Copper at the crossroads : Assessing the interactions of the low carbon energy transition with a non-ferrous and structural metal☆

Clément BONNET[a], Gondia Sokhna SECK[a], Emmanuel HACHE [a,b,c *] Marine SIMOËN[a],

Samuel CARCANAGUE[b]

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Abstract

The aim of this article is to assess the impact of copper availability on the energy transition and to answer the question whether or not copper might become critical due to the high copper content of low-carbon technologies of the electricity and the transport sectors. Due to its physical properties and to its numerous applications, the consumption of copper has significantly increased since the beginning of the 1960s. Because low-carbon technologies have higher copper contents compared to conventional technologies, we can expect the energy transition toward a low-carbon system to contribute to increase further the demand for copper. In order to assess the copper availability in 2055, we rely on our linear programming World energy-transport model, TIAM-IFPEN based on the ETSAP-TIAM model (Times Integrated Assessment Model. ETSAP-TIAM) which is the global multiregional incarnation of the TIMES (The Integrated MARKAL-EFOM System) model generator to compute a partial equilibrium and we conduct two climate scenarios (2°C and 4°C) with two shapes of mobility each and we also introduce recycling policy. The penetration of low-carbon technologies in the transport and energy sectors (electric vehicles, low-carbon power generation technologies, etc.) tends to increase copper demand drastically by 2055. However, our article highlights the public policy drivers that can mitigate our results. On the one hand, public policy based on an integrated approach to urban land-use and transport planning could help to reduce copper consumption in transport sector. On the other hand, recycling policies must be better targeted to reduce the dependency of some countries on copper imports.

Keywords: Energy transition, copper, transport, electrification, Bottom-up modeling, development

JEL Classification: Q42, R40, C61

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a. IFP Énergies Nouvelles, 1–4 av. de Bois Préau, F-92852 Rueil-Malmaison, France.
b. The French Institute for International and Strategic Affairs, (IRIS), France.
c. EconomiX-CNRS, University of Paris Nanterre, France.

* Corresponding author. Tel.: +33 1 47 52 68 26; fax: +33 1 47 52 70 66.
E-mail address: clément.bonnet@ifpen.fr

1. Introduction

The issue of mineral resource dependency is a relevant illustration of the challenges the world is likely to face in the energy transition process. Many studies (ANCRE, 2015, World Bank, 2017; OECD, 2018) underline the need to take these constraints into account in the dynamics of the global energy transition, and more especially the location of resources, the organisation of industrial markets or actors' strategies that can make the use of a raw material critical. This notion of criticality thus covers all the risks related to the production, use or end-of-life management of a raw material (Graedel et Nuss, 2014): geopolitical risks (Hache et al., 2019a; Habib et al., 2016; Hache, 2018; O'Sullivan et al., 2017; Scholten, 2018; Overland, 2019), economic risks (embargo, market manipulation, lack of financial contracts to hedge price volatility, etc.) (Habib et al., 2016; Maxwell, 2015), production risks (under-investment and time-lag between investment decisions and production) and environmental or social risks (emissions of pollutants related to production, health consequences, landscape destruction, etc.) (Ali et al., 2017 ; Conde, 2017; Fizaine et Court, 2015 ; Ossa-Moreno et al., 2018; Perez-Rincon et al., 2019). While economic literature generally focus on lithium, cobalt and rare earth elements (Alonso, 2012; Baldi, 2014; Hache et al., 2018, 2019; Helbig, 2018; Kushnir, 2012; Nassar, 2015, Spiers, 2014) to illustrate the systemic aspects of the energy transition on raw materials, this dynamic will also potentially have major consequences on the major non-ferrous metal markets (copper, nickel, zinc), but also on the steel, aggregates and water sectors (Hache et al., 2019a). Today, almost 35% of copper is used for electrical purposes (distribution and transmission) and this share could accelerate with the deployment of renewable energies.

Copper has been the focus of economists and geologists, as evidenced by articles and responses between Tilton (2003), Gordon et al. (2006), Tilton and Lagos (2007), Gordon et al. (2007) and more recently Vidal (2018) on the subject of copper criticality. In the context of energy transition and because copper is used in many applications in the transport and power sectors, this structural raw material appears to be an interesting case study on criticality issues. We have then developed the first detailed global energy model with an endogenous representation of the copper supply chain in order to assess its dynamic criticality along with technological changes through to 2055. . As these sectors are major greenhouse gas emitters, it is a crucial question to understand if copper availability can constitute a brake to the deployment of low carbon technologies.

In order to assess the copper availability in 2055, we rely on a partial equilibrium linear programming model TIAM-IFPEN which is the global incarnation of the TIMES (The Integrated MARKAL-EFOM System) model generator. We conduct two climate scenarios (2°C and 4°C) with two shapes of mobility each with an implementation of recycling policy scenario. The rest of the paper is organized as follows. Section 2 provides describes the methodology, the overall structure of the TIAM-IFPEN model, and the specific features and assumptions considered for a detailed copper criticality analysis. Section 3 presents our findings that are then discussed in Section 4. Section 5 concludes the paper.

2. Methodology

We have developed the first global bottom-up energy system optimization model with an endogenous representation of raw material supply chains in the TIAM-IFPEN (TIMES[1] Integrated Assessment Model) model which is using MARKAL[2]-TIMES framework (Fishborne et al., 1983; Loulou et al., 2004; Loulou et al., 2016). Thus, TIAM-IFPEN is able to assess a dynamic raw material criticality in a global energy prospective exercise subject to different

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[1] The Integrated MARKAL-EFOM System.

[2] MARKet Allocation model

climate and sectorial constraints through to 2055. Contrary to our previous article (Hache et al., 2019b) where the assessment of future risks related to the lithium supply chain with a fast roll-out of electric vehicles in the coming years have been done, we implemented a complete copper supply chain and analysed in this paper its dynamic criticality up to 2055 according to the known resources.

2.1. TIAM-IFPEN model

TIAM-IFPEN is a multiregional and inter-temporal partial equilibrium model of the entire system of the World, based on TIMES model generator (Loulou et Labriet, 2008). A complete description of the TIMES equations appears in ETSAP documentation[3]. It is a bottom up techno-economic model which estimates energy dynamics through a minimization of the total discounted cost of the system over the selected multi-period time horizon via powerful linear programming optimizers. The components of the cost of the system are yearly expressed while the constraints and variables are related to period. The cost profile has been represented to have a more realistic representation of payments flows performed in the energy system (Loulou et Labriet, 2008). The total cost, which is an aggregation of the total discounted net present value of the stream of annual costs for each region in the model, constitutes the objective function (Eq. (2.1)) to be minimized by the model in its equilibrium computation. A detailed description on the objective function equations are fully described in section 6.2 of Part II (Loulou et al., 2016). We limit our description to giving general indications on the yearly cost elements comprising the objective function, as follows:

- The investment costs incurred for investing into processes;
- Fixed and variable annual costs,

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[3] Energy Technology Systems Analysis Program.Created in 1976, it is one of the longest running Technology collaboration Programme of the International Energy Agency (IEA). https://iea-etsap.org/index.php/documentation

- Costs incurred for exogenous imports;
- Revenues from exogenous exports;
- Delivery costs for required commodities consumed by processes;
- Taxes and subsidies associated with commodity flows and process activities or investments;

All costs are discounted to the base year 2005. TIAM-IFPEN is set up to explore the development of the World energy system from 2005 till 2055 and is calibrated to the 2005-2010 data provided by energy statistics.

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r,y) \qquad \text{Eq. (2.1)}$$

NPV is the net present value of the total cost for all regions (the TIMES objective function);

ANNCOST(r,y) is the total annual cost in region *r* and year *y* (more details in section 6.2 of PART II(Loulou et al., 2016))

$d_{r,y}$ is the general discount rate;

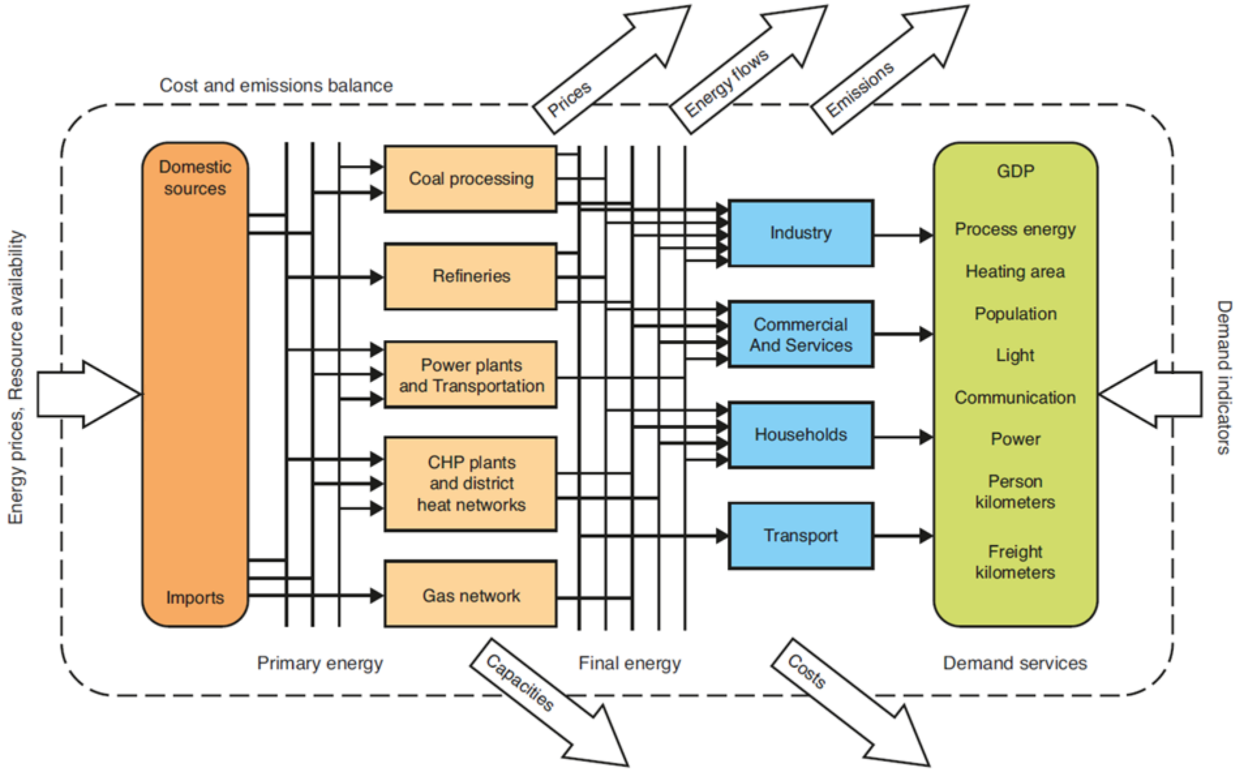
REFYR is the reference year for discounting;

YEARS is the set of years for which there are costs, including all years inthe horizon, plus past years (before the initial period) if costs have been defined for past investments, plus a number of years after EOH where some investment and dismantling costs are still being incurred, as well as the Salvage Value; and

R is the set of regions in the area of study.

The model includes explicit detailed descriptions of numerous technologies in each region, logically interrelated in a Reference Energy System, the chain of processes with transform, transport, distribute and convert energy into services from primary resources and raw materials to the energy services needed by the end-use sectors (Fig. 1). The existing and future technologies in the sectors over a given time horizon are considered with techno-economic parameters (capacity, energy intensity, efficiency, availability factor, investment costs, fixed and variable costs, economic and technical life, etc.) and their related strategic orientation parameters (taxes, subsidies, etc.). TIAM-IFPEN represents the energy system of the World divided in 16 regions (Table 1). Each region can carry out exchanges of fossil resources, biomass, materials or emission permits, with other regions or within a centralized market. The long-distance trade between the regions has been endogenously modeled for coal (rail and ship), natural gas (pipeline), liquefied natural gas (methane tankers), crude oil (oil tankers, pipelines), distillates, gasoline, heavy fuel oil, naphta, natural gas liquids (NGL) and biofuels. In those regions that contain OPEC countries, trade is further disaggregated into OPEC and Non OPEC (Remme et al., 2007). Thus, the model determines the optimal mix of technologies (capacity and activity) and fuels at each period, the associated emissions, the mining and trading activities, the quantity and prices of all commodities, the equilibrium level of the demands for energy services, all in time series from the base year 2005 to 2055 our time horizon. It should be noted that the results of the model should not be considered as forecasts but rather as projections of the possible pathways of a future energy system development.

Fig. 1:Simplified view of the TIAM's Reference Energy System



Source: Remme et Jussi, 2001

All energy demand projections have been done considering macro-economic drivers such as the GDP, the population growth, etc. (Statistics/outlook of the IMF , results from GEMINI-E3 or GEM-E3 macro-economic models). All assumptions related to regional fossil fuel reserves and trade capacities have also been implemented along with the regional renewable energy potentials (Remme et al., 2007, World Energy Council, BP Statistics, US Geological Survey, specialized literature and experts involved in the projects). For the power generation, the general sources of data are the National Renewable Energy Laboratory (NREL), PLATTS database, IRENA, WEO IEA and specialized literature (Hache et al., 2019b). Although various recent studies have been already conducted with the TIAM model such as the effects of global GHG reduction on the bioenergy sector expansion (Kang et al., 2018) or carbon capture and storage in power supply

(Selosse et Ricci, 2014) using TIAM-FR[4], long-term investigation for large-scale low-GHG energy diffusion in Africa using TIAM-ECN[5] (Van der zwaan et al, 2018) or the decarbonisation of road transport using TIAM-UCL[6] (Anandarajah et al., 2013), none has yet implemented raw material supply chains in a TIAM model within their energy transition analyses at the best of our knowledge.

Table 1 : Regions of the TIAM-IFPEN model

TIAM name	Region
AFR	Africa
AUS	Australia, New Zealand and Oceania
CAN	Canada
CHI	China
CSA	Central and South America
IND	India
JAP	Japan
MEA	Middle-east
MEX	Mexico
ODA	Other Developing Asian countries
SKO	South Korea
USA	United States of America
EUR	Europe 28+
RUS	Russia
CAC	Central Asia and Caucase (Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan)
OEE	Other Eastern Europe (Albania, Belarus, Bosnia-Herzegovina, Macedonia, Montenegro, Serbia, Ukraine, Moldova)

~~7.0.~~2.2. Copper supply chain modeling and scenarios

~~7.0.0.~~2.2.1. Overview of the copper supply chain

As explained by Gordon et al., copper is not uniformly distributed in Earth’s crust (Gordon et al., 2007) as observed in the geographical distribution of copper ore reserves and resources (Fig. 2). Almost half of worldwide reserves and resources are located in the region CSA (Central and

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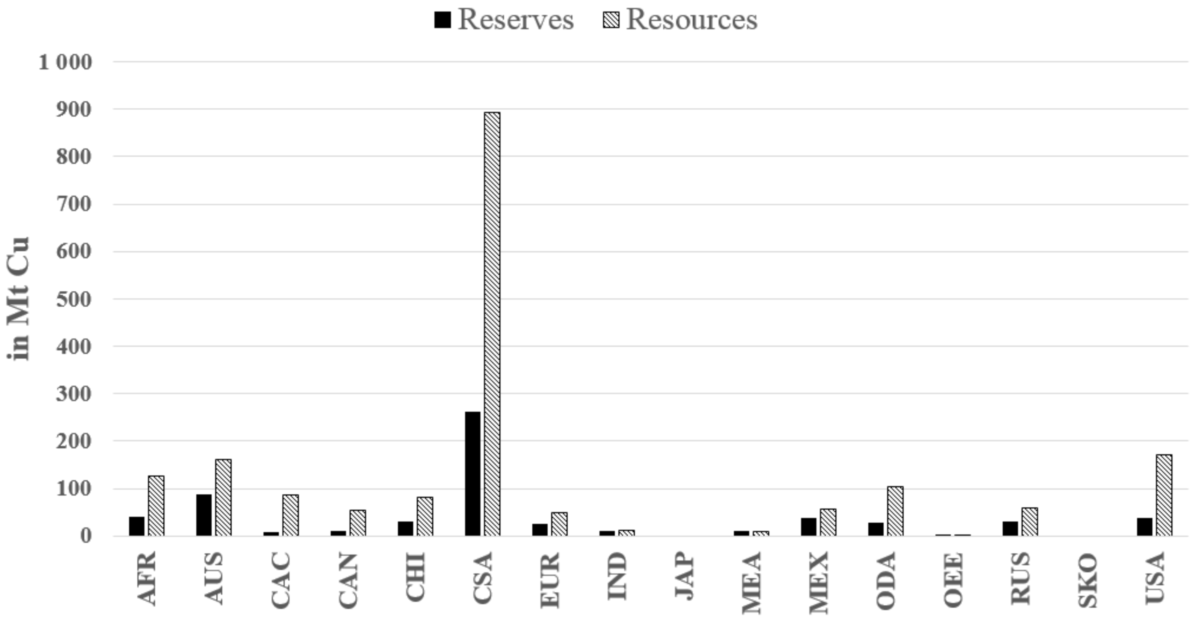
[4] TIAM-FR is a version of TIAM adapted at the Center of Applied Mathematics of Mines ParisTech in Sophia-Antipolis (France)

[5] TIAM-ECN is the version of TIAm developed at the Energy research Centre of the Netherlands (ECN).

[6] This version of TIAM has been developed at the University College of London (UCL) through the UK Energy Research Centre (UKERC).

South America), mostly in Chile. The copper supply chain has been built from ore deposits to its end-uses via various transformation processes and trade flows (Fig. 3).

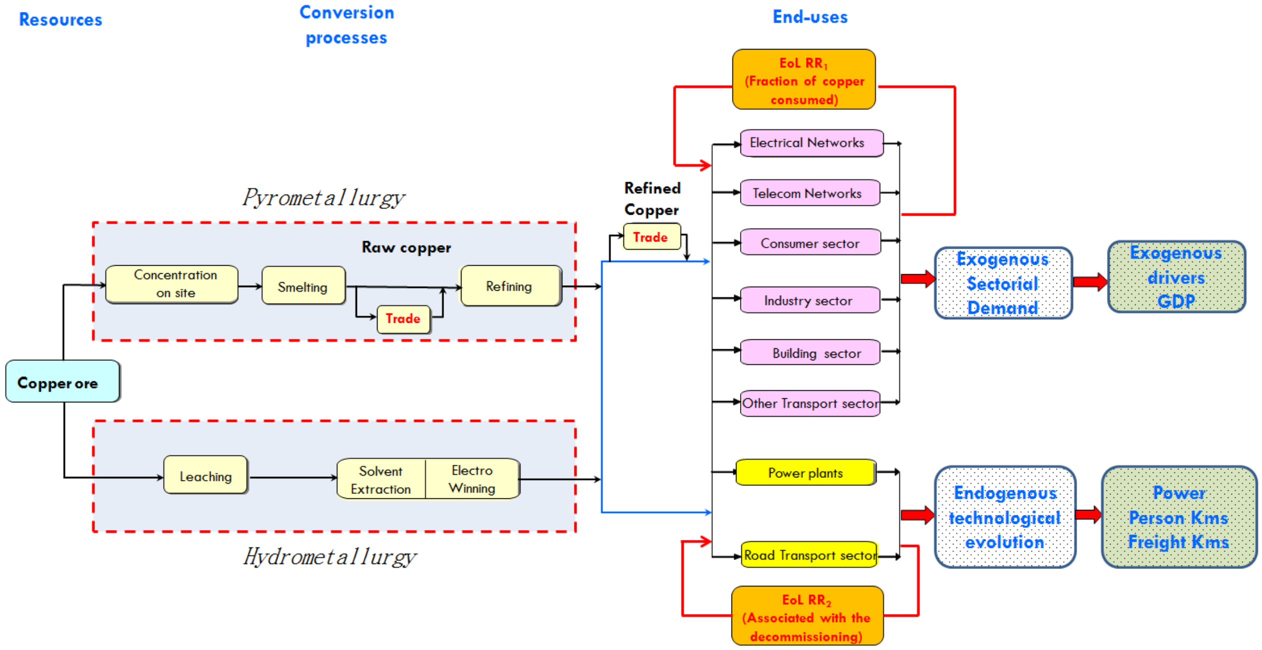
Fig. 2: Geographical distribution of copper resources and reserves worldwide



Source: USGS ; Mudd et al., 2013; Habib et al., 2016

Two ways of the copper ore transformation have been considered in the model, pyrometallurgy and hydrometallurgy, which are respectively related to concentrate and leached ores. Regionalized mining CAPEX and OPEX have been done and obtained from weighted averages of real projects around the world (Davenport et al., 2002; Boulamanti et al., 2016; Companies reports).

Fig. 3: Detailed description of the copper supply chain in each TIAM region



A regional disaggregation of these two copper process transformations using production weights since 1990 has been also considered as displayed in the Table 2. The repartition between concentrates and leached ores has been stable over time within a country between 2005 and 2015 due to the characteristics of the deposit.

Table 2: Average share of concentrates ores (pyrometallurgy) in the cumulative mine production (in %) over the period 2005-2015 in the main producer countries

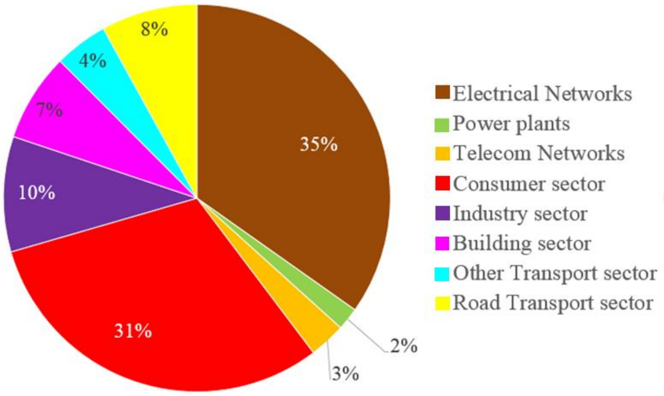
	AFR	AUS	CAC	CAN	CHI	CSA	EUR	IND	JAP	MEA	MEX	ODA	OEE	RUS	SKO	USA
Pyro	0.65	0.96	0.95	1	0.98	0.71	0.92	1	1	0.95	0.73	0.89	0.94	1	1	0.59

Source: USGS

As seen in Fig. 3, copper is used in many various sectors, such as the construction industry (plumbing, roofing, shipbuilding and cladding), the power sector (power plants and electrical infrastructures), the industry sector, the transportation sector, in our everyday life (the main component of coins for many countries, dwelling accessories, water heaters…)…etc. (Fig. 4). "Electrical Networks" which include power distribution, lightning and connection to ground, is with the “consumer sector”[7] by far the largest users of copper as they consume respectively 35% and 31% of semi-finished copper products in 2015. These two sectors illustrate a general fact about copper: it is widely used in long-lived applications with useful spans that can last several decades. It is estimated that two thirds of the copper produced since 1900 was still in use in 2010 (Batker and Schmidt, 2015). Moreover, it appears that “consumer sector” pertaining to the manufacturing of equipment that are not related to transport, is the most dissipative end-use sectors. Hence a major risk regarding the reuse of copper is the long period during which it may be fixed in products that are still in use.

Thus, copper would certainly have a central role in this context of low-carbon energy transition due to the large and increasing number of applications.

Fig. 4: End-use consumption of worldwide copper in 2015



Source: IWCC/ICA

In a future driven by more stringent environmental constraints and economic growth, the increasing copper content in all decarbonisation innovations, particularly in the transport and

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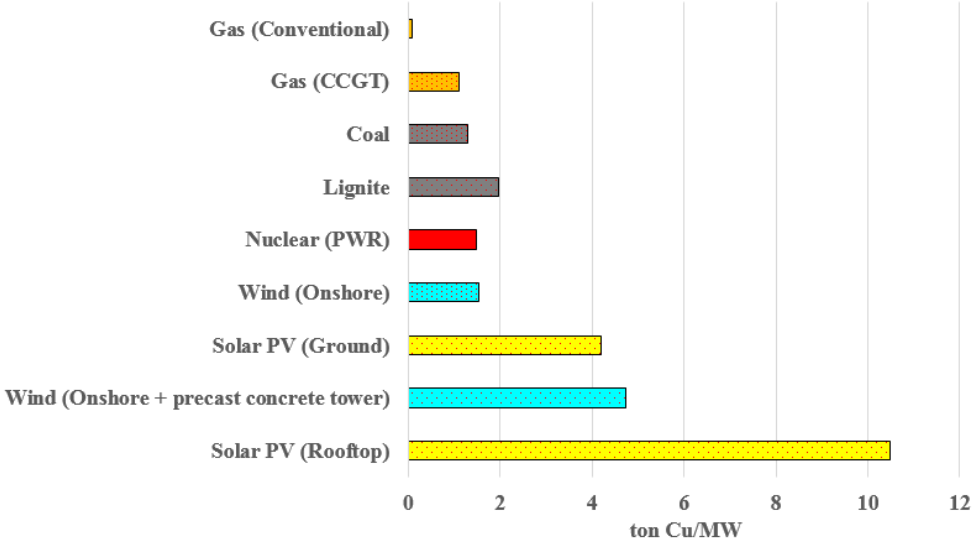
[7] It includes consumer and general products (Appliances, instruments, tools and other), cooling (Air conditioning and refrigeration), electronic (Industrial/ commercial electronics and PCs) and diverse (Ammunition, clothing, coins and other).

power sectors, could, along with future copper resource availability, be a hindrance to this transition.

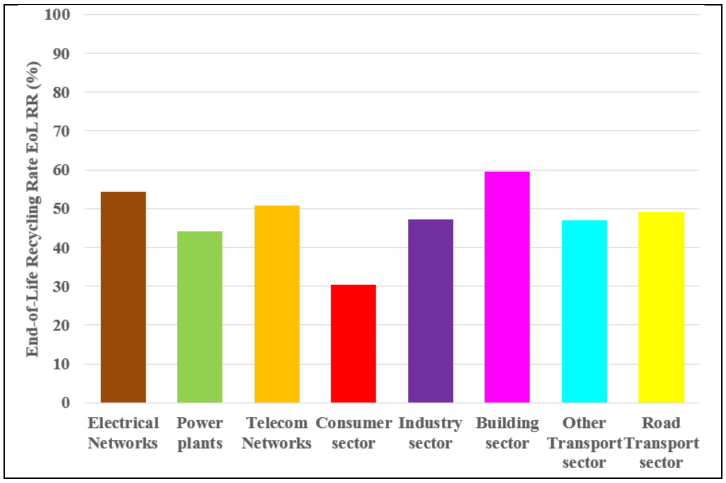
Fig. 5: Copper content of different energy mean of production (kg/MW)



Source: Ecoinvent. CCGT: Combine Cycle Gast turbine; PWR: Pressurized Water Reactor; PV: Photovoltaic

Indeed, the copper content per unit capacity will increase tenfold in a rooftop solar power plant compared to a combine cycle gas turbine for example, while it will triple in an onshore wind turbine compared to a nuclear power plant (Fig. 5). The same trend is observed in road transport vehicles. Compared to conventional vehicles, electric vehicles contain three to nine times more copper. Generally, between 96% and 100% of the copper is in the vehicle body, while it falls to 45% because 55% of the copper is used in the battery which is much heavier (Burnham, 2012). Thus, more emphasis will be placed on the need to increase the recycling efficiency of copper from old scrap in all end-use economic sectors. Indeed, Glöser et al. have discussed on several commonly used indicators to measure it at the global level (Glöser et al., 2013). In this paper, we choose to implement the End-of-Life Recycling Rate (EoL-RR) indicator in our TIAM-IFPEN model in order to take into account the efficiency of the old scrap recycling. This indicator is determined as the fraction of metal contained in EoL products that is collected, pre-treated and finally recycled back in the anthropogenic cycle (Eurométaux and Eurofer, 2012, cited in Tercero and Soulier, 2018).

Fig. 6: End-of-life recycling rate (EoL RR) by end-use sectors



Source: Glöser et al., 2013

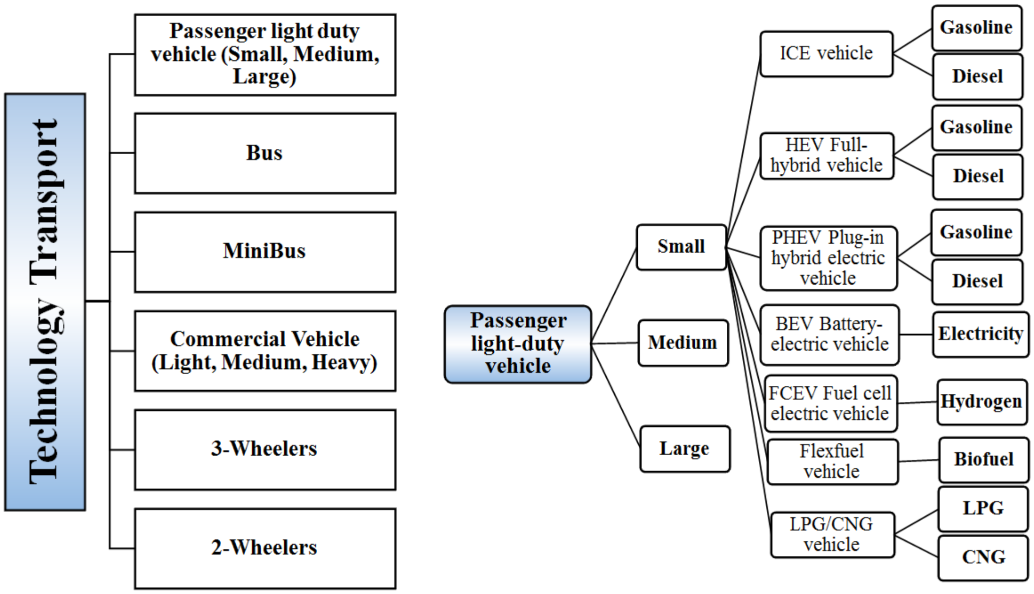
There is a lack of data on recycling activity in copper consuming sectors but Glöser et al. provide global estimates over the period 2000-2010 (Glöser et al., 2013). The value of the EoL RR for the eight copper consuming sectors considered in the model has been displayed in Fig. 6. The average value all sectors combined is around 45%. As seen in Fig. 3, we distinguished two EoL RR according to the way we implement them. For the copper consuming sectors which have not been represented in details technologically, i.e. the sectors in pink, we assume the EoL RR_1 as a fraction of the demand which is recycled back. While for the end-use sectors in yellow, transport and power sectors, which have a detailed technological representation, it has been provided EoL RR_2 when there is a copper recycled associated with the decommissioning. Thus, we did take into account the recycling activity by using the sectorial EoL RR values. With the lack of evolving EoL RR data considering that major efforts would certainly be done to improve the recycling of copper in “consuming sector” as one example due to its dissipative characteristic and its weight in copper consumption, we make a conservative hypothesis by assuming them constant in the model over our horizon period 2005-2055. In other words, the EoL RR implemented in the model (Fig. 6) are our pessimistic view of recycling activity (probable minimum values).

Copper is traded in three forms in the world. The first is copper concentrate that is processed by pyrometallurgy techniques. The second one is refined copper cathode that are sold from the refineries. It is the purest form of copper and it is used to produce wires, sheets, strip, etc.. The last traded product is copper blister. Custom refineries transform copper blister to produce cathode; however it is a relatively small market. So, we assume, in order to simplify matters, two types of trade in the model: the first one is to gather the three categories of products “Copper mattes”, “copper anodes and unrefined copper” and “copper ores and concentrates” into a single category called raw copper in Fig. 3. The second type concerns the refined copper. Taking into account the trade capabilities will allow analyzing future international copper exchanges and strategies according to the each regional needs and growth as we have already noticed for example for China between 2005 and 2015 (See Appendix A). Trade data have been extracted from the UN Comtrade database.

~~7.0.0.~~2.2.2. The road transport and power sector in TIAM-IFPEN

The road transport sector is characterized by passenger light-duty vehicles (PLDV) (small, medium and large), bus, minibus, commercial vehicles (CV) (light, heavy and medium trucks) and 2/3-wheelers (Fig. 7). The existing and future vehicles have been implemented with their techno-economical parameters. For all technologies across entire study period 2005–2055, we took into account efficiency (fuel consumption in short and long distance), average annual vehicle mileage, lifespan cost (purchase cost, O&M fixed and variable costs), etc. All these attributes have been derived from the IEA data on transport, and the BEAVeR[8] and FSIM[9] models developed by IFPEN. The copper content have been implemented in each technology segment.

Fig. 7: Overview of the road transport technologies in TIAM-IFPEN model



In the power sector, a wide range of fossil-based and renewables sources have been considered with the characterization of the existing and future technologies (additionally categorised as centralised or decentralised related to their size) in detail (cost and technical parameters). The following power generation technologies have been covered by the model: renewable energy technologies (RETs) (solar PV and CSP, wind onshore and offshore, hydro, biomass), fossil-based technologies (coal, natural gas, oil) and nuclear. The inventories of the existing and future generation technologies were taken from the World Energy Outlook 2018 (IEA, 2018), IRENA (IRENA, 2018) and the European Commission database. Electricity grids are not explicitly

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[8] BEAVeR (Economic and Life-Cycle Assessment of road vehicles) model is a TCO model which allows calculation and comparison of ownership and usage costs for various road vehicles, whether private vehicles, utility vehicles, buses or heavy trucks

[9] FSIM (Fleet SIMulator) model enables the study of dynamics in the private vehicle market, the impact of a wide range of instruments and public policies, and assesses the environmental impact of these policies. FSIM is based on individual behavior, in that it simulates changes in consumer behavior in response to changing economic conditions

modeled and electricity is not traded between regions. This is probably not a major limitation as most electricity trade will be intra-region (between countries). However, it is important for some regions (e.g., the United States and Canada) to consider this in further development of the model.

~~7.0.0.~~2.2.3. Scenario specification and sectorial demand evolution

Several scenarios have been defined in order to analyse the evolution of the copper demand and assess its criticality in response to more stringent environmental constraints or sustainable behaviour. We run for the copper the same four scenarios as done in our previous study on lithium criticality (Hache et al., 2019b) where we have considered two climate scenarios[10] with two different shapes of mobility each in order to assess the impact on the lithium market along with the transportation electrification:

- Scen 4D which is consistent with limiting the expected global average temperature increase to 4°C above pre-industrial levels by 2100.
- Scen 2D which is a more ambitious scenario, which translates the climate objectives of limiting global warming to 2°C by 2100.

In each climate scenario, different future shapes of mobility have been assumed and derived from the IEA Mobility Model (MoMo Model). The MoMo model is a technical-economic database spreadsheet and simulation model that enables detailed projections of transport activity according to user-defined policy scenarios to 2060. The model covers 29 countries and regions including a urban/non-urban split, and the potential for municipal-level policies to reduce transport energy use. In this paper, we incorporate the outputs of the MoMo model as inputs of transport mobility in our TIAM-IFPEN, there are two mobility scenarios for each climate scenario (More details of the MoMo model in Appendix B):

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[10] The climate module per se is directly inspired by Nordhaus-Noyer model.

- A “BAU mobility” shape equivalent to a continuing increase of the ownership rate, more private transit mode share and lower city densities. It is assumed an impact of urban dispersal, a worldwide phenomenon, on mobility and travel as well as the influence of urban land coverage on travel where we keep on having a huge car dependency and usage. As acknowledged by the UN, urban dispersal has an unmistakable and profound influence on travel because of the fact that spread-out growth increases the use of private motorized vehicles. Nowadays, this “urban sprawl”[11] is increasingly widespread in developing countries and should be considered in transport modelling.
- A “Sustainable mobility” shape where the idea of a sustainable mobility is assumed. This assumption implies more impact of stronger fiscal and regulatory policies, less vehicle mileage with more compact cities. It underpins an integrated approach to urban land-use and transport planning and investment, and gives priority to sustainable modes of mobility such as public and non-motorized transport as seen in Appendix B (Fig. 12) with the bus and minibus travel demands.

When considering future copper demand, all end-uses have to be considered in the modelling exercise as depicted in the copper supply chain in Fig. 3. Two methodologies have been considered. Firstly, the demands for the sectors in pink in Fig. 3, Electrical and Telecom networks, Consumer, Industry sector, Building and Other road transport sectors, are linked to the GDP per capita (extracted from the IEA MoMo model) projection via sensitivities. The sensitivity series represents the sensitivity of each end-use demand to one unit change in its driver, here the GDP per capita (GDPP). These sensitivities have been derived from the analysis

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[11] The term “urban sprawl” describes low-density, dispersed, single-use, car-dependent built environments and settlement patterns that, critics charge, waste energy, land and other resources and divide people by race, ethnicity and income/wealth.

of the sectorial copper demands along with the GDP per capita between 1975 and 2015[12] in order to intend to reflect changing patterns in relation to socio-economic growth. The end-use demands in copper for future years are projected using the equation (Eq.(2.2)):

$$D_t = D_{t-1} * (1 + \left(\frac{GDPP_t}{GDPP_{t-1}} - 1\right) * Sensitivity) \qquad \text{(Eq.(2.2))}$$

For the case of the demand in copper needed in power plants and the road transport sector, an endogenous technological evolution will be derived by the model while satisfying respectively the needs in electricity and the mobility demand. TIAM-IFPEN will assess the copper needed according to new installed capacities of power plants and the vehicle fleet evolution at any period. Finally, this paper is intended to contribute to the analyses of the impact of the roll-out of emerging low carbon technologies on copper criticality for a low carbon energy transition using a global energy system optimization model.

3. Results

3.1. How the energy transition will impact copper resources

We aim at quantifying the impact of the energy transition on copper resources. We therefore compare the copper resources that will remain available in 2055, in the 4°C and 2°C climate scenarios. Both are simulated by considering that resources are available for copper extraction at the current cost. This optimistic assumption does not impose any delay of conversion of resources into reserves. This greatly simplifies the simulations and allows us to avoid any arbitrary assumption on the future development of copper reserves. More, assuming that the copper contained in resources is fully available enables quantifying the total copper amount of copper

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[12] In one year time step and the data have been extracted from the International Copper Study Group

required by the IEA energy scenarios. The real-world constraints on copper extraction are then discussed in Section 4.

Figure 9 shows the total cumulative copper extraction between 2011 and 2055. The two leftmost bars represent the cumulative global extraction in the 4°C and 2°C scenarios, and its distribution among consumer regions. The checkered bar depicts the global copper resources in 2010. On the right axis, we report two rates measuring the shares of resources that will still be available in 2055 in each climate scenario.

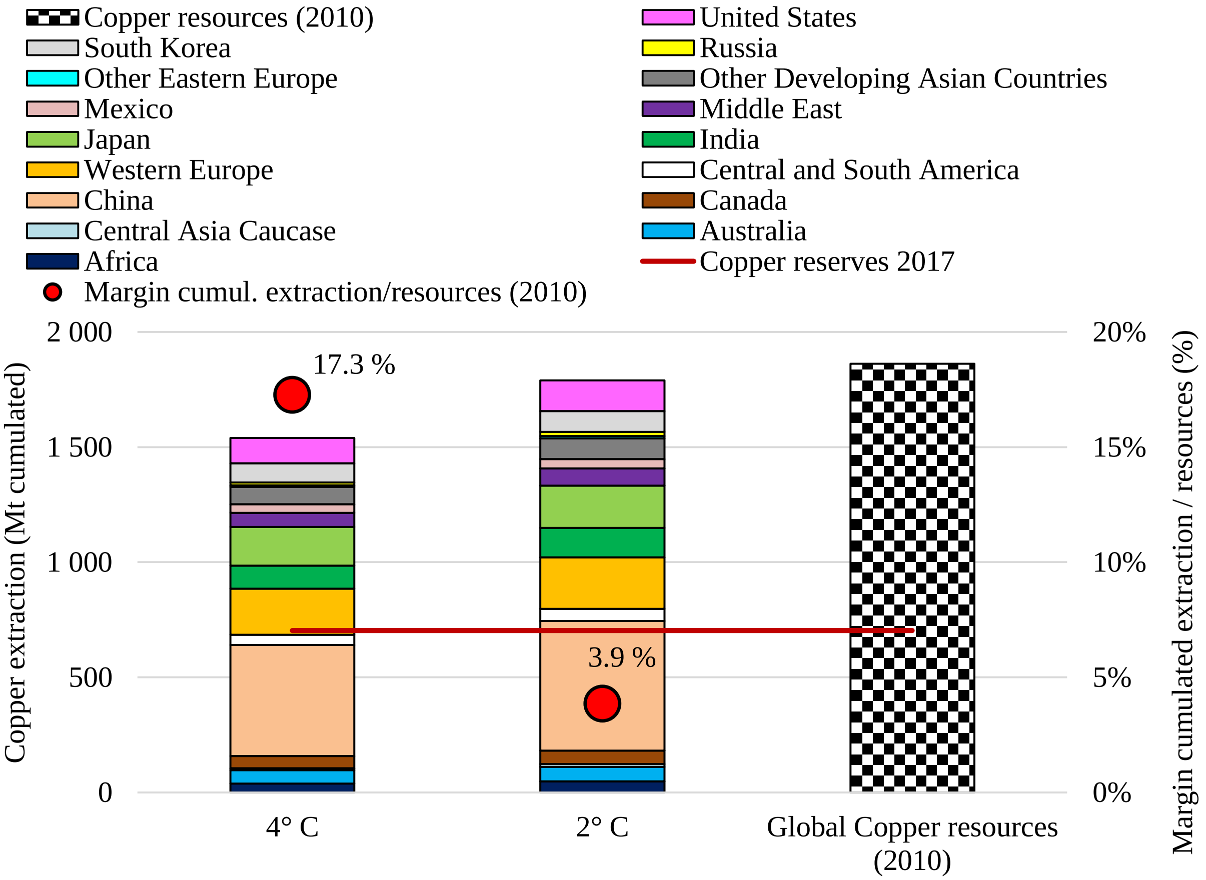

Figure 1: Comparison of cumulated consumption of primary copper over 2011-2055 in the two climate scenarios and global copper resources in 2010.

A first observation is that the copper production sector will have to considerably increase in terms of production capacity in both climate scenarios. To understand the scale of these transformations, we use the horizontal red line to represent the 2017 world's copper reserves. They will have to be multiplied by 2.2 and by 2.55 between 2010 and 2055 in a 4°C scenario and a 2°C scenario, respectively. Decarbonizing the electricity production and mobility sectors is not, *per se*, the future driver of copper extraction. Nonetheless, it will impose a significant additional effort on the development of copper reserves. In view of historical developments, such an increase in available copper reserves is nonetheless plausible. In 1996, the USGS estimated that overall copper reserves were 310 Mt. In 2015, the institute reviewed its estimates as it does every year and concluded that overall copper reserves were 700 Mt. This evolution corresponds to a 2.25-fold increase in reserves over 20 years, which suggests that world copper requirements can be met by 2055.

The assessment of the geological scarcity of copper at the global level, in the context of the energy transition, is a first indication of the interdependence between the diffusion of low-carbon technologies and copper resources. However, the adoption of a global scope should not hide the specificities of regional situations. They suggest that the availability of copper is likely to be a more or less constraining factor for the material growth of economies.

Each region may fulfill its copper needs by recycling, extracting or importing copper. It is possible to apprehend to what extent a region will rely on foreign copper resources by considering a resources scenario in which probable but undiscovered copper resources are added to current resources. By doing so, we can capture the dependency of a region to copper imports given that even in an optimistic scenario about copper resources, some region will be not able to meet their domestic copper needs.

These geographical discrepancies are highlighted on Figure 10 that puts the emphasis on several regions. For each, the yellow and green bar represent the cumulative domestic extractions of copper over the 2011-2055 period in both climate scenario. The grey bars represents the current level of copper resources and the dashed ones these same resources, augmented by the probable but undiscovered resources.

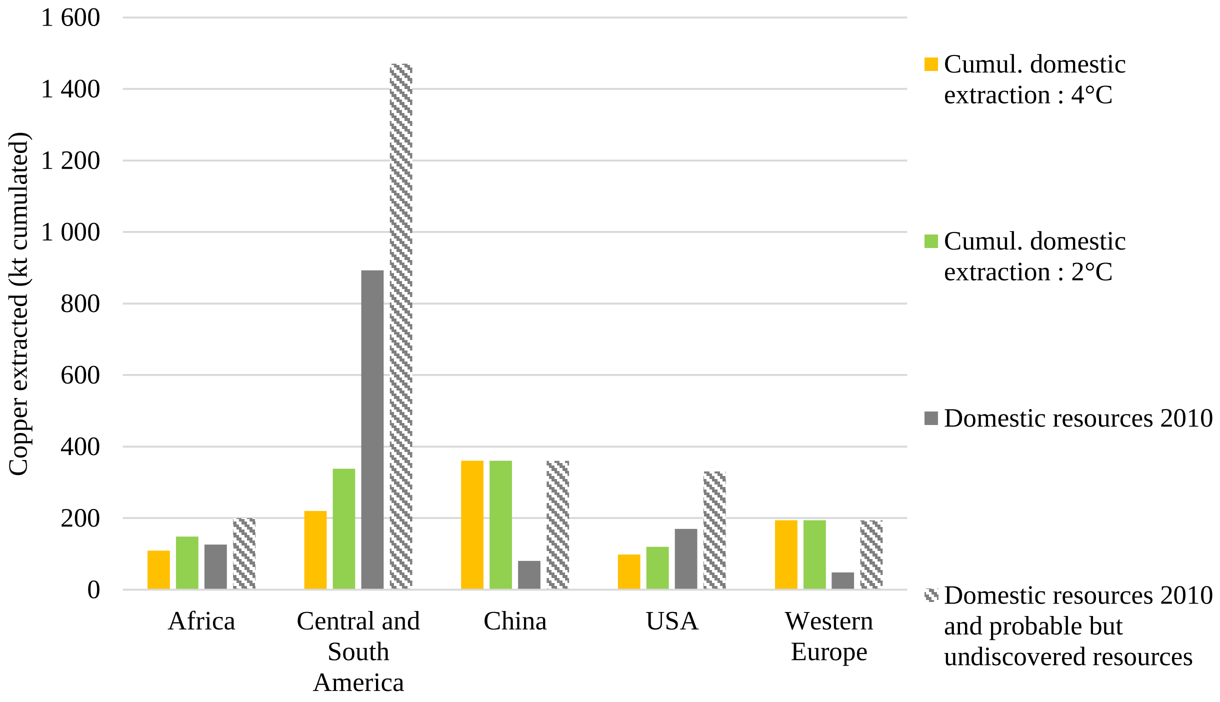

Figure 2: Cumulative domestic extractions over the 2011-2055 period in the two climate scenarios and domestic copper resources (in kt Cu).

It should be remembered that our model minimizes the total cost of the energy system. Due to the existence of positive transport costs, the model will generally meet the copper needs of a geographical area by focusing on the use of domestic copper resources before reviewing the opportunities offered by other copper-producing regions. However, this rule is not systematic because of the differences in refining costs between geographical areas and the existence of trade in both crude and refined copper. Imports can then be more economical than domestic production.

This feature explains why China and Western Europe, as can be observed on Figure 10, extract the totality of their domestic existing and probable resources in both climate scenario. Indeed, these two regions of the world are expected to continue to grow over the next decades, especially China, and this will contribute to considerably increase their demands for copper. To this extent, energy transition will contribute to increase the dependence of these countries of copper imports. The case of China is striking and raises the specific issues of copper: as a structural metal it is consumed in many applications so that its availability for the energy transition can be constrained by the dynamics of other sectors. Thus, taking the USGS estimates of undiscovered resources into account would multiply China's copper resources by 4.48 compared to their 2010 level. Assuming these resources become exploitable by 2055, we can see that the projected growth of the Chinese economy and its copper needs push the country to consume all the resources available on its territory and to import part of the copper it uses. As will be discussed in Section 5, these figures raise concerns about how these two regions will manage to deal with this.

Three other regions are represented on Figure 10, namely Africa, Central and South America and the United States. They share the common characteristic of having abundant copper resources that allow them to meet their domestic demands in each of the two climate scenarios, while exporting surplus extraction to other countries. As expected, Latin America could obtain an additional rent from resource extraction in a 2°C scenario. It is the geographical area that records the greatest difference in the quantity of copper extracted according to the chosen climate scenario. The countries in the region that hold the vast majority of copper resources are Chile and Peru, and they could form a powerful duopoly in the emerging copper market. However, the Chile/Peru duopoly may face a competitive fringe of smaller copper producers. Africa, Central Asia and the Caucasus, Canada, Mexico, Russia, USA and the Others Developing Asian countries[13] are the regions that have enough copper resources to meet their domestic demand and to export toward other regions, in both climate scenario.

The emphasis must be now put on regions that are net importers of copper. Indeed, Western Europe for instance imports raw copper, refines it and then export it; to this extent the region is a net exporters. Consequently, the scarcity of copper is expected to primarily impact European refining sector. At the contrary, several regions are net importers as their copper imports is intended to domestic consumption. The reliance of these regions on external copper resources can be measured by expressing net imports as a share of the total consumption of primary copper from these regions over the 2011-2055 period. Japan and South Korea do not have any copper resources so that in both scenario they fully rely on external resources. Middle East and Other Eastern Europe have low copper resources that they extract and they meet their residual domestic demands by importing 37.5 % and 29% of their cumulative consumption of primary copper, respectively, in the 4 degrees scenario. Their reliance on external resources increases in the 2 degrees scenario, the shares of imports in their cumulative consumption increasing to 46.5% for the other Eastern Europe countries, and to 48.6% for Middle East. Two major consumers of copper are also expected to increase their reliance on external resources: India and China. Both are net importers in the 4 degrees scenario, with 24% and 66% of their domestic consumption met through import for China and India, respectively. In the 2 degrees scenario these share increase to 35% for China and 73.5% for India. This additional reliance on imports can constitute

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[13] This region of the model includes several countries but whose copper resources known in 2010 are located in Indonesia (49.6 Mt Cu), the Philippines (25 Mt Cu) and Pakistan (24 Mt Cu).

a factor that weakens climate policies and slows the diffusion of low carbon technologies. To this extent, two policy options are assessed in the next two subsections.

3.2. Assessing the importance of copper recycling

Our results show that the energy transition will require the development of new copper reserves, we can highlight the importance of recycling as a key lever for preserving copper resources. To do so, we represent on Figure 12 the evolution of copper consumption in the 2°C climate scenario over five decades for several large consumer regions. We distinguish between the two sources of copper consumed: primary production and secondary production from recycling; the weight of recycled copper in consumption is expressed in percentages on the data labels.

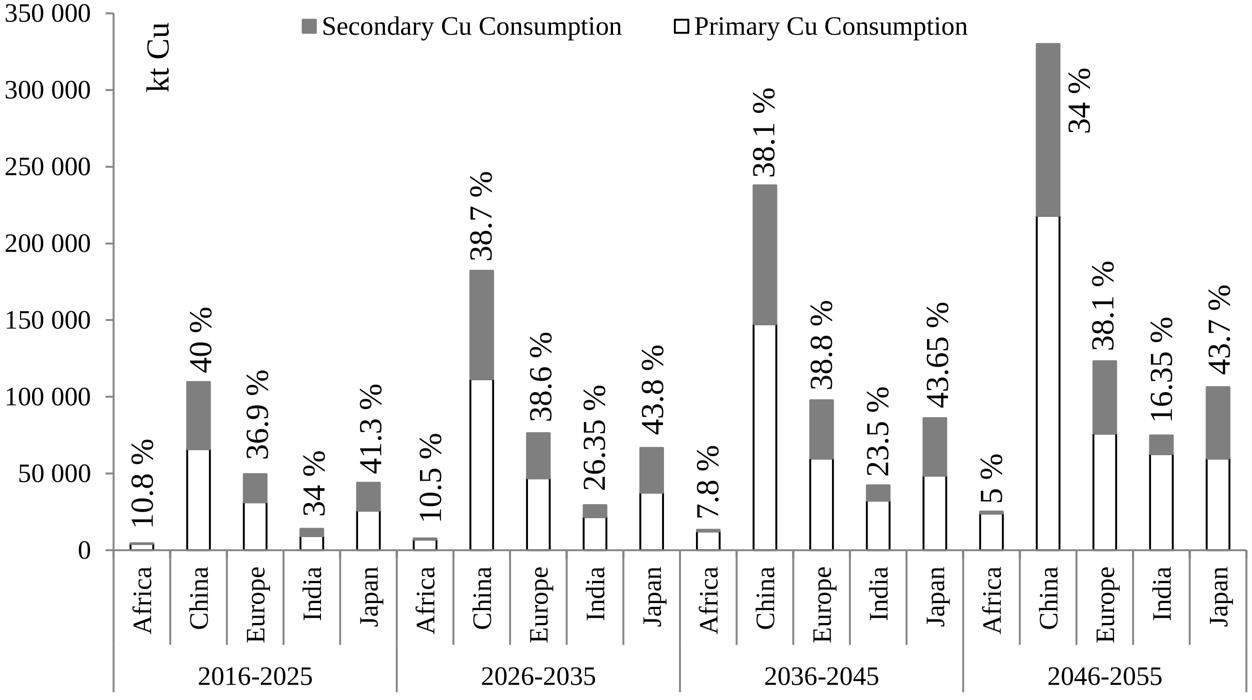

Figure 3: Evolution and distribution of domestic copper consumption for majors consumers (2006-2055).

Although recycling practices are calibrated on historical data, the weights of recycling in the copper consumed do not remain stable over time because the consumption dynamics specific to each sector within a country build up the copper stock available for recycling over time. This factor is particularly important for countries for which strong economic growth is expected: China and India, and to a less extent Africa. Secondary production represents the largest share of domestic consumption in these countries during the decade 2016-2025. Over the decades, the acceleration in consumption outweighs the rate of accumulation of copper scrap available for recycling and demand for copper is increasingly met through primary production. This result demonstrates the importance for countries experiencing strong economic growth to develop an efficient copper recycling sector upstream to reduce their import dependency. Europe and Japan, due to their more moderate expected economic growth, are able to maintain relatively stable recycling performance over time. However, Europe has a major margin for improvement compared to Japan in the use of recycled copper.

3.3. Transport habits and the copper sector

The transport sector is crucial for the future evolution of copper consumption because it is at the heart of reducing GHG emissions. We represent the changes in sectorial consumption, all regions combined, in Figure 13 in a 2°C scenario in which mobility needs evolve according to a BAU trajectory. The dotted line represents the evolution of total copper consumption in the "sustainable mobility" scenario. Thus, the difference between this dotted line and the upper boundary of the upper area that represents copper consumption attributable to the transport sector is the copper savings achieved through softer mobility.

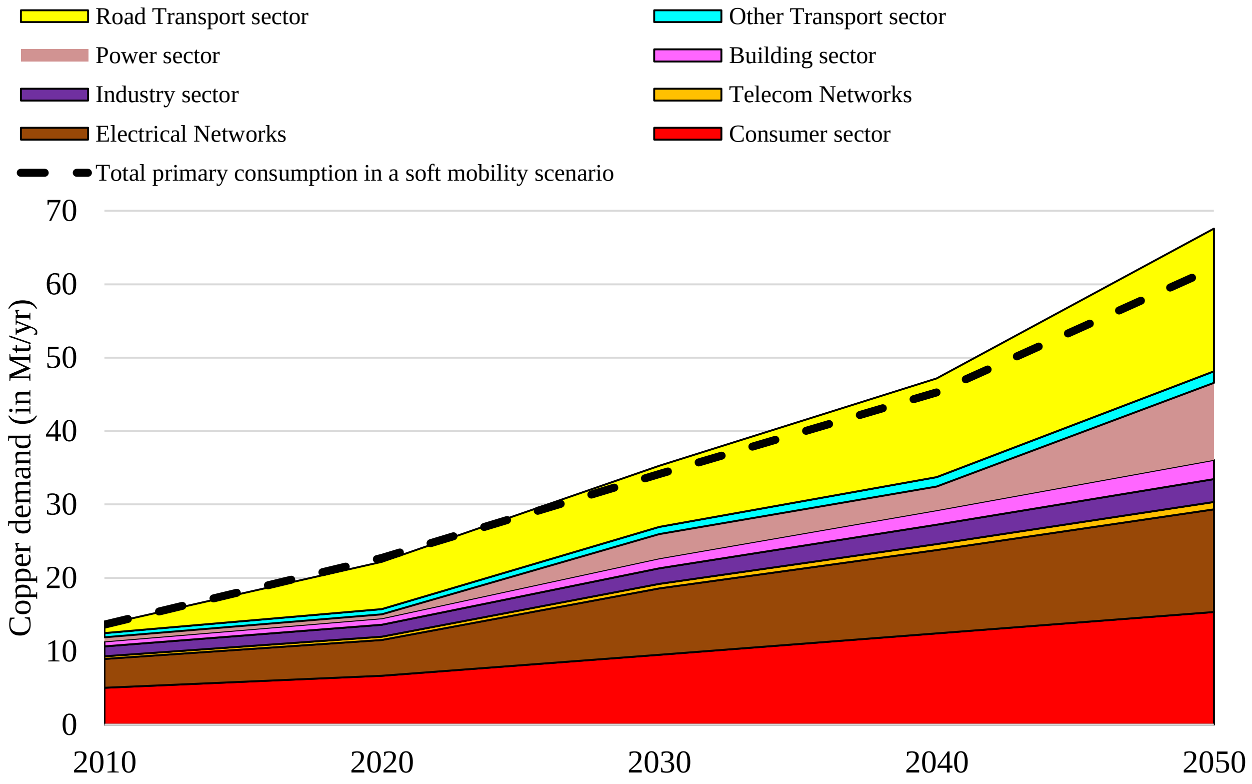

Figure 4: Evolution of primary copper consumption in the 2°C scenario, an assessment of the role of road transport.

The results indicate that copper consumption will be driven by three major sectors: transport, consumer goods and networks. During the last decade of the simulated period, the power generation sector also gains significant weight. Of these sectors, only one really lends itself to a public policy strategy that can reduce the demand for copper and thus preserves resources. Indeed, energy transport and telecommunications networks enable the deployment of smart grids and make energy demand more flexible. The consumer goods sector is a highly heterogeneous group of goods and market forces will in fact make it possible to regulate consumption more effectively than to ration it; the latter being subject to both practical and political limits. It is therefore the road transport sector that allows saving copper: the implementation of a sutainable mobility policies would make it possible to reduce the ecological impacts of mobility while limiting the use of copper resources.

How road transport is modeled is discussed in the Appendix B. Here, we focus on the consequences of a more sustainable mobility on copper consumption. It can vary significantly across the regions of the model. To account for these differences we represent in Figure 14 the share of reduction in total copper consumption over the period 2011-2055 imputable to sustainable mobility in a 2°C climate scenario, compared to a “BAU mobility” scenario.

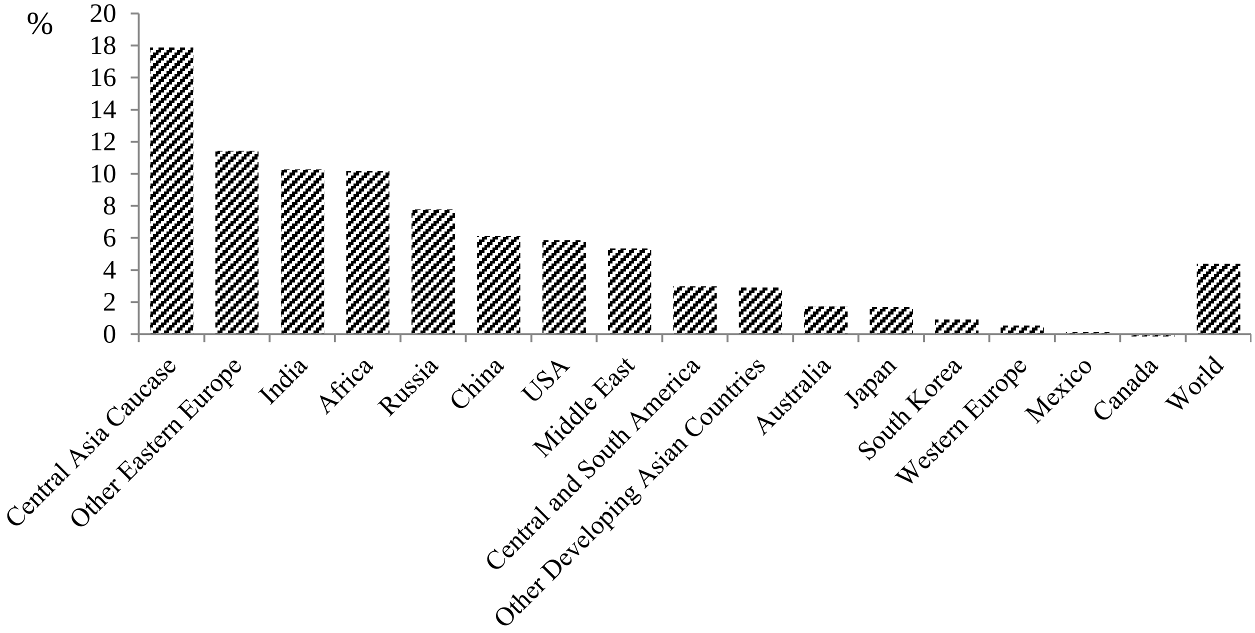

Figure 5: Share of saved consumption of primary copper saved in a sustainable mobility scenario (in kt), 2011-2055.

The results shown in Figure 14 illustrate the importance that a more sustaineble mobility policy can have for the use of copper resources. For the majority of countries, it reduces their cumulative copper consumption over the period 2011-2055 from 5% to 18%. The countries for which it has only a small effect on copper consumption are Western Europe, Mexico, Japan, South Korea, Canada and Australia. This is explained by the combined effects of economic development and population density. On one hand, a high population density in a rich country leaves few option for urban land-use planning aiming at reducing demand for individual vehicles. On the other hand, countries where population density is very low also have very few ways to reduce individual vehicles uses. At the global level, if all regions implemented policies aimed at achieving smoother mobility, overall cumulative copper consumption would be reduced by 4.4%. Some countries are decisive: this is the case of China and India. Due to their size, their relatively high population density and their dynamic growth forecasts, they can significantly reduce the use of private vehicles and thus do without large quantities of copper.

4. Discussion

4.1. Limits of our assumptions

Our modeling strategy is based on several assumptions that we can describe as optimistic. First, we consider that copper resources are freely exploitable by industry players without the need to convert them into reserves. Secondly, these resources are exploitable at a constant cost. Third, we consider that the copper content of the extracted ore remains stable over time, while it decreases as the cumulative extraction progresses, which implies greater energy consumption to extract the same amount of copper.

These choices make it possible to represent a copper production chain constrained exclusively by existing resources, without our attempting to formulate questionable assumptions as to the time required to convert resources into reserves, cost trends whose increase is expected to be at least partially offset by technological progress, or changes in the metal content of the ores extracted. The evolution of these various factors is indeed endogenous to the system and will be largely influenced by changes in the market price of copper. The projections detailed in the previous

Section are therefore not intended to predict the future but to assess the evolution that the copper sector must follow if it is to supply world demand, and in particular that of the energy transition sectors as represented by the IEA scenarios. These projections are worth comparing with reality and weak signals from the copper sector. To do this, we focus on two key players: Chile, as the world's leading copper producer, and China, which is on its way to becoming the world's largest consumer of this metal.

4.2. Chile and its mining industry

Large amounts of waste volumes are associated with copper extraction. These are mainly composed of waste rocks, tailings, mine waters and sludge. Depending on the mine type and the processes used, the waste associated with copper extraction varies in amount and composition. In Chile, the impact of the extractive sector on the availability of drinking water has been known for many years and is beginning to challenge the development model of the copper sector. For instance, public authorities have recently refused to grant water extraction permits for supplying the Escondida mine, currently the largest in the world. More and more copper mines are using sea water, both desalinated and direct from the ocean, to produce copper. This substitution is necessary to avoid drinkable water shortages and to guarantee to local communities an access to water. Uncertainties remain however on the impact of these new processes on the production cost; for the moment using sea water increases the production cost and R&D toward more efficient processes will be needed. More generally, if Chile wants to increase its production capacity the country will have to develop environmentally friendly mining processes in order to convince the local communities of the benefit of this industry. Indeed, most copper mines are localized near urbanized centers and local opposition to new projects is growing.

4.3. China and the difficulties in securing copper supply

Our projections indicate that China, even while developing its probable but undiscovered domestic resources, will have to import copper from abroad. The copper needs of China are expected to considerably increase, and it makes the security of supply a crucial objective for the Chinese government. Several signs indicate that the Chinese government have already start to implement its strategy aiming at increasing its control on several metal sectors. In the context of the “Made in China 2025” strategy the Chinese economy is expected to reduce its exports of refined metals in order to give priority to its domestic industries that will then export products will high value-added. In this context, Chinese FDIs aim at acquiring foreign mines and copper seems to be a major target since 33% of the total FDIs in metal sectors were directed toward copper during the 2005-2017 period. In addition, state-owned enterprises have invested in low-quality scrap in South Asia countries while the Chinese government have imposed a ban on the import of low-quality copper scrap. Coupled with the dominant position of China in the copper refining sector, one could expect the success of a long-term strategy aiming at better controlling the supply chain of copper. This being said, it generates uncertainties about the future availability of copper for other countries, and the resulting price.

5. Conclusion

This article assesses the criticality risk of copper in the context of the energy transition. An energy system optimization model has been developed to integrate, on the one hand, a detailed representation of the copper supply chain and, on the other hand, the copper content of the technologies available in two major sectors of the energy transition: the power sector and the individual road transport sector. The primary interest of our modeling approach is to link the diffusion of low-carbon technologies to copper resources. Thus, the technological mix and its evolution interact directly with the rate of depletion of copper resources. Using the model, it is possible to simulate technological scenarios that respond to various types of constraints, first and foremost climate constraints. Our simulations indicate that in 2055, 82.7% of the copper resources known in 2010 will have to be extracted from the ground in a climate scenario of 4 degrees of global average temperature warming. The energy transition clearly seems to have a strong link with copper resources : in a 2 degree scenario the quantity extracted reaches 96.1% of the world's known copper resources in 2010. As copper resources are likely to increase in the coming decades due to the rarefication of copper, these results are not intended to alert us on a possible end of copper resources, but to show that the rate of increase in world copper consumption, by accelerating, will exert strong pressure on existing copper production capacity. In this context, there are fears of a rapid increase in copper prices and competition between sectors for copper consumption. Such a phenomenon would slow down the energy transition and therefore underlines the importance of policies aimed at smoothing future demand trends. Our simulation exercises show that China and Europe are two geographical areas with high copper consumption that will become highly dependent on external sources. In addition, Central and South America provides a significant portion of copper production to meet the additional demand resulting from the energy transition. While our simulations show the importance of the copper resources held by Chile and Peru, they do not remove the uncertainty about the ability and willingness of these countries to continue to increase their copper production capacities, particularly due to local pollution caused by the exploitation of the ore produced. Two options are therefore being considered to reduce the copper demand rate of growth in: strengthening recycling capacities and a change of individual travel behaviour in road passenger transport , made possible by more sustainable mobility policies. With regard to recycling, our results highlight the importance of strengthening copper recycling channels now without waiting for copper price to increase, particularly in countries with strong growth prospects. Indeed, these countries are the ones where the rate of deployment of copper-intensive and long-life technologies is the highest. This changes the sectoral composition of the copper scrap flow available for recycling each year and, ultimately, can reduce over time the weight of secondary copper in the total copper consumed. Another option is to implement sustainable mobility policies to reduce demand for low-carbon and copper-intensive passenger vehicles. It will pass by strong transport policies to reduce car-dependencies and promote the use of alternative forms of transport (walking, cycling, shared mobility and public transport). While at the global level, the copper savings may seem minor, this strategy can be important for some countries. Indeed, several regions of the model such as India, Africa, other East European countries or Central Asia and the Caucasus can reduce their cumulative consumption of primary copper by more than 10% over the period 2011-2055.

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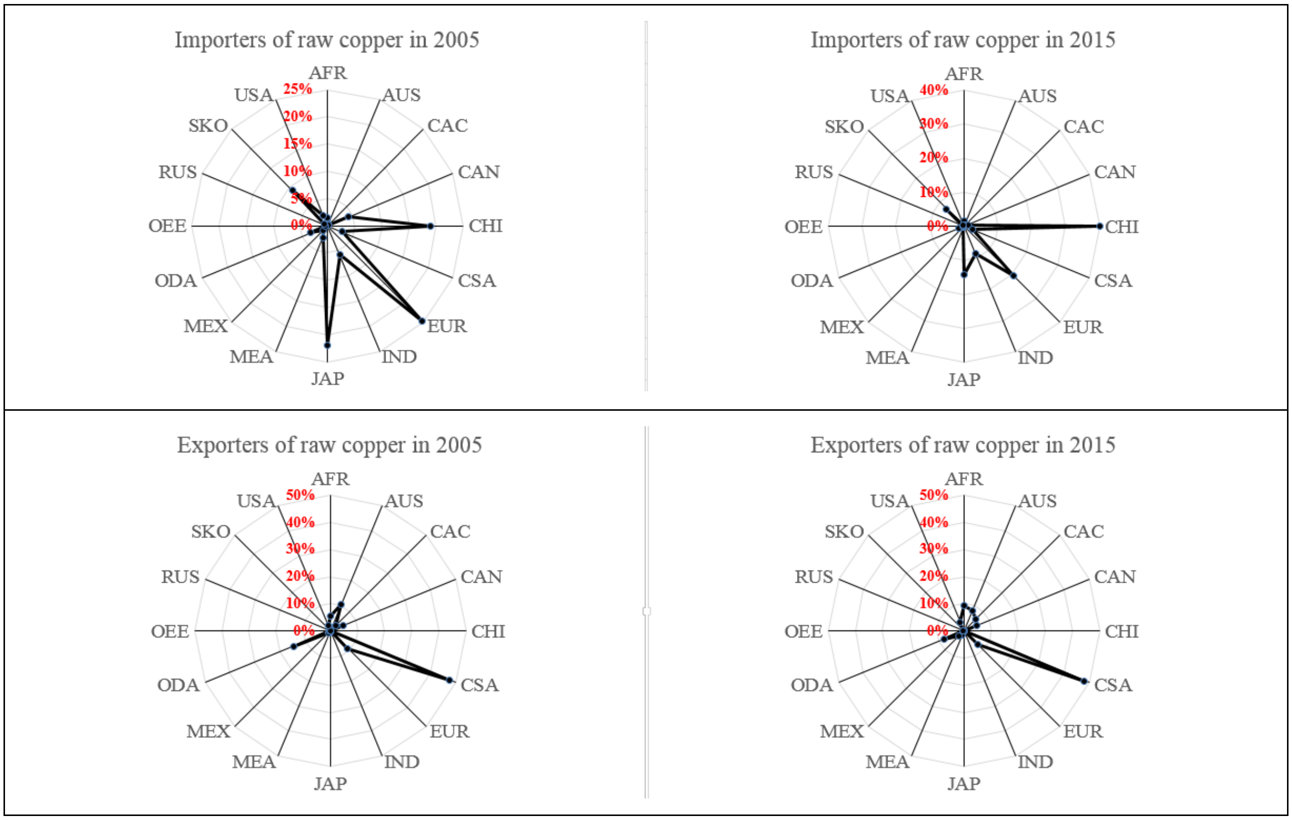
7. Supplementary materials

Appendix A

The evolution of raw copper trade between 2000 and 2015 is depicted in Fig. 8. The increasing importance of China in the importation of raw copper is clearly pinpointed while it is decreasing in other parts of the world. It illustrates the strategy of China to specialize in the refining of copper, as further supported by the evolution of the trade structure of refined copper discussed below. Considering the exporting region CSA-Central and South America (Chile) dominates the exports of raw copper, reflecting its high reserves of copper.

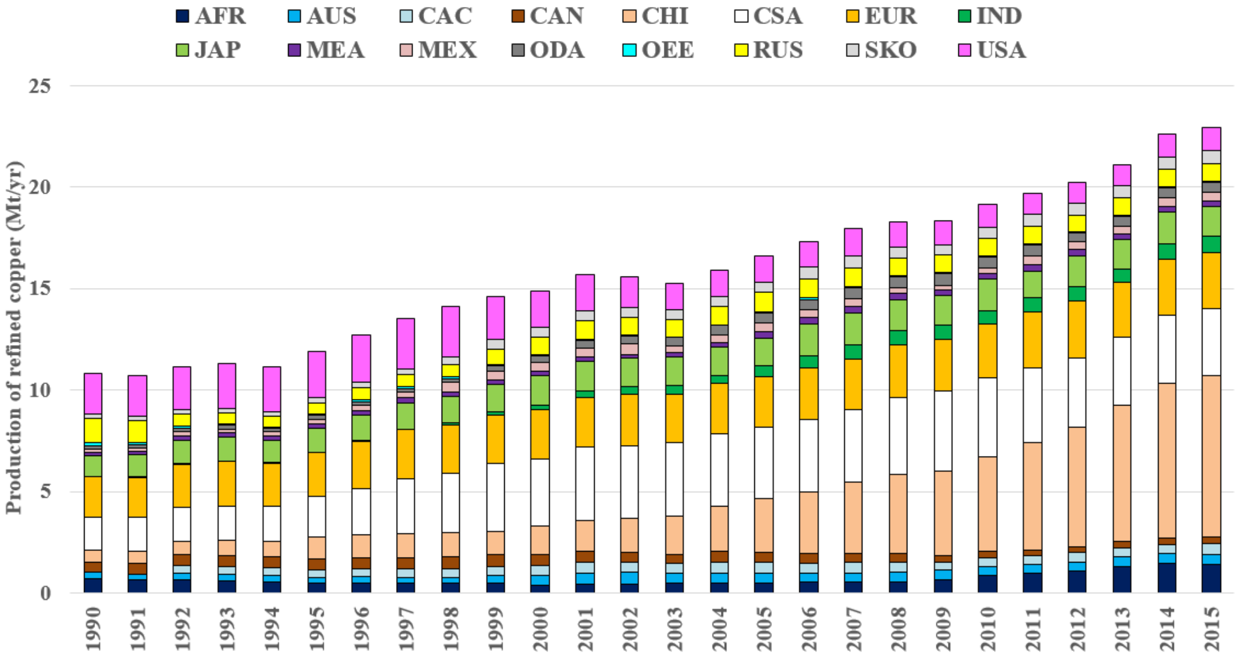
Fig. 8: Distribution of raw copper imports and exports (in % of the global monetary value) for the years 2005 and 2015



<u>Source</u> : UN Comtrade

The annual production of refined copper disaggregated by region over the 1990-2015 period is represented on the Fig. 9. Consistent with its growing imports of raw copper, China has become the leader in the production of refined copper. This performance is all the more outstanding given the fact the production of refined copper from other regions has stayed rather stable, suggesting that China has acquired a leadership on the refined copper market while facing low competition coming from countries such as Japan, Russia and the USA.

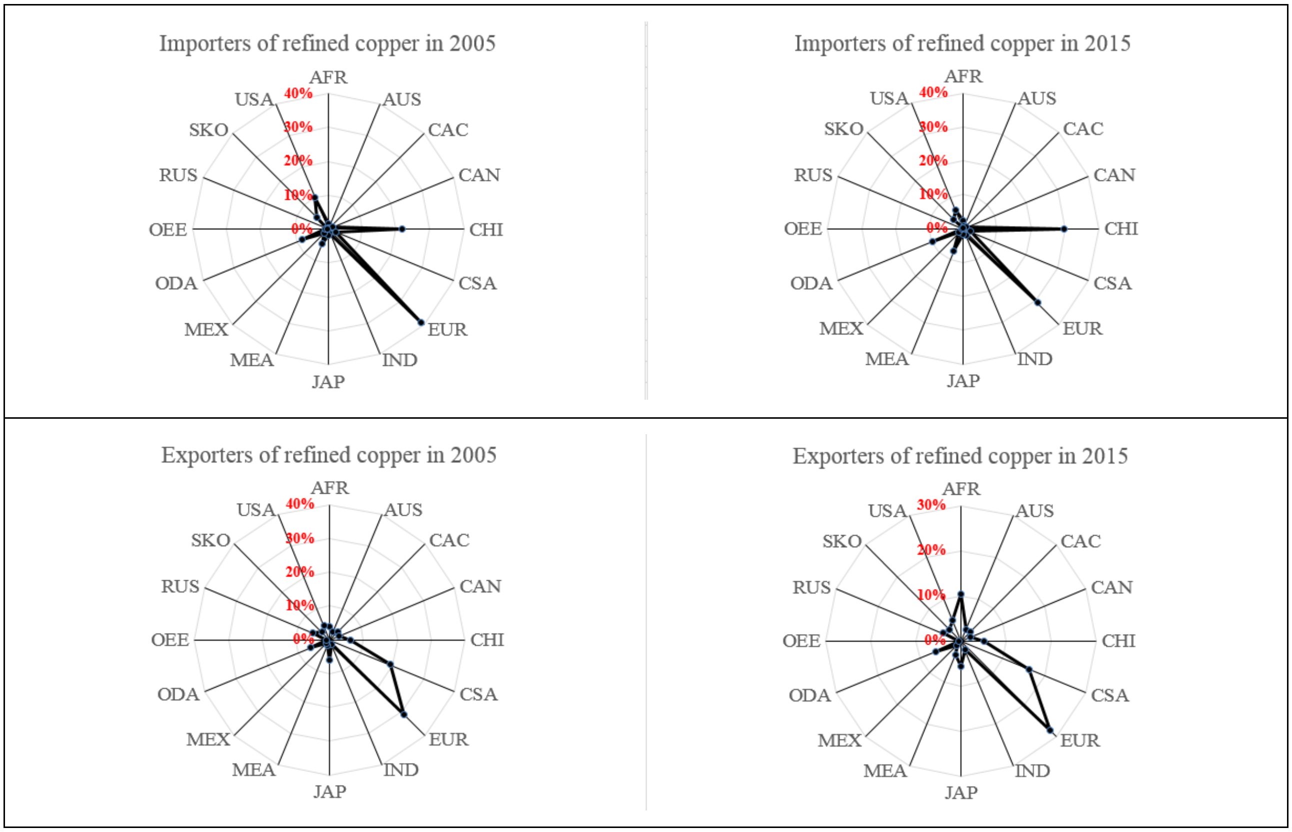
Fig. 9: Production of refined copper (Mt/yr)



<u>Source</u>: USGS

The CSA production has increased until 1999 before stabilizing. Further insights about the Chinese strategy can be deduced from the trade structure of the refined copper and its evolution, represented inFig. 10. Indeed, it seems that China has increased its production of refined copper in order to feed its domestic production of copper-containing products. While being the leader in the production of refined copper, China is also the second biggest importer of refined copper, weighting for around 30% of the global monetary import value of copper in 2015

Fig. 10: Distribution of refined copper imports and exports (in % of the global monetary value) for the years 2005 and 2015



Importers of refined copper in 2005

Importers of refined copper in 2015

Exporters of refined copper in 2005

Exporters of refined copper in 2015

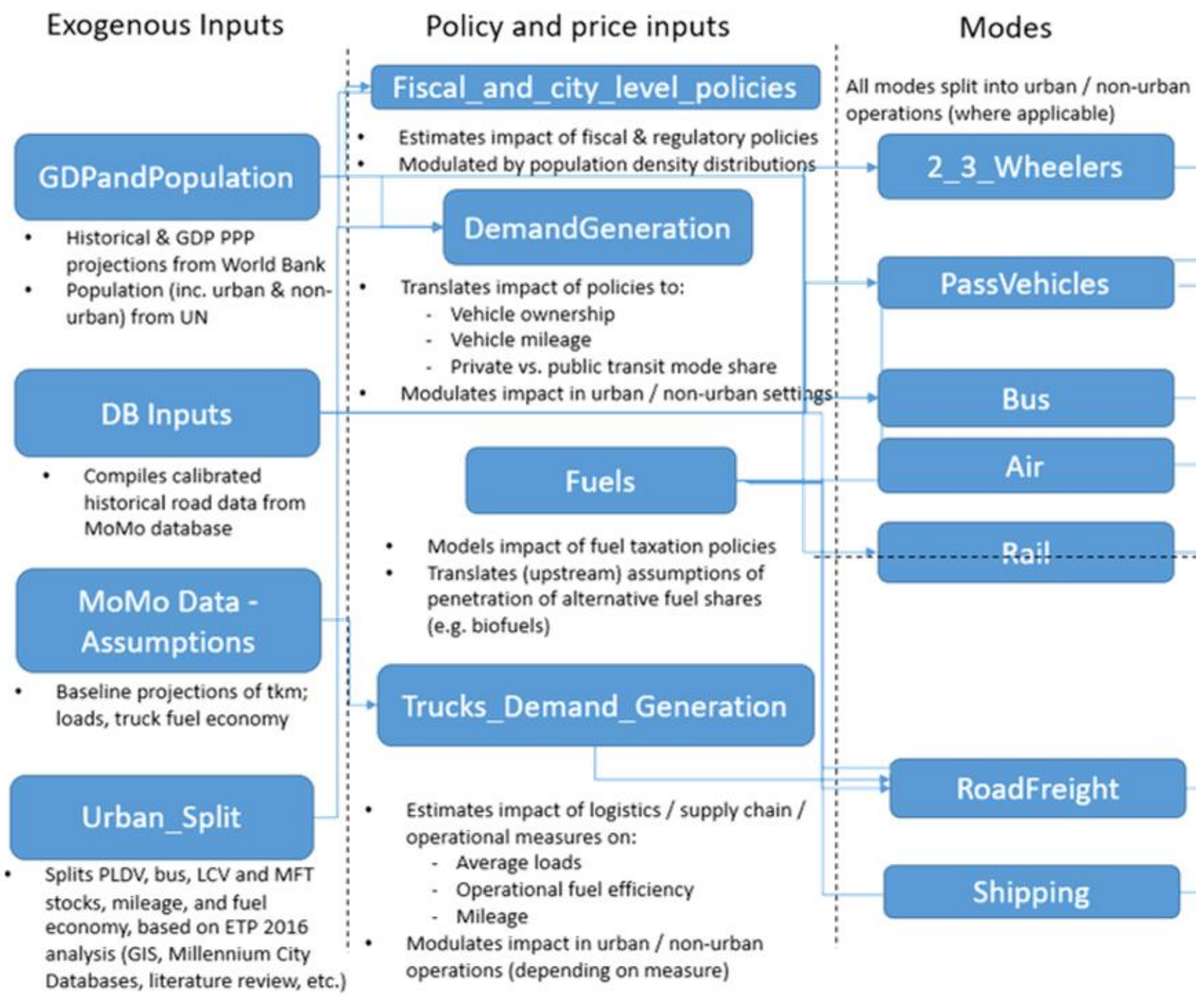
Source : UN Comtrade

Comparing countries' weights in the exportation of refined copper, we can conclude that it is not dominated by the countries that have the higher reserves of copper. To this extend, the implementation of the copper trade module would give new geopolitical insights into the future regions' strategies in response to environmental and economic constraints.

Appendix B

As explained by the IEA, “the MoMo model includes key elasticities, based upon representative "consensus" literature values, are used to model vehicle activity and fuel consumption responses to changes in fuel prices – which are themselves driven by projections and policy scenarios (i.e. GHG or fuel taxes). Elasticities also enable vehicle ownership to vary according to fuel prices and income, as proxied by GDP per capita”. Thus, they derived two future shape of mobility which would take into account the evolution of the ownership rates (number of vehicles per inhabitants), evolution of city density (density of cities with potential access public transport) according to their size. The research strategy of the MoMo project is detailed on the Fig. 11

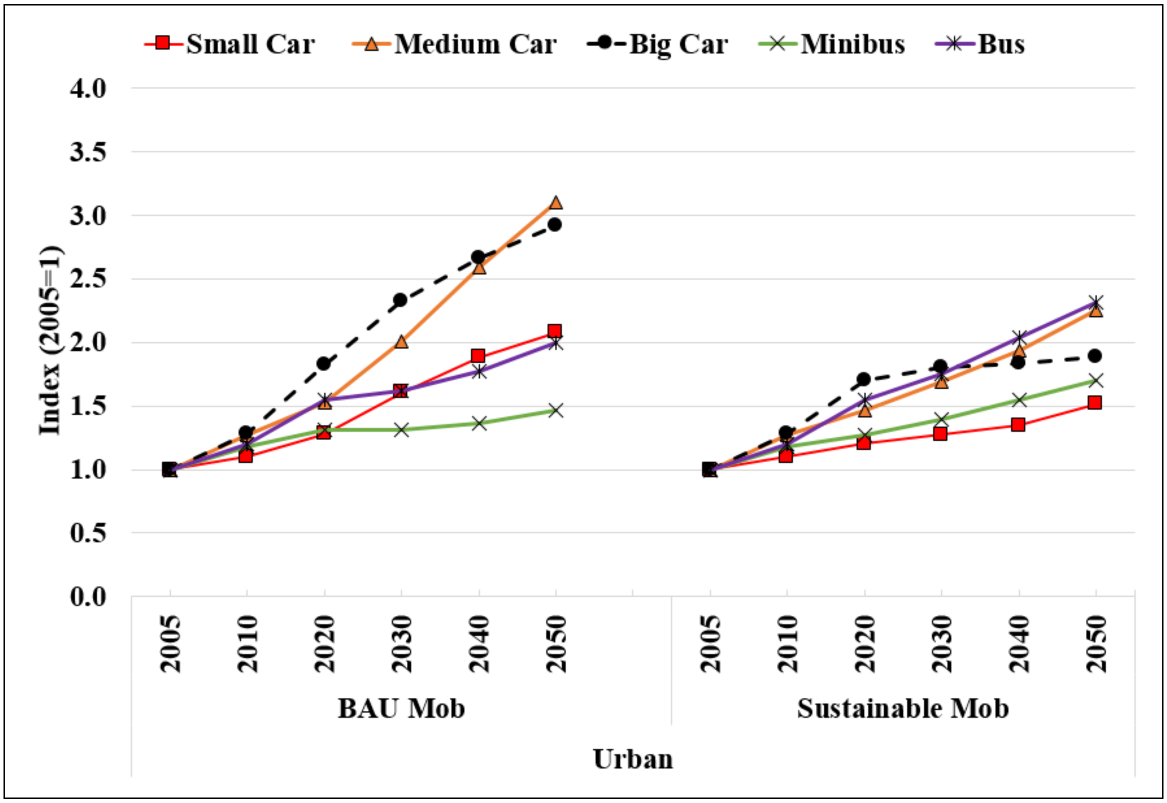
Fig. 11 : The network of spreadsheets of the IEA Mobility Model (MoMo model)

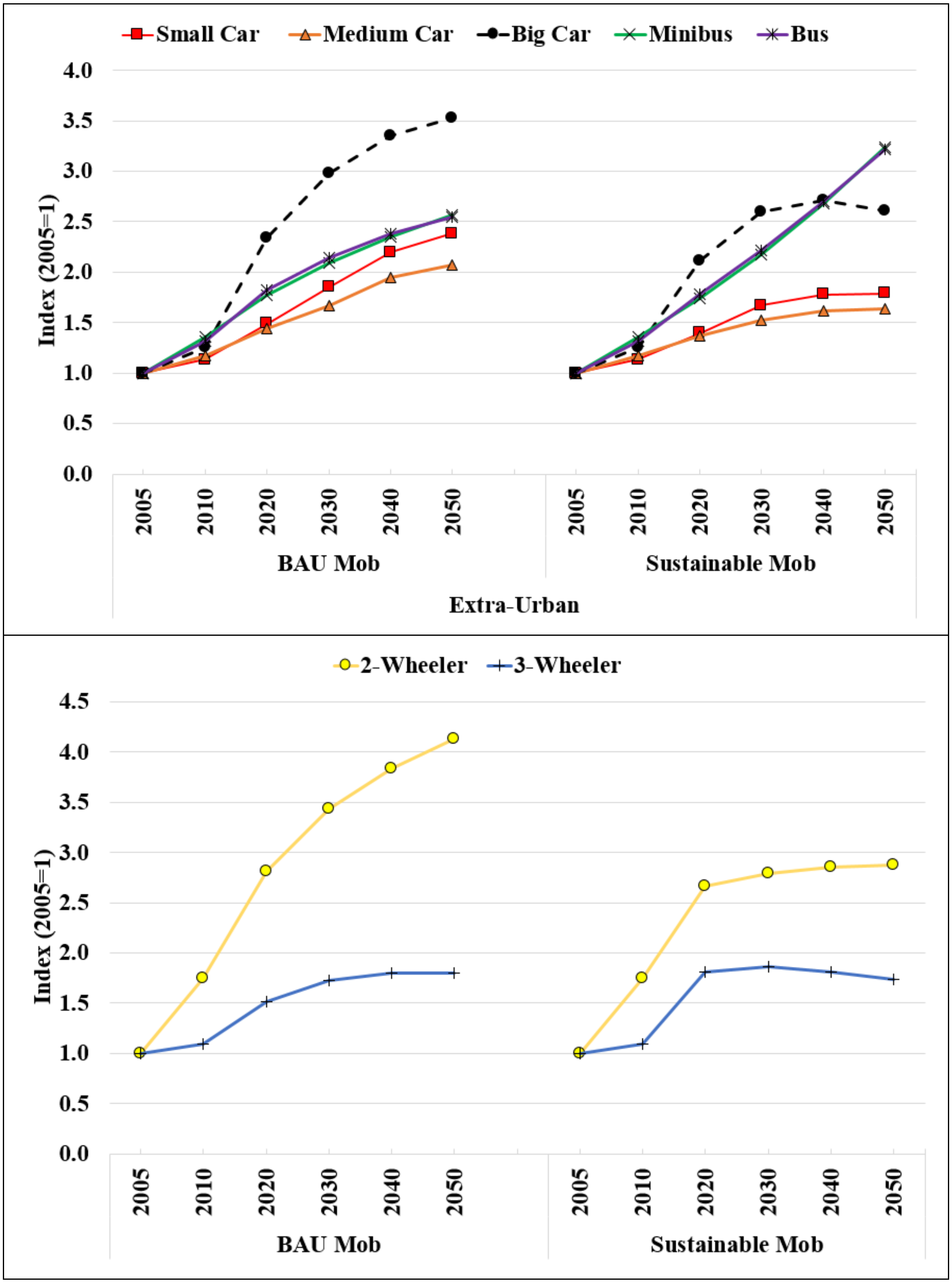


Source: IEA Mobility model

As seen in Fig. 12, the travel demand has been also disaggregated into two types of vehicle usages: short distance (urban) and long distance (extra-urban) for all vehicles except for the heavy commercial vehicle (HCV) and the 2/3-wheelers. This paper aim to contribute to the transport policy literature by modeling the implications of different forms of mobility along with climate constraints, firstly on cars fleet evolution and secondly on the regional copper needs in regards to the resource availability in the future.

Fig. 12 : Evolution of the two different shape of mobility (BAU and Sustainable) with the travel mode (urban and extra-urban)





Source: IEA Mobility model