter required less high-cost insulating material.

However, copper has stood out for low-voltage electrical cables in buildings, and wires, cables and other conductors for electrical transmission in machines, electrical products and industrial plants. This advantage occurs due to fire risks from using aluminum cables with a small diameter, which are vulnerable to large pressure and the fact that aluminum wires and cables would take up more space because of larger cable diameter required for the same capacity (Messner, 2002).

With copper been mainly used for electrical purposes, aluminum is the primary substitute for copper in most applications. Table 4.2 summarizes main applications of copper and brings the primary substitute for each application and its performance and share in total use, according to selected studies in the scientific literature.

Henckens and Worrell (2020) assumed a maximum copper substitutability of 10% for modelling copper demand, to happen especially in applications that are not related to electricity generation, transmission, distribution, and use, such as in roofs, gutters, radiators, ammunition, water distribution, chemicals, and other applications. Reijnders (2021), on the other hand, suggested that copper substitutability might be about 60% of current copper use or more.

Copper substitutability based on Graedel, Harper, Nassar and Reck (2015), who explored potential substitutes for copper and other 61 different metals in all their major uses and assessed the performance of the substitutes in those applications, classifying them as poor, adequate, good, and exemplary, would be about 40% considering the primary substitute performance of equal to or better than adequate. In electrical, transportation, cooling, electronics, and architecture applications, aluminum is the copper primary substitute of copper, which should be thought of as substitute for the case that the metals of focus are not available at all (not even at high prices). For electrical, transportation, and electronics, aluminum presents a poor performance, according to the authors, while for cooling and architecture, aluminum performance is classified as adequate and good, respectively. In industrial equipment and machine tools and in building plant (nails, rivets, soldering copper, and metal seals), steel is the primary substitute, with an adequate performance for both purposes. In plumbing, plastics is the main substitute, with a good performance. In communications, optical fiber is the main threat for copper, having an exemplary performance.

Table 4.2 - Copper applications and primary substitutes

(Continue)

Main application	Application details	Primary substitute	Substitute Performance	Application share in total use (%)
Messner (2002)				
Electrical	Low-voltage electrical cables in buildings	Al	Poor	N.A.
	Wires, cables and other conductors for electrical transmission in machines, electrical products and industrial plants	Al	Poor	N.A.
	Long-distance power transmission lines for a high-voltage capacity of more than 100 kV	Al	Exemplary	N.A.
	Power transmission lines and cables for medium and low-voltage (1–60kV).	Al	Exemplary	N.A.
Graedel et al. (2015)				
Electrical	Electric motors and generators, power transmission lines, and housing and industrial wiring	Al	Poor	26
Industrial	Industrial equipment and machine tools	Steel	Adequate	19
Transportation	Aircraft, marine, tanks, automotive, and train systems	Al	Poor	13
Cooling	Air conditioning equipment and heating tubing	Al	Adequate	7
Plumbing	Fixtures and pipes	Plastics	Good	6
Communication	Telecommunications wiring	Optical fiber	Exemplary	5
Electronics	Switches, printed circuit foils, transistor bases, microwave tubes, and computers	Al	Poor	4
Architecture	Roofing and decorative items	Al	Good	2
Building plant	Nails, rivets, soldering copper, and metal seals	Steel	Adequate	1
Other	Pigments, watches, clocks, and jewelry	N.A.	N.A.	17

(Continuation)

Main application	Application details	Primary substitute	Substitute Performance	Application share in total use (%)
Henckens and Worrell (2020)[1]				
Electrical	High voltage overhead transmission lines	Al	Exemplary	14
	Underground lines	Al	Poor	
	Interior wiring	Al	Poor	22
Industrial	Motor-generator windings	Cu can be replaced, no substitute mentioned	Poor	11
Electronics	Electronic circuitry	Cu can be replaced, no substitute mentioned	Poor	5
Transportation	Automobile radiators	Al	Poor	13
Cooling	Heat exchangers	Titanium and steel	Poor	
	Cooling and refrigeration tubes	Al	Poor	9
Plumbing	Water pipes, drainpipes, and plumbing fixtures	Plastic	Poor	4
Communication	Telecommunication	Glass fiber	Exemplary	3
Architecture	Roofing	Cu can be replaced, no substitute mentioned	N.A.	1

(Conclusion)

Main application	Application details	Primary substitute	Substitute Performance	Application share in total use (%)
Reijnders (2021)				
Electrical	High voltage underground transmission lines	Al / Superconducting materials	Further research efforts needed for substitution	More than 50% of current Cu use
	Medium-and low voltage underground cables for local electricity distribution	Al	In used, performance not mentioned	
	Electricity transport in buildings	Al	Feasible substitute	
Industrial	Low-cost electrical machines	Al	In used, performance not mentioned	
Transportation	Wiring in transportation applications	Al	In used, performance not mentioned	
Electronics	Electronic circuitry	Carbonaceous nanomaterials	Further research efforts needed for substitution	
Various	Roofs, gutters, drainpipes, plumbing fixtures, heat exchangers, cooling and refrigeration tubes, radiators, telecommunication cables, ammunition, water distribution and chemicals	Cu may be replaced, no substitute mentioned	N.A.	About 10% of current Cu use

Source: Developed by the author based on Messner (2002), Graedel et al. (2015), Reijnders (2021), Henckens and Worrell (2020)
Note: based on the available information in the referenced studies, when copper is preferred to its potential substitute, we classified the substitute performance as poor. When the substitute is preferred, we classified its performance as exemplary. Graedel et al. (2015), however, detailed the substitute performance in their analysis, so we used their classification.
[1] Percentage into application refers to the main application and not the application details. As definition may differ among studies, percentage may be read as an approximation.

4.3 Methodology

4.3.1 Econometric approach

The model specification follows an autoregressive distributed lag model (ADL) (p; q; r) of a demand function, where p; q, and r refer to the number of lags included of the explanatory variables (Equation 1). Consequently, the use of distributed lags accounts for the effects of the explanatory variables on the dependent variable across several periods (Enders, 2015).

$$c_t = \alpha + \sum_{j=1}^{p} \beta_{1_j} c_{t-j} + \sum_{l=0}^{q} \beta_{2_l} y_{t-l} + \sum_{m=0}^{r} \beta_{3_m} p_{Cu_{t-m}} + \epsilon_t \qquad (1)$$

Where c_t is copper consumption per capita at time t (with t going from 1960 to 2019), which is explained by the real gross domestic product per capita y_t, by the real price of copper p_{Cu_t} and by the lagged values of these variables. The residual unexplained random error ϵ_t follows a white-noise process.

In a second specification, I added real aluminum prices as explanatory variables, as aluminum is the main metal that can replace copper in most current applications.

$$c_t = \alpha + \sum_{j=1}^{p} \beta_{1_j} c_{t-j} + \sum_{l=0}^{q} \beta_{2_l} y_{t-l} + \sum_{m=0}^{r} \beta_{3_m} p_{Cu_{t-m}} + \sum_{n=0}^{s} \beta_{4_n} p_{Al_{t-n}} + \epsilon_t \qquad (2)$$

The third specification considers the impact that the diffusion of solar and wind energy technologies and electric vehicles could have on demand. I estimate $cadj_t$ in Equation 3 by removing from total copper consumption the amount used by solar and wind energy technologies and electric vehicles, as the effect of these applications did not emerge in past statistics given their recent adoption. However, these applications will be disruptive for copper demand, likely growing at a faster pace than traditional uses, which can impact projections of copper demand if not considered separately.

$$cadj_t = \alpha + \sum_{j=1}^{p} \beta_{1_j} c_{t-j} + \sum_{l=0}^{q} \beta_{2_l} y_{t-l} + \sum_{m=0}^{r} \beta_{3_m} p_{Cu_{t-m}} + \sum_{n=0}^{s} \beta_{4_n} p_{Al_{t-n}} + \epsilon_t \quad (3)$$

The ARDL model is applicable for time series that are stationary at level or at first difference, with the possibility of having mixed order of integration (Pesaran, Shin; 1997).

We tested the stationarity of the variables with augmented Dickey–Fuller Augmented (ADF) tests, whose null hypothesis is that unit root is present in the sample. We used an automatic selection of maximum lags based on the Schwarz Info Criterion (SIC), but we also run the test adopting the Akaike Info Criterion (AIC) with the purpose of comparison.

We also ran the models using both SIC and AIC as the first is asymptotically consistent while the latter is biased toward selecting an overparametrized model (Enders, 2015). Indeed, the models run with SIC were more parsimonious, leading us to adopt it. Nevertheless, the residuals were checked to make sure they are white noise.

The Breusch-Godfrey Serial Correlation Lagrange Multiplier Test were applied to verify whether the residuals from the model are serially uncorrelated. The null hypothesis of this test is that there is no serial correlation for some order less than or equal to 2. For testing for residual homoskedasticity, the Breusch-Pagan-Godfrey Lagrange Multiplier Test was selected, whose null hypothesis is that the residuals are homoscedastic (Greene, 2012).

4.3.2 Data description

Demand for a certain good is a function of the good's price, substitute good's price, if there is any, and income, following the microeconomic theory (Varian, 2014). Most of studies in Table 4.1 used GDP per capita as a gauge of economic activity to reflect how changes in wealth affect demand. Using variables divided by the size of the population is an alternative to control for the effect of population growth. In this sense, we used copper consumption per capita as dependent variable and real gross domestic product per capita as independent variable.

Other independent variables were copper price and aluminum price, with the Producer Price Index being used to bring values at constant 2019 US$. The units and sources of the dependent and independent variables are in Table 4.3.

Table 4.3 - Description of variables directly and indirectly used in the models

Variable	Unit	Source
Copper consumption	Metric tonnes per capita	International Copper Study Group (ICSG)
Gross Domestic Product (GDP)	Real US$ per capita	World Bank
Population	Number of people	World Bank
Copper price	Real US$ per metric tonne	International Copper Study Group (ICSG) and London Metal Exchange (LME)
Aluminum price	Real US$ per metric tonne	United States Geological Survey (USGS) and London Metal Exchange (LME)
Solar and wind installed capacity	Gigawatt	International Energy Agency (IEA)
Electric vehicles fleet	Number of vehicles	International Energy Agency (IEA)
Producer Price Index	Index	Federal Reserve Bank of St. Louis

Source: Developed by the author.

Copper demand was forecast until 2030 using the parameters from the autoregressive distributed lag models applied to the projections of the explanatory variables.

Estimates for GDP and population came from IEA (2022b) that relied on data from Oxford Economics (2022) and IMF (2022) for GDP projection and United Nations (2022) for population. Copper and aluminum real prices were kept stable, being the average of realized prices from 2012 to 2021.

Solar and wind installed capacity and electric vehicles fleet were from IEA (2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019d, 2020, 2021, 2022b) that designed three scenarios for the path the energy system can follow. The Announced Pledges Scenario (APS) considers all the climate commitments made by governments around the world, including Nationally Determined Contributions as well as longer term net zero targets, and assumes that they will be met in full and on time while the Stated Policies Scenario (STEPS) considers that governments will not reach all announced goals. The Net Zero Emissions by 2050 (NZE) sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050 and it designed to meet key energy-related United Nations SDGs (IEA, 2022b). All scenarios are available for installed capacity of wind and solar energy in the world, while for EVs, the scenarios used are STEPS and APS. Given that, when we present the NZS scenario for copper demand, we combine the APS scenario for EVs and the NZS for wind and solar energy.

4.4 Discussion of results

The results of the unit root tests under the SIC and AIC maximum lag selection procedure show that all variables are stationary after applying the first difference (Table 4.4). These results hold for the models with constant and trend, with constant only and without constant and trend, ie., random walk. Therefore, an ARDL model can be adopted.

Table 4.4 - Unit root tests at level and at difference

Variable	Model with constant and trend				Model with constant				Random walk			
	SIC		AIC		SIC		AIC		SIC		AIC	
	Prob.	Lag	Prob.	Lag	Prob.	Lag	Prob.	Lag	Prob.	Lag	Prob.	Lag
c_t	0.776	0	0.947	2	0.928	0	0.976	2	0.994	0	0.999	2
$cadj_t$	0.648	0	0.897	2	0.877	0	0.946	2	0.990	0	0.998	2
y_t	0.996	0	0.995	2	1.000	0	1.000	2	1.000	0	1.000	2
p_{Cu_t}	0.447	0	0.447	0	0.182	0	0.182	0	0.449	0	0.449	0
p_{Al_t}	0.000	1	0.001	5	0.033	0	0.033	0	0.226	0	0.033	10
$d(c_t)$	0.000	1	0.000	1	0.000	1	0.000	1	0.000	0	0.000	1
$d(cadj_t)$	0.000	1	0.000	1	0.000	1	0.000	1	0.000	0	0.000	1
$d(y_t)$	0.000	0	0.000	1	0.000	0	0.000	0	0.005	0	0.758	9
$d(p_{Cu_t})$	0.000	0	0.000	1	0.000	0	0.000	0	0.000	0	0.000	0
$d(p_{Al_t})$	0.000	0	0.004	9	0.000	0	0.001	9	0.000	0	0.000	5

Source: Original research data.

Table 4.5 shows the ARDL regression fit results for Model 1, Model 2, and Model 3. For all of them, the R2 was above 0.98, indicating that most part of the dependent variable's variance is explained by the selected variables of the regression model. The number of lags used is determined by the Schwarz information criterion. We included a linear time trend in Model 1 and Model 2 as a test to capture technological development and policy changes, similar to the approach of Elshkaki et al. (2016). However, the time trend was not significant. Appendix B shows the results for those models including a time trend. For this reason, the ARDL models with time trend will be discarded in the following discussion.

In all cases, copper consumption per capita with one lag as well as GDP per capita at level and with one lag are significant at 1% threshold (Table 4.5Table *2.1*). The coefficients of GDP per capita at level and GDP per capita with one lag have opposite signs and almost same magnitudes. In the case of Model 1, the complete lag terms of the GDP per capita variable read $0.000584y_t - 0.000537y_{t-1}$ which is approximately equal to $0.000561(y_t -$

y_{t-1}). The later simplification shows that no annual change of the GDP per capita leads to no annual change of the copper demand. In other words, the annual change in copper demand increases linearly with the annual increase in GDP per capita. An increase of annual GDP change also leads to an increase in annual change in copper demand and a decrease of annual GDP change leads to a decrease in annual change in copper demand. Moreover, this indicates that the relative change of copper demand is mostly dependent on the relative change of GDP per capita.

The interpretation of the impact of copper price on copper demand should also be read as the combination of the lag terms, although only copper price with 3 lags has a statistical significance of 1% in Model 1 and Model 2, with the remaining lags having insufficient statistical relevance. In Model 3, copper price with 1 lag and with 3 lags are significant, with $p_{Cu_{t-1}}$ having a negative coefficient and $p_{Cu_{t-3}}$ having a positive one, which suggests that the copper demand reacts rather slowly to price changes given the lag structure.

In Model 2 and Model 3, the coefficient of the aluminum price with 1 lag was significant at 5% and positive, indicating the higher prices of aluminum tend to contribute to higher demand. The coefficient of the aluminum contemporaneous price is positive but with no statistical relevance.

With aluminum price being statistically significant to explain copper demand and supported by the qualitative analysis that shows that aluminum is the main substitute for copper, we chose to include the aluminum price as explanatory variable of Model 3, where the sum of wind and solar energy and electric vehicles (in copper content per capita) are subtracted from the copper demand data.

We tested a model where wind and solar energy and electric vehicles are an explanatory variable of copper demand per capita. However, RNEV is not a significant variable as RNEV is bigger than zero only for 20 years, while for the remaining years (ie., 40 years), it is equal to zero. Although we understand that, in reality, for the remaining years, there was copper consumption from wind and solar energy and EVs, the numbers for that period should be very near zero. Additionally, as copper demand reduced its growth rate particularly in the period when RNEV presented an important growth, the coefficient of RNEV is negative. We believe that more data points are necessary to run the model with RNEV as explanatory variable. Results for this test are in the Appendix B.

Table 4.5 - Econometric results of the ARDL models

		Model 1	Model 2	Model 3
		c_t	c_t	$cadj_t$
α		0.151844	0.084422	0.129951
	Std error	*0.055724*	*0.089204*	*0.093575*
	t	*2.724930****	*0.946392*	*1.388735*
c_{t-1}		0.738717	0.742507	
	Std error	*0.062089*	*0.060489*	
	t	*11.897740****	*12.275060****	
$cadj_{t-1}$				0.719996
	Std error			*0.065011*
	t			*11.075070****
y_t		0.000584	0.000605	0.000591
	Std error	*0.000102*	*0.000100*	*0.000101*
	t	*5.721220****	*6.029996****	*5.832134****
y_{t-1}		-0.000537	-0.000556	-0.000541
	Std error	*0.000103*	*0.000101*	*0.000102*
	t	*-5.237065****	*-5.489301****	*-5.282634****
${p_{Cu}}_t$		0.000006	0.000009	0.000009
	Std error	*0.000009*	*0.000009*	*0.000009*
	t	*0.680469*	*1.041608*	*1.083449*
${p_{Cu}}_{t-1}$		-0.000012	-0.000019	-0.000019
	Std error	*0.000011*	*0.000011*	*0.000011*
	t	*-1.111081*	*-1.686933*	*-1.711122**
${p_{Cu}}_{t-2}$		-0.000008	-0.000007	-0.000007
	Std error	*0.000009*	*0.000009*	*0.000009*
	t	*-0.826626*	*-0.803700*	*-0.759495*
${p_{Cu}}_{t-3}$		0.000029	0.000030	0.000029
	Std error	*0.000007*	*0.000007*	*0.000007****
	t	*4.199091****	*4.419176****	*4.183031*
${p_{Al}}_t$			-0.000023	-0.000022
	Std error		*0.000019*	*0.000019*
	t		*-1.206560*	*-1.164392*
${p_{Al}}_{t-1}$			0.000040	0.000040
	Std error		*0.000018*	*0.000018*
	t		*2.170528***	*2.168852***
Obs.		57	57	57
R2		0.985	0.986	0.985
Adj. R2		0.983	0.984	0.982
F-statistic		463.7	381.3	332.0
Prob (F-statistic)		0.000	0.000	0.000

Source: Original research data.
Note: *** significant at 1%; ** significant at 5%; * significant at 10%.

Table 4.5 shows the fit results of model 2 with wind and solar energy and EV copper demand subtracted from the total copper demand. The Schwartz information criterion yields the same lag orders for all variables. The difference in the coefficients from Model 2 and Model 3 suggests the effect of wind and solar energy and EV on copper demand onwards is small, with the coefficients of Model 3 varying within the standard residuals of the respective coefficients of Model 2. Despite that, we can observe that the coefficients of copper demand with one lag and GDP per capita at level and with one level reduced in Model 3 compared to Model 2.

Table 4.6 shows the results of the Breusch-Godfrey Serial Correlation LM Test and Breusch-Pagan-Godfrey Heteroskedasticity Test. We cannot reject the null hypothesis related to the residuals of the regression of no serial correlation of any order up to 2 (for all models). The same happens with the heteroscedasticity test, where we cannot reject the null hypothesis of homoscedasticity for Models 1, 2 and 3. Results regarding the normality of the residues are in the Appendix C.

Table 4.6 - Post-estimation regression tests

Test		Model 1	Model 2	Model 3
Breusch-Godfrey Serial Correlation LM Test	F-statistic	0.014	0.038	0.139
	Prob. F	0.986	0.963	0.870
Breusch-Pagan-Godfrey Heteroskedasticity Test	F-statistic	1.630	0.842	1.158
	Prob. F	0.149	0.582	0.343

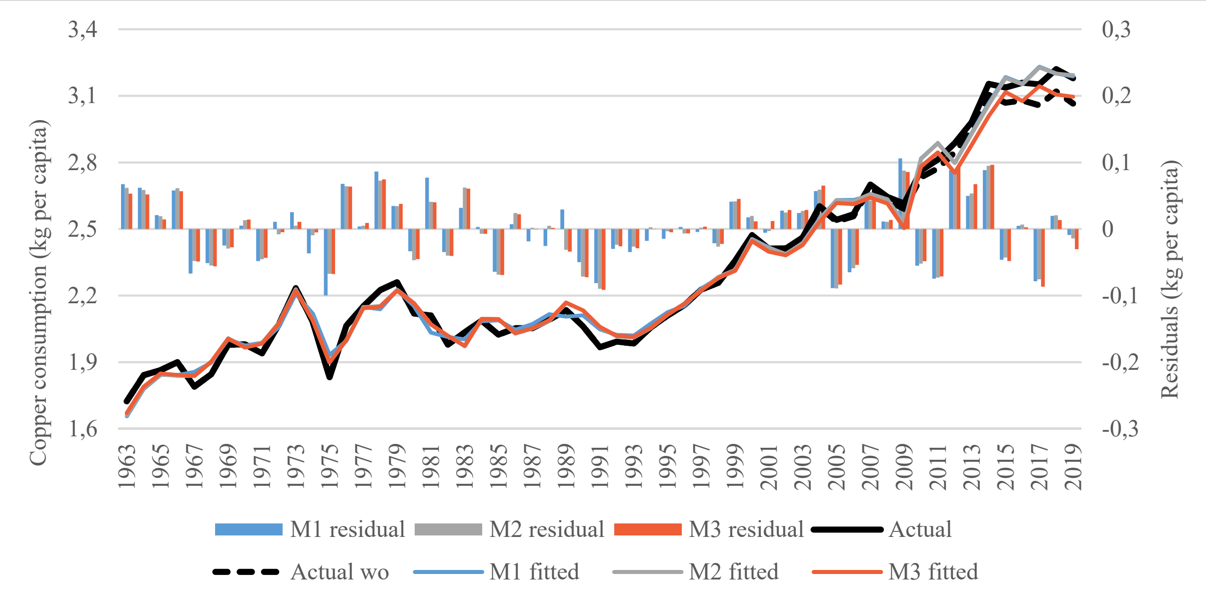
Source: Original research data.

The residuals of the models 1 and 2 are very similar, although results from Model 2 had a slightly better fit than Model 1 (Figure 4.1). While the main difference between models 1 and 2 is the addition of aluminum price as explanatory variable, Model 3 has the same explanatory variables, but the dependent variable is copper consumption minus wind and solar energy and electric vehicles in copper content.

As Figure 4.1 shows, the main difference between the actual numbers of copper consumption per capita and copper consumption per capita deducted from wind and solar energy and electric vehicles start to be relevant from 2015. The number of years where this difference occurs is very small, consequently the error of Model 3 tends to be bigger during these periods given the fact that the coefficients of the dependent variables do not fully capture (or deduct) the impact of wind and solar energy and EVs on copper consumption.

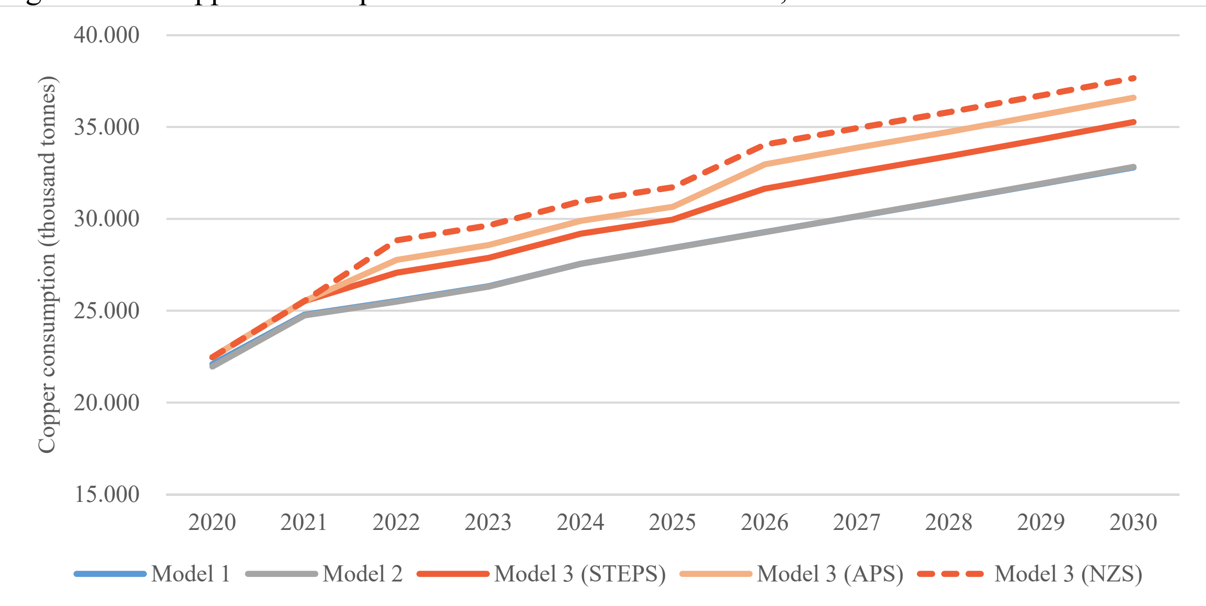
Using the three models to forecast copper demand, we have an insignificant difference between Model 1 and Model 2. This occurs because copper prices and aluminum prices were kept stable over the years, while it is the change in prices that would result in slightly different results for models 1 and 2, but also because aluminum price did not add substantial explanatory power to the model although it is a key substitute for copper based on the theory.

Figure 4.1 - Performance of models 1, 2 and 3 from 1963 to 2019



Source: Original research data.
Note: 'Actual' refers to realized copper consumption while 'Actual wo' means realized copper consumption minus wind and solar energy and EVs in copper content.

Figure 4.2 - Copper consumption forecast based on models 1, 2 and 3 from 2020 to 2030



Source: Original research data.
Note: 'Actual' refers to realized copper consumption while 'Actual wo' means realized copper consumption minus wind and solar energy and EVs in copper content.

In Model 3, copper consumption forecast for 2030 was around 2,400 thousand tonnes different from models 1 and 2 for the STEPS forecast and around 4,800 thousand tonnes for the NZS projection. This gap is evidence that traditional models that do not account for the key trends that impact copper demand are not suitable for forecast purposes. We recognize, however, that the small number of datapoints given the emerging nature of renewables and EVs is a deficiency statistically wise, and probably wealth, measured by GDP per capita in this study, will have a reduced role in the future. This is expected due to the increasing role of renewables and EVs in copper demand that is not associated with GDP growth but with initiatives to fight climate change.

In 2020 and 2021, realized number for copper demand pointed to a growth of 2.5% and 1.2% year over year, respectively, despite global real GDP having fallen 3.1% in 2020 affected by the COVID-19 pandemic and risen 5.9% in 2021 following a strong rebound supported by government incentives in several parts of the world. Solar panels and wind turbines installations, however, increased 20.4% in 2020 and 16.6% in 2021 as clean energy has been used to boost the economy while fostering the energy matrix transition (IEA, 2022b). Models 1, 2 and 3 performed poorly in 2020 as GDP had a strong effect in forecasting and drop in GDP was historically unprecedent; in 2021, however, Model 3 performed better as the addition of wind and solar energy and EVs into copper demand led the estimated results to be closer to the realized number from the ICSG (2022).

4.5 Conclusions

The autoregressive distributed lag models showed that copper demand is indeed impacted by the world economy conditions and copper prices. Aluminum is the main metal that can replace copper in several applications and its price proved to be significant to explain copper demand, although the statistical gain by including aluminum price is very small.

Using autoregressive distributed lag models brought more confidence to the interpretation of the coefficients once the existent literature based their research on traditional estimates where the key characteristics of time series were not taken into consideration, such as autocorrelation. The distributed lags showed that it is not the level of GDP that is important for demand, but instead the change in GDP over the years.

The main contribution from the different tested models, however, is the approach where wind and solar energy and electric vehicles were subtracted from copper consumption. Although these technologies are emergent, they are expected to receive growing incentives due to their low and sometimes zero-carbon emission nature. Being copper an important component of these technologies, they are expected to be key drivers of copper demand. Conventional top-down models that include only explanatory variables related to economic activity and prices can underestimate the potential growth of copper demand.

Important advancements could be made by understanding demand growth regionally, as to support governments, investors, and other stakeholders in the policy making and strategic planning. Another contribution could come from the simulation of different economic scenarios, where short-term and long-term cycles would reflect in a more volatile GDP. Additionally, copper and aluminum prices could be forecast based on the supply and demand perspective while this study assumed stable prices. There are many avenues to improve the models presented and the understanding of a topic that is vital for the energy transition.

5. FINAL REMARKS

The primary objective of this thesis was to evaluate the potential trajectories of modern copper-intensive technologies, specifically solar and wind energy, as well as electric vehicles, and predict the global demand for copper. Furthermore, this study aimed to assess the market dynamics surrounding secondary sources of copper, which present a viable alternative to the extraction of virgin ores.

The growth of solar and wind energy technologies and electric vehicles has been significant in recent years. Solar and wind installed capacity rose 33.2% and 13.9% annually from 2010 to 2021, respectively, and the electric vehicle fleet increased 86.6% in the same period.

However, it is important to recognize that the future expansion of these technologies are heavily reliant on governmental decisions and policies. The continued support and commitment from governments play a critical role in sustaining the growth trajectory of these sectors. Policies that provide incentives, such as subsidies and tax credits, can encourage further investment in renewable energy infrastructure and accelerate the adoption of electric vehicles.

Furthermore, governments have the power to shape regulations that facilitate the integration of solar and wind energy into existing power grids. This includes establishing favorable net metering policies, streamlined permitting processes, and grid infrastructure upgrades to accommodate increased renewable energy capacity.

Government support can also address challenges associated with electric vehicle adoption, such as establishing widespread charging infrastructure, incentivizing consumer purchases through subsidies or grants, and implementing favorable emission standards and regulations.

The demand for copper is highly contingent upon future scenarios surrounding solar energy, wind energy, and electric vehicles. Moreover, the difference in copper demand becomes even more pronounced when considering the uncertainty associated with the copper content in these technologies. It is imperative to comprehend the influence of these technologies on copper demand to ensure a stable supply and facilitate the transition towards sustainable energy sources. This becomes especially important due to the inherent inflexibility of copper supply compared to other commodities, making it challenging to adjust production levels rapidly in response to fluctuating demand.

The evolving landscape of environmental and sustainability considerations can significantly impact copper demand. The global focus on transitioning to cleaner and more sustainable energy sources has led to an increased reliance on copper-intensive technologies. Consequently, the demand for copper is influenced not only by economic factors but also by environmental policies, government incentives, and consumer preferences for greener alternatives.

Because of this importance, modelling copper demand requires some attention as the evolution of traditional variables that influences consumption may be detached from the evolution of these technologies. However, the emerging nature of solar panel and wind turbines and electric vehicles also create an econometric challenge, given the few data points available.

We tried to overcome this challenge by deducting copper from solar and wind energy and EVs from total copper demand in the dependent variable. Although the problem of few data points persists, this is an alternative to better assess the potential impact of these segments on copper demand in the future. Additionally, we used the scenarios from the article 'Scenarios of copper requirement in renewable energy and electric vehicles' to forecast copper demand based on the equation from the article 'Projection of global copper demand in the context of energy transition'.

The study on copper demand used autoregressive distributed lag models, which showed that copper demand is influenced by the global economic conditions and copper prices. The study also revealed that changes in GDP over time, not the level of GDP, are important for demand. The use of autoregressive distributed lag models in the study brought more credibility to the interpretation of the coefficients compared to traditional estimates, as it took into consideration key characteristics of time series such as autocorrelation.

This thesis represents an advancement in the field by integrating two elements: the assessment of the impact of key technologies employed to address climate change on copper demand and the utilization of an autoregressive distributed lag model to analyze the demand function. The existing literature has focused on the use of contemporaneous effects on the demand, except for a few exceptions where distributed lags were applied but the impact of solar and wind energy and EVs on copper demand has been not considered.

Further advancements in understanding copper demand can be achieved by conducting detailed analyses and improving the projection of explanatory variables.

This could involve the development of a regional analysis of demand growth. By examining the demand dynamics on a regional level, policymakers, investors, and other stakeholders can make more informed decisions and engage in strategic planning.

In addition, incorporating the simulation of various economic scenarios can provide a more comprehensive understanding of copper demand and supply dynamics. By considering different economic scenarios, including both short-term and long-term cycles, the analysis can capture the potential impact of economic fluctuations on copper demand.

Forecasting copper and aluminum prices based on supply and demand fundamentals can also enhance the accuracy of future projections. By considering factors such as production levels, consumption patterns, market trends, and trade dynamics, a more robust assessment of price movements can be achieved.

Another advancement in understanding copper demand is the acknowledgment of the complexity inherent in global supply chains and trade patterns. These complexities introduce additional factors that are often not fully captured by conventional models and were not taken into account in this particular study. Factors such as geopolitical events, trade policies, and supply disruptions can significantly impact copper demand and are crucial to consider.

Geopolitical events, such as trade wars or political instability in copper-producing regions, can significantly impact the availability and flow of copper in global markets. Likewise, trade policies, such as tariffs or trade agreements, can affect the import and export of copper, altering the demand dynamics in different regions. Moreover, supply disruptions, such as natural disasters or labor strikes, can disrupt the production and distribution of copper, leading to sudden shifts in demand-supply equilibrium.

Copper demand is expected to rise under all scenarios, but this does not necessarily mean that all additional volume will be extracted from the earth as copper can be recycled from worn out, discarded or obsolete products without losing its key characteristics.

The article ‘systematic review on the drivers of secondary sources of copper’ identified several drivers of copper scrap, such as product lifetime, scrap collection rate, recycling efficiency, copper prices, and trade barriers. Knowing the factors that affect the dynamic of the copper scrap market can help governments to design policies to promote the secondary sector. Companies that are keen to invest in this sector can also take advantage of the study by better understanding the key aspects around the copper recycling landscape.

Over the period of 2010 to 2020, the number of publications about the copper scrap market increased, likely due to the growing importance of secondary sources from a circular economy perspective and copper's role in technologies addressing climate change. The potential for copper scrap to reduce the need for primary material is significant, and this study identified various drivers of demand and supply, including copper in-use stocks, product lifetime, scrap collection rate, recycling efficiency, copper prices, and trade barriers. These drivers should be considered in an integrated manner to support policy development, assisting policy makers and stakeholders in making more informed decisions to promote the copper recycling industry and help countries achieve a circular economy. Additionally, the results provide guidance on factors to be considered in future research and highlight the scientific literature gaps in terms of region coverage.

However, despite the expected increase in the availability of copper scrap, it is important to recognize the utmost importance of adhering to environmentally and socially responsible recycling practices on a global scale. This is necessary to ensure that recycling truly offers advantages over the use of virgin materials and to support the energy transition through the adoption of low-carbon processes across the entire supply chain. By implementing and promoting sustainable recycling practices, we can maximize the positive impact of recycling on the environment, society, and the overall sustainability of the copper industry.

REFERENCES

Aaldering, L. J., Leker, J., & Song, C. H. (2019). Analysis of technological knowledge stock and prediction of its future development potential: The case of lithium-ion batteries. *Journal of cleaner production*, *223*, 301-311.

Agrawal, A., & Sahu, K. K. (2010). Problems, prospects and current trends of copper recycling in India: An overview. *Resources, Conservation and Recycling*, *54*(7), 401-416.

Anadon, L. D., Jones, A., & Peñasco, C. (2022). Ten Principles for Policymaking in the Energy Transition: Lessons from Experience. University of Exeter. Economics of Energy Transition and System Transition. Available at: https://eeist.co.uk/eeist-reports/

Bader, H. P., Scheidegger, R., Wittmer, D., & Lichtensteiger, T. (2011). Copper flows in buildings, infrastructure and mobiles: a dynamic model and its application to Switzerland. *Clean Technologies and Environmental Policy*, *13*(1), 87-101.

Beylot, A., Guyonnet, D., Muller, S., Vaxelaire, S., & Villeneuve, J. (2019). Mineral raw material requirements and associated climate-change impacts of the French energy transition by 2050. *Journal of Cleaner Production*, *208*, 1198-1205.

Bonnin, M., Azzaro-Pantel, C., Pibouleau, L., Domenech, S., & Villeneuve, J. (2013). Development and validation of a dynamic material flow analysis model for French copper cycle. *Chemical Engineering Research and Design*, *91*(8), 1390-1402.

Carrara S., Alves Dias P., Plazzotta B. and Pavel C., Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, EUR 30095 EN, Publication Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-16225-4, doi:10.2760/160859, JRC119941.

Chan, C. C. 2007. The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE 95(4): 704-718.

Chen, W., Wang, M., & Li, X. (2016). Analysis of copper flows in the United States: 1975–2012. *Resources, Conservation and Recycling*, *111*, 67-76.

Chen, J., Wang, Z., Wu, Y., Li, L., Li, B., Pan, D. A., & Zuo, T. (2019). Environmental benefits of secondary copper from primary copper based on life cycle assessment in China. *Resources, Conservation and Recycling*, *146*, 35-44.

CDA (Copper Development Association). Resources. Available from: https://www.copper.org/. Access: 05/25/2022.

Ciacci, L., Vassura, I., & Passarini, F. (2017). Urban mines of copper: Size and potential for recycling in the EU. *Resources*, *6*(1), 6.

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*, *63*, 102093.

Crowson, P. (2012). Some observations on copper yields and ore grades. *Resources Policy*, *37*(1), 59-72.

Deetman, S., Pauliuk, S., Van Vuuren, D. P., Van Der Voet, E., & Tukker, A. (2018). Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. *Environmental science & technology*, *52*(8), 4950-4959.

Denyer, D., & Tranfield, D. (2009). *Producing a systematic review.* In D. A. Buchanan & A. Bryman (Eds.), *The Sage handbook of organizational research methods* (p. 671–689). Sage Publications Ltd.

Dong, D., Tukker, A., & Van der Voet, E. (2019). Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. *Journal of Industrial Ecology*, *23*(6), 1363-1380.

Dong, D., Espinoza, L. A. T., Loibl, A., Pfaff, M., Tukker, A., & Van der Voet, E. (2020). Scenarios for anthropogenic copper demand and supply in China: implications of a scrap import ban and a circular economy transition. *Resources, Conservation and Recycling*, *161*, 104943.

Duffner, F., Wentker, M., Greenwood, M., & Leker, J. (2020). Battery cost modeling: A review and directions for future research. *Renewable and Sustainable Energy Reviews*, *127*, 109872.

Eheliyagoda, D., Wei, F., Shan, G., Albalghiti, E., Zeng, X., & Li, J. (2019). Examining the Temporal Demand and Sustainability of Copper in China. *Environmental Science & Technology*, *53*(23), 13812-13821.

Emel'yanov, A. A., Voronov, D. S., Dolzhenko, R. A., & Dushin, A. V. (2018). Analysis of the expected resources of copper scrap. *Studies on Russian Economic Development*, *29*(2), 174-181.

Elshkaki, A., Graedel, T. E., Ciacci, L., & Reck, B. K. (2016). Copper demand, supply, and associated energy use to 2050. *Global Environmental Change*, *39*, 305-315.

Fernandez, V. (2018). Price and income elasticity of demand for mineral commodities. *Resources Policy*, *59*, 160-183.

EIA (Energy Information Administration). (2020). Energy explained. U.S. Energy Information Administration. Available at: https://www.eia.gov/energyexplained/. Access: Sep., 2020.

Enders, W. (2015). *Applied econometric time series* (4th ed.). John Wiley & Sons.

EPA (United States Environmental Protection Agency) (2019). Global Greenhouse Gas Emissions Data. Available from: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Reference%201. Access: 07/10/2019.

EPE (Energy Research Office). Anuário Estatístico de Energia Elétrica 2022. Ano base 2021. (2022a). Rio de Janeiro: author. Available at: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-pde

EPE (Energy Research Office). Plano Decenal de Expansão de Energia 2031 (2022b). Brasília: author. Available at: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-pde

Fu, X., Ueland, S. M., & Olivetti, E. (2017). Econometric modeling of recycled copper supply. *Resources, Conservation and Recycling*, *122*, 219-226.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm?. *Journal of cleaner production*, *143*, 757-768.

Gorman, M. R., & Dzombak, D. A. (2019). An Assessment of the Environmental Sustainability and Circularity of Future Scenarios of the Copper Life Cycle in the US. Sustainability, 11(20), 5624.

Gotzens, F., Heinrichs, H., Hake, J. F., & Allelein, H. J. (2018). The influence of continued reductions in renewable energy cost on the European electricity system. *Energy strategy reviews*, *21*, 71-81.

Graedel, T. E., Harper, E. M., Nassar, N. T., & Reck, B. K. (2015). On the materials basis of modern society. *Proceedings of the National Academy of Sciences*, *112*(20), 6295-6300.

Greene, W. (2012). Econometric Analysis (7th ed.). Pearson Education.

Guzmán, J. I., Nishiyama, T., & Tilton, J. E. (2005). Trends in the intensity of copper use in Japan since 1960. *Resources Policy*, *30*(1), 21-27.

Habib, K., Hamelin, L., & Wenzel, H. (2016). A dynamic perspective of the geopolitical supply risk of metals. *Journal of Cleaner Production*, *133*, 850-858.

Hao, M., Wang, P., Song, L., Dai, M., Ren, Y., & Chen, W. Q. (2020). Spatial distribution of copper in-use stocks and flows in China: 1978–2016. *Journal of Cleaner Production*, *261*, 121260.

Hardman, S., Chandan, A., Tal, G., & Turrentine, T. (2017). The effectiveness of financial purchase incentives for battery electric vehicles–A review of the evidence. *Renewable and Sustainable Energy Reviews*, *80*, 1100-1111.

Harzing, A. W., & Alakangas, S. (2016). Google Scholar, Scopus and the Web of Science: a longitudinal and cross-disciplinary comparison. *Scientometrics*, *106*(2), 787-804.

Hegerty, S. W. (2016). Commodity-price volatility and macroeconomic spillovers: Evidence from nine emerging markets. *The North American Journal of Economics and Finance*, *35*, 23-37.

Henckens, M. L. C. M., & Worrell, E. (2020). Reviewing the availability of copper and nickel for future generations. The balance between production growth, sustainability and recycling rates. *Journal of Cleaner Production*, *264*, 121460.

Higashida, K., & Managi, S. (2014). Determinants of trade in recyclable wastes: evidence from commodity-based trade of waste and scrap. *Environment and Development Economics*, *19*(2), 250-270.

Hu, X., Wang, C., Lim, M. K., & Chen, W. Q. (2020). Characteristics of the global copper raw materials and scrap trade systems and the policy impacts of China's import ban. *Ecological Economics*, *172*, 106626.

ICSG (International Copper Study Group) (2022). The world copper factbook 2022. Available from: https://icsg.org/copper-factbook/Access: 10/08/2022.

IdTechEx (2017). Copper intensity in the electrification of transport and the integration of energy storage. Available from: https://copperalliance.org/wp-content/uploads/2017/05/2017.04-E-Mobility-Factsheet-4.pdf. Access: 07/02/2019.

ICA (International Copper Association) (2022). Market Intelligence. Available from: https://copperalliance.org/trends-and-data/market-intelligence/. Access: 05/09/2022.

IEA (International Energy Agency) (2019c). Global EV Outlook 2019, IEA, Paris, www.iea.org/publications/reports/globalevoutlook2019/.

IEA (International Energy Agency) (2022a). Global EV Outlook 2022, IEA, Paris, https://www.iea.org/reports/global-ev-outlook-2022.

IEA (International Energy Agency) (2012). *World Energy Outlook-2012*, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2012.

IEA (International Energy Agency) (2013). *World Energy Outlook-2013*, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2013.

IEA (International Energy Agency) (2014). *World Energy Outlook-2014*, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2014.

IEA (International Energy Agency) (2015). *World Energy Outlook-2015*, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2015.

IEA (International Energy Agency) (2016). *World Energy Outlook-2016*, IEA, Paris, https://webstore.iea.org/world-energyoutlook-2016.

IEA (International Energy Agency) (2017). *World Energy Outlook-2017*, IEA, Paris, https://webstore.iea.org/world-energyoutlook-2017.

IEA (International Energy Agency) (2018). *World Energy Outlook-2018*, IEA, Paris, https://webstore.iea.org/world-energyoutlook-2018.

IEA (International Energy Agency) (2019d). *World Energy Outlook-2019*, IEA, Paris, https://webstore.iea.org/world-energyoutlook-2019.

IEA (International Energy Agency) (2020). *World Energy Outlook-2020*, IEA, Paris, https://webstore.iea.org/world-energyoutlook-2020.

IEA (International Energy Agency) (2021). *World Energy Outlook-2021*, IEA, Paris, https://webstore.iea.org/world-energyoutlook-2021.

IEA (International Energy Agency) (2022b). *World Energy Outlook-2022*, IEA, Paris, https://webstore.iea.org/world-energyoutlook-2022.

Inoue, Y., Kishita, Y., Fukushige, S., Kobayashi, H., & Umeda, Y. (2012, September). Evaluating risks of copper depletion based on sustainability scenarios. In *2012 Electronics Goes Green 2012+* (pp. 1-6). IEEE.

IPCC (Intergovernmental Panel on Climate Change) (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IRENA (International Renewable Energy agency). (2020). Renewable Power Generation Costs in 2019. International Renewable Energy Agency, Abu Dhabi.

IRENA (International Renewable Energy agency). (2022). IRENASTAT Online Data Query Tool. https://pxweb.irena.org/pxweb/en/IRENASTAT/IRENASTAT__Power%20Capacity%20and%20Generation/RECAP_2022_cycle2.px/table/tableViewLayout1/ Access: 09/07/2022.

Jain, P. K. (2012). Recycling of metal scraps—a positive concept leading to augmentation of reserve base. *Mineral Economics*, *25*(1), 45-51.

Knapp, F. L. (2016). The birth of the flexible mine: Changing geographies of mining and the e-waste commodity frontier. *Environment and Planning A: Economy and Space*, *48*(10), 1889-1909.

Krautkraemer, J. A. (1998). Nonrenewable resource scarcity. *Journal of Economic literature*, *36*(4), 2065-2107.

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: the concept and its limitations. *Ecological economics*, *143*, 37-46.

Kwakkel, J. H., Auping, W. L., & Pruyt, E. (2013). Dynamic scenario discovery under deep uncertainty: The future of copper. *Technological Forecasting and Social Change*, *80*(4), 789-800.

Liao, F., Molin, E., & van Wee, B. (2017). Consumer preferences for electric vehicles: a literature review. *Transport Reviews*, *37*(3), 252-275.

Liao, M. I., Shih, X. H., & Ma, H. W. (2019). Secondary copper resource recycling and reuse: A waste input-output model. *Journal of Cleaner Production*, *239*, 118142.

Liu, Z. (2018). What is the future of solar energy? Economic and policy barriers. *Energy Sources, Part B: Economics, Planning, and Policy*, *13*(3), 169-172.

Liu, S., Zhang, Y., Su, Z., Lu, M., Gu, F., Liu, J., & Jiang, T. (2020). Recycling the domestic copper scrap to address the China's copper sustainability. *Journal of Materials Research and Technology*, *9*(3), 2846-2855.

Mackey, P. J., Cardona, V., & Reemeyer, L. (2019). The Role of Scrap Recycling in the USA for the Circular Economy: A Case Study of Copper Scrap Recycling. In *REWAS 2019* (pp. 319-320). Springer, Cham.

Mahmoud, M., Garnett, R., Ferguson, M., & Kanaroglou, P. (2016). Electric buses: A review of alternative powertrains. *Renewable and Sustainable Energy Reviews*, *62*, 673-684.

Mathis, W. (2020). Battle Over World's Biggest Wind Turbine Is Heating Up. Bloomberg. Available at: https://www.bloomberg.com/news/articles/2020-05-19/battle-over-world-s-biggest-wind-turbine-is-heating-up. Access: Sep., 2020.

Maung, K. N., Hashimoto, S., Mizukami, M., Morozumi, M., & Lwin, C. M. (2017). Assessment of the secondary copper reserves of nations. *Environmental Science & Technology*, *51*(7), 3824-3832.

Månberger, A., & Stenqvist, B. (2018). Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy*, *119*, 226-241.

Messner, F. (2002). Material substitution and path dependence: empirical evidence on the substitution of copper for aluminum. *Ecological Economics*, *42*(1-2), 259-271.

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: a comparative analysis. *Scientometrics*, *106*(1), 213-228.

Negro, S. O., Alkemade, F., & Hekkert, M. P. (2012). Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renewable and Sustainable Energy Reviews*, *16*(6), 3836-3846.

Nguyen, R. T., Eggert, R. G., Severson, M. H., & Anderson, C. G. (2020). Global Electrification of Vehicles and Intertwined Material Supply Chains of Cobalt, Copper and Nickel. *Resources, Conservation and Recycling*, 105198.

Northey, S., Mohr, S., Mudd, G. M., Weng, Z., & Giurco, D. (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling*, *83*, 190-201.

Nykvist, B., Sprei, F., & Nilsson, M. (2019). Assessing the progress toward lower priced long range battery electric vehicles. *Energy policy*, *124*, 144-155.

OECD (Organization for Economic Cooperation and Development). (2008). *Measuring material flows and resource productivity*. OECD Publishing, Volume I.

OECD (Organization for Economic Cooperation and Development) (2012). *OECD Environmental Outlook to 2050*. OECD Publishing.

Opitz, A., Badami, P., Shen, L., Vignarooban, K., & Kannan, A. M. (2017). Can Li-Ion batteries be the panacea for automotive applications?. *Renewable and Sustainable Energy Reviews*, *68*, 685-692.

Pfaff, M., Glöser-Chahoud, S., Chrubasik, L., & Walz, R. (2018). Resource efficiency in the German copper cycle: Analysis of stock and flow dynamics resulting from different efficiency measures. *Resources, Conservation and Recycling*, *139*, 205-218.

Pereirinha, P. G., González, M., Carrilero, I., Anseán, D., Alonso, J., & Viera, J. C. (2018). Main trends and challenges in road transportation electrification. *Transportation research procedia*, *33*, 235-242.

Pesaran, M. H., & Shin, Y. (1995). An autoregressive distributed lag modelling approach to cointegration analysis.

Poulton, M. M., Jagers, S. C., Linde, S., Van Zyl, D., Danielson, L. J., & Matti, S. (2013). State of the world's nonfuel mineral resources: Supply, demand, and socio-institutional fundamentals. *Annual Review of Environment and Resources*, *38*(1), 345-371.

RE100. (2022) RE100 Members. Available at: https://www.there100.org/companies. Access: Sep., 2022

Reijnders, L. (2021). Copper substitutability might be about 60% or more of current copper use. *Journal of cleaner production*, *284*, 124774.

Sahni, S., & Gutowski, T. G. (2011, May). Your scrap, my scrap! The flow of scrap materials through international trade. In *Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology* (pp. 1-6). IEEE.

Schlabach, T. D. (1984). Substitution: technology. *Conservation & Recycling*, *7*(1), 15-20.

Schipper, B. W., Lin, H. C., Meloni, M. A., Wansleeben, K., Heijungs, R., & van der Voet, E. (2018). Estimating global copper demand until 2100 with regression and stock dynamics. *Resources, Conservation and Recycling*, *132*, 28-36.

Seck, G. S., Hache, E., Bonnet, C., Simoën, M., & Carcanague, S. (2020). Copper at the crossroads: Assessment of the interactions between low-carbon energy transition and supply limitations. *Resources, Conservation and Recycling*, *163*, 105072.

Shah, I. H., Hiles, C., & Morley, B. (2018). How do oil prices, macroeconomic factors and policies affect the market for renewable energy?. *Applied energy*, *215*, 87-97.

Smith, B. J., & Eggert, R. G. (2018). Costs, substitution, and material use: the case of rare earth magnets. *Environmental science & technology*, *52*(6), 3803-3811.

Soulier, M., Pfaff, M., Goldmann, D., Walz, R., Geng, Y., Zhang, L., & Espinoza, L. A. T. (2018). The Chinese copper cycle: Tracing copper through the economy with dynamic substance flow and input-output analysis. *Journal of Cleaner Production*, *195*, 435-447.

Stuermer, M. (2017). Industrialization and the demand for mineral commodities. *Journal of International Money and Finance*, *76*, 16-27.

Sverdrup, H. U., Ragnarsdottir, K. V., & Koca, D. (2014). On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. *Resources, Conservation and Recycling*, *87*, 158-174.

Sverdrup, H. U., Olafsdottir, A. H., & Ragnarsdottir, K. V. (2019). On the long-term sustainability of copper, zinc and lead supply, using a system dynamics model. *Resources, Conservation & Recycling: X*, *4*, 100007.

Tanimoto, A. H., Durany, X. G., Villalba, G., & Pires, A. C. (2010). Material flow accounting of the copper cycle in Brazil. *Resources, conservation and recycling*, *55*(1), 20-28.

Tilton, J. E. (1984). Substitution: economics. *Conservation & recycling*, *7*(1), 21-26.

Tokimatsu, K., Murakami, S., Adachi, T., Ii, R., Yasuoka, R., & Nishio, M. (2017). Long-term demand and supply of non-ferrous mineral resources by a mineral balance model. *Mineral Economics*, *30*(3), 193-206.

Tromly, K. (2001). *Renewable energy: An overview* (No. DOE/GO-102001-1102; NREL/BR-810-27955). National Renewable Energy Lab., Golden, CO (US). Available at: https://www.nrel.gov/docs/fy01osti/27955.pdf

Twidell, J., & Weir, T. (2015). *Renewable energy resources*. Routledge.

UN (United Nations) Department of Economic and Social Affairs (2022), World Population Prospects 2022, https://population.un.org/wpp/

USGS (United States Geological Survey). Mineral Commodity Summaries 2022. United States Geological Survey, 202p. https://doi.org/10.3133/mcs2022

Valero, A., Valero, A., Calvo, G., & Ortego, A. (2018). Material bottlenecks in the future development of green technologies. *Renewable and Sustainable Energy Reviews*, *93*, 178-200.

Valero, A., Valero, A., Calvo, G., Ortego, A., Ascaso, S., & Palacios, J. L. (2018). Global material requirements for the energy transition. An exergy flow analysis of decarbonisation pathways. *Energy*, *159*, 1175-1184.

Varian, H. R. (2014). *Intermediate Microeconomics: A Modern Approach: Ninth International Student Edition*. WW Norton & Company.

Wagner, L. A., Sullivan, D. E., & Sznopek, J. L. (2002). Economic drivers of mineral supply. *US Geological Survey Open-File Report*, *2*, 335.

Wang, M., Chen, W., Zhou, Y., & Li, X. (2017). Assessment of potential copper scrap in China and policy recommendation. *Resources Policy*, *52*, 235-244.

Wang, M., Liang, Y., Yuan, M., Cui, X., Yang, Y., & Li, X. (2018). Dynamic analysis of copper consumption, in-use stocks and scrap generation in different sectors in the US 1900–2016. *Resources, Conservation and Recycling*, *139*, 140-149.

Wang, J., Ju, Y., Wang, M., & Li, X. (2019). Scenario analysis of the recycled copper supply in China considering the recycling efficiency rate and waste import regulations. *Resources, Conservation and Recycling*, *146*, 580-589.

Wang, C., Huang, X., Lim, M. K., Tseng, M. L., & Ghadimi, P. (2020). Mapping the structural evolution in the global scrap copper trade network. *Journal of Cleaner Production*, *275*, 122934.

Watari, T., Nansai, K., & Nakajima, K. (2020). Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation and Recycling*, *155*, 104669.

Watari, T., McLellan, B. C., Giurco, D., Dominish, E., Yamasue, E., & Nansai, K. (2019). Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resources, Conservation and Recycling*, *148*, 91-103.

Wellmer, F. W., & Dalheimer, M. (2012). The feedback control cycle as regulator of past and future mineral supply. *Mineralium Deposita*, *47*(7), 713-729.

Wen, Z., Zhang, C., Ji, X., & Xue, Y. (2015). Urban mining's potential to relieve China's coming resource crisis. *Journal of industrial ecology*, *19*(6), 1091-1102.

Whitfield, S. C., Rosa, E. A., Dan, A., & Dietz, T. (2009). The future of nuclear power: Value orientations and risk perception. *Risk Analysis: An International Journal*, *29*(3), 425-437.

Wirth, H., Kulczycka, J., Hausner, J., & Koński, M. (2016). Corporate Social Responsibility: Communication about social and environmental disclosure by large and small copper mining companies. *Resources Policy*, *49*, 53-60.

World Bank. World Bank Data. Available at: https://data.worldbank.org/. Access: 19 Oct. 2022.

Zeng, X., Ali, S. H., Tian, J., & Li, J. (2020). Mapping anthropogenic mineral generation in China and its implications for a circular economy. *Nature communications*, *11*(1), 1-9.

Zhang, L., Yuan, Z., & Bi, J. (2012). Estimation of copper in-use stocks in Nanjing, China. *Journal of Industrial Ecology*, *16*(2), 191-202.

Zhang, L., Yang, J., Cai, Z., & Yuan, Z. (2014). Analysis of copper flows in China from 1975 to 2010. *Science of the Total Environment*, *478*, 80-89.

Zhang, L., Cai, Z., Yang, J., Yuan, Z., & Chen, Y. (2015). The future of copper in China—A perspective based on analysis of copper flows and stocks. *Science of the Total Environment*, *536*, 142-149.

Zhou, S., Wang, Y., Zhou, Y., Clarke, L. E., & Edmonds, J. A. (2018). Roles of wind and solar energy in China's power sector: Implications of intermittency constraints. *Applied energy*, *213*, 22-30.

APPENDIX

APPENDIX A - Search code in Scopus and PBi

Scopus

(TITLE-ABS-KEY (copper W/30 scrap W/30 demand) OR TITLE-ABS-KEY (copper W/30 secondary W/30 demand) OR TITLE-ABS-KEY (copper W/30 recycl* W/30 demand) OR TITLE-ABS-KEY (copper W/30 waste W/30 demand) OR TITLE-ABS-KEY (copper W/30 scrap W/30 consumption) OR TITLE-ABS-KEY (copper W/30 secondary W/30 consumption) OR TITLE-ABS-KEY (copper W/30 recycl* W/30 consumption) OR TITLE-ABS-KEY (copper W/30 waste W/30 consumption) OR TITLE-ABS-KEY (copper W/30 scrap W/30 supply) OR TITLE-ABS-KEY (copper W/30 secondary W/30 supply) OR TITLE-ABS-KEY (copper W/30 recycl* W/30 supply) OR TITLE-ABS-KEY (copper W/30 waste W/30 supply) OR TITLE-ABS-KEY (copper W/30 scrap W/30 availability) OR TITLE-ABS-KEY (copper W/30 secondary W/30 availability) OR TITLE-ABS-KEY (copper W/30 recyc* W/30 availability) OR TITLE-ABS-KEY (copper W/30 waste W/30 availability) OR TITLE-ABS-KEY (copper W/30 scrap W/30 trade) OR TITLE-ABS-KEY (copper W/30 secondary W/30 trade) OR TITLE-ABS-KEY (copper W/30 recycl* W/30 trade) OR TITLE-ABS-KEY (copper W/30 waste W/30 trade)) AND (LIMIT-TO (SUBJAREA,"ENVI") OR LIMIT-TO (SUBJAREA,"ENER") OR LIMIT-TO (SUBJAREA,"SOCI") OR LIMIT-TO (SUBJAREA,"BUSI") OR LIMIT-TO (SUBJAREA,"ECON") OR LIMIT-TO (SUBJAREA,"MULT") OR LIMIT-TO (SUBJAREA,"MATH") OR LIMIT-TO (SUBJAREA,"ARTS")) AND (LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012) OR LIMIT-TO (PUBYEAR,2011) OR LIMIT-TO (PUBYEAR,2010)) AND (LIMIT-TO (LANGUAGE,"English"))

PBi

("copper scrap" AND (demand OR consumption OR supply OR availability OR trade)) OR ("copper secondary" AND (demand OR consumption OR supply OR availability OR trade)) OR ("copper recycl*" AND (demand OR consumption OR supply OR availability OR trade)) OR ("copper waste*" AND (demand OR consumption OR supply OR availability OR trade))

APPENDIX B - Econometric results of the ARDL model: tests

(Continue)

	Model 1 with time trend	Model 2 with time trend	Model 3 with time trend	Model 4 with time trend	Model 4 without time trend
	c_t	c_t	$cadj_t$	c_t	c_t
α	0.007436	0.002455	0.094725	-0.157577	0.070769
Std error	*0.126061*	*0.128519*	*0.123511*	*0.199096*	*0.113396*
t	*0.058990*	*0.019099*	*0.766936*	*-0.791463*	*0.624088*
t	-0.009257	-0.006779	-0.003133	-0.016268	
Std error	*0.007260*	*0.007635*	*0.007085*	*0.009031*	
t	*-1.275135*	*-0.887826*	*-0.442182*	*-1.801344*	
c_{t-1}	0.630715	0.663631		0.610267	0.750576
Std error	*0.104787*	*0.107556*		*0.107576*	*0.073413*
t	*6.019025*	*6.170099*		*5.672913*	*10.224080*
$cadj_{t-1}$			0.683076		
Std error			*0.106167*		
t			*6.433950*		
y_t	0.000620	0.000633	0.000603	0.000678	0.000608
Std error	*0.000105*	*0.000105*	*0.000106*	*0.000114*	*0.000102*
t	*5.888138*	*6.011825*	*5.708498*	*5.922358*	*5.937693*
y_{t-1}	-0.000473	-0.000511	-0.000519	-0.000461	-0.000560
Std error	*0.000114*	*0.000114*	*0.000114*	*0.000115*	*0.000104*
t	*-4.154027*	*-4.505131*	*-4.546940*	*-4.022764*	*-5.391549*
p_{Cu_t}	0.000003	0.000007	0.000009	0.000002	0.000009
Std error	*0.000009*	*0.000009*	*0.000009*	*0.000009*	*0.000009*
t	*0.306232*	*0.771452*	*0.938874*	*0.169180*	*1.025004*
$p_{Cu_{t-1}}$	-0.000012	-0.000018	-0.000019	-0.000012	-0.000019
Std error	*0.000011*	*0.000011*	*0.000011*	*0.000011*	*0.000011*
t	*-1.082274*	*-1.584567*	*-1.655339*	*-1.069806*	*-1.671539*
$p_{Cu_{t-2}}$	-0.000010	-0.000009	-0.000008	-0.000011	-0.000007
Std error	*0.000009*	*0.000009*	*0.000009*	*0.000009*	*0.000009*
t	*-1.044297*	*-0.963961*	*-0.821494*	*-1.174298*	*-0.788528*
$p_{Cu_{t-3}}$	0.000028	0.000029	0.000028	0.000028	0.000030
Std error	*0.000007*	*0.000007*	*0.000007*	*0.000007*	*0.000007*
t	*4.069795*	*4.159725*	*3.975055*	*3.930601*	*4.349321*
p_{Al_t}		-0.000025	-0.000023	-0.000014	-0.000023
Std error		*0.000019*	*0.000019*	*0.000018*	*0.000019*
t		*-1.305672*	*-1.196275*	*-0.798998*	*-1.202535*
$p_{Al_{t-1}}$		0.000036	0.000038		0.000039
Std error		*0.000019*	*0.000019*		*0.000018*
t		*1.883092*	*2.002955*		*2.139774*
$rnev_t$				-0.000106	-0.000014
Std error				*0.000088*	*0.000072*
t				*-1.211353*	*-0.198407*

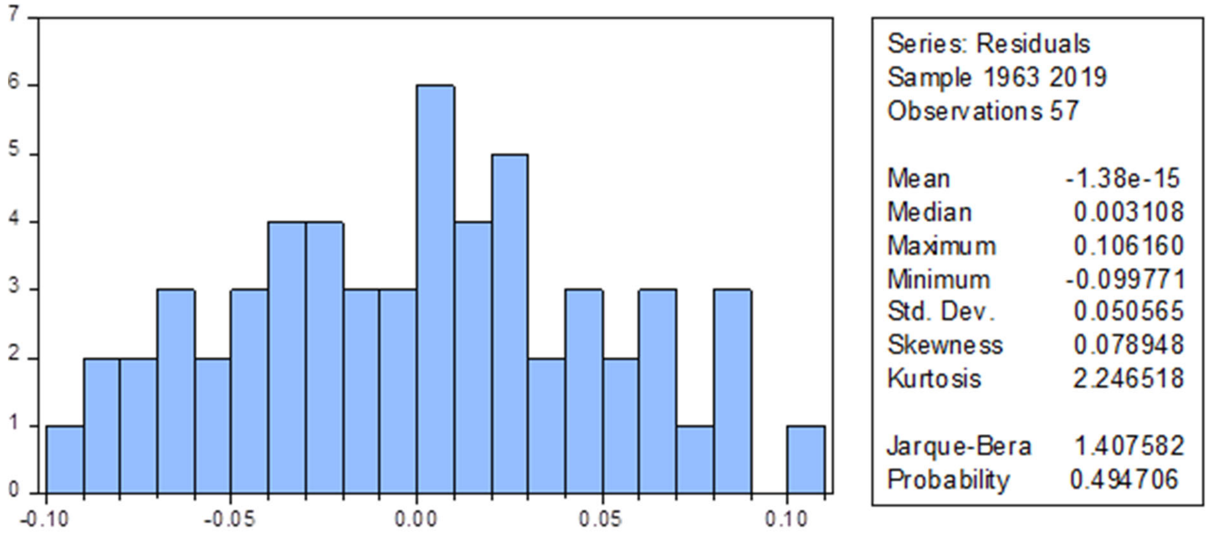
(Conclusion)

	Model 1 with time trend c_t	Model 2 with time trend c_t	Model 3 with time trend $cadj_t$	Model 4 with time trend c_t	Model 4 without time trend c_t
Obs.	57	57	57	57	57
R2	0.986	0.987	0.985	0.986	0.987
Adj. R2	0.983	0.984	0.981	0.983	0.984
F-statistic	411.2	341.7	293.7	327.2	336.2
Prob (F-statistic)	0.000	0.000	0.000	0.000	0.000

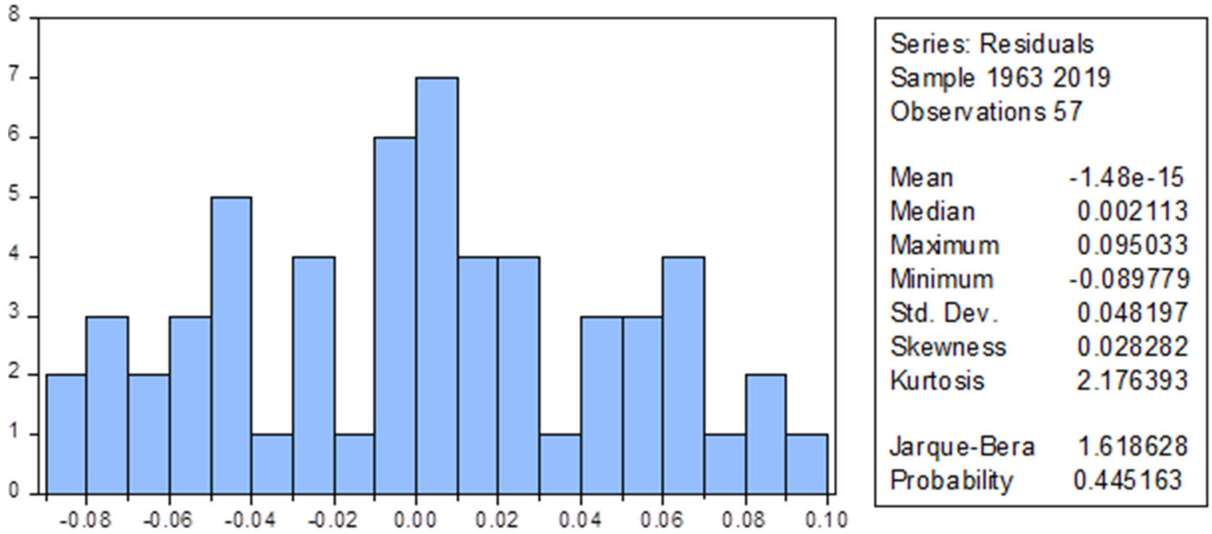
Source: Original research data.

APPENDIX C - Post-estimation regression normality tests

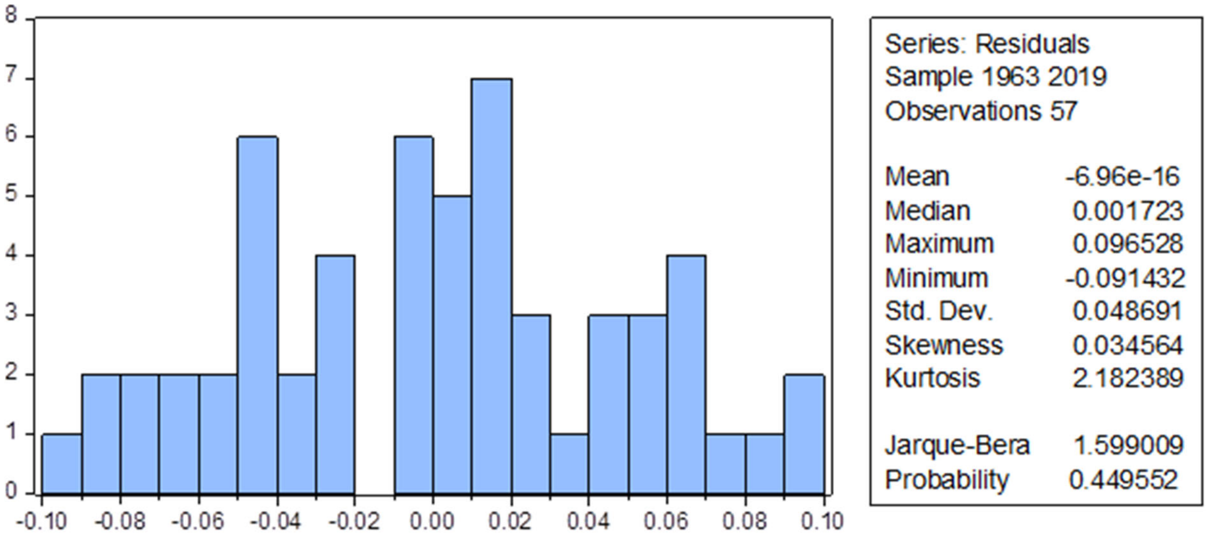
Model 1



Model 2



Model 3


8
7
6
5
4
3
2
1
0
-0.10
-0.08
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
0.08
0.10
Series: Residuals
Sample 1963 2019
Observations 57
Mean -6.96e-16
Median 0.001723
Maximum 0.096528
Minimum -0.091432
Std. Dev. 0.048691
Skewness 0.034564
Kurtosis 2.182389
Jarque-Bera 1.599009
Probability 0.449552