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COPPER AT THE CROSSROADS

The aim of this article is to assess the impact of copper availability on the energy transition and to answer the question whether copper could become critical to the power and the transport sectors due to the high copper content of low-carbon technologies compared to conventional technologies.

Clément Bonnet
Gondia Seck
Emmanuel Hache
Marine Simoën
Samuel Carcanague

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Pour toute information complémentaire
For any additional information

Victor Court
IFP School
Centre Economie et Management de l’Energie
Energy Economics and Management Center
victor.court@ifpen.fr
Tél +33 1 47 52 73 17

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Authors:

- Dr Clément Bonnet, IFP Energies nouvelles: clement.bonnet@ifpen.fr
- Dr Gondia Sokhna Seck, IFP Energies nouvelles : gondia-sokhna.seck@ifpen.fr
- Dr Emmanuel Hache, IFP Energies nouvelles (Corresponding author and Project Leader): emmanuel.hache@ifpen.fr
- Marine Simoën, IFP Énergies nouvelles : marine.simoen@ifpen.fr
- Samuel Carcanague, IRIS: carcanague@iris-france.org

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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 copper could become critical to the power and the transport sectors due to the high copper content of low-carbon technologies compared to conventional technologies. In order to assess the copper availability by 2055, we rely on our linear programming world energy-transport model, TIAM-IFPEN. We conduct two climate scenarios (2°C and 4°C) with two mobility scenarios implemented with a recycling chain. The penetration of low-carbon technologies in the transport and energy sectors (electric vehicles and low-carbon power generation technologies) tends to significantly increase copper demand by 2055. In order to investigate how the tension over copper resources can be reduced in the energy transition context, we consider several public policy drivers: a sustainable mobility and recycling practices. Results show that in the most stringent scenario, 96.1% of the copper resources known in 2010 have to be extracted. They also pinpoint the importance of China and Chile in the future copper market evolution.

Keywords: Copper, Bottom-up modeling, Energy transition, Transport sector, Power sector, Recycling

JEL Classification: Q42, R40, C62

I. INTRODUCTION

The issue of mineral resource dependency is a relevant illustration of the challenge 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. The first criticality matrix was only established in 2008 in the United States (National Research Council, 2008) based on a double criterion: the economic importance of the resource and the potential risk of supply restrictions. Since 2011, the European Commission has also been producing a list of critical materials for the various countries of the European Union (European Commission, 2008, 2011, 2014, 2017). However, the issue of criticality has been addressed much earlier in literature, particularly in studies dealing with the criticality of natural capital (De Groot et al., 2003 among others). This notion of criticality thus covers all the risks related to the production, use or end-of-life management of a raw material (Graedel and Nuss, 2014): geopolitical risks (Hache et al., 2019a; Habib et al., 2016; Hache, 2018; O'Sullivan et al., 2017; Scholten and Bosman, 2016; 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 (production-related pollutant emissions), health consequences, landscape destruction, etc.) (Ali et al., 2017; Conde, 2017; Fizaine and Court, 2015 ; Ossa-Moreno et al., 2018; Perez-Rincon et al., 2019). A third dimension recently added to criticality studies is the consideration of the environmental consequences of material production (Graedel et al., 2012). In this methodological framework, ecological issues are represented on a third axis that completes the twodimension criticality matrix. The ecological consequences of producing a material include, based on life cycle analysis inventories, impacts on ecosystems and human health (Graedel et al., 2012; Graedel et al., 2015).

Whereas economic literature generally focuses on lithium, cobalt and rare earth (Alonso, 2012; Baldi, 2014; Hache et al., 2018, 2019b; Helbig, 2018; Kushnir and Sanden, 2012; Nassar et al., 2015; Speirs et al., 2014) to illustrate the systemic impacts of the energy transition on raw materials, this shift will also potentially impact the major non-ferrous metal markets (copper, nickel, zinc), as well as the steel, cement, aggregates and water sectors (Hache et al., 2019a).

Several economists and geologists have been focused on copper, as evidenced by articles and responses by Tilton (2003a, 2003b), Gordon et al. (2006), Tilton and Lagos (2007), Gordon et al. (2007) and more recently Vidal (2018) on the subject of copper criticality. Today, almost 35% of copper is used for electrical purposes (distribution and transmission) and this share could accelerate with the deployment of renewable energies. 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 until 2055. As these sectors are the main greenhouse gas emitters, it is crucial to understand whether the availability of copper can hinder the deployment of low-carbon technologies.

In order to assess the copper availability by 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 mobility scenarios each, and recycling has been also implemented in all these scenarios. The rest of the article is organized as follows. Section 2 describes the methodology, the overall structure of the TIAM-IFPEN model, and the specific features and assumptions considered for a detailed analysis of copper criticality. Section 3 presents an analysis of our findings, followed by an additional discussion in Section 4. Finally, Section 5 summarizes the main conclusions.

II. 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 using a 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 climate and sectoral constraints until 2055. In our previous article (Hache et al., 2019b) the assessment of future risks related only to the lithium supply chain with a fast roll-out of electric vehicles[3] in the coming years. In the study performed in the present paper, we have added a complete copper supply chain and analysed in this paper its dynamic criticality up to 2055 based on known resources.

2.1. Overview of the TIAM-IFPEN model

TIAM-IFPEN is a multiregional and inter-temporal partial equilibrium model of the entire energy system of the world, based on the TIMES model generator (Loulou and Labriet, 2008). A complete description of the TIMES equations appears in the ETSAP documentation[4]. It is a bottom-up techno-economic model that estimates energy dynamics by minimizing the total discounted cost of the system over the selected multi-period time horizon via powerful linear programming optimizers. The components of the system cost are expressed on an annual basis while the constraints and variables are linked to a period. A special care is taken to precisely track the cash flows related to process investments and dismantling in each year of the horizon. Different investment tracking cases have been considered in the model in order to help guarantee a smooth trajectory, a more realistic representation (Loulou and Labriet, 2008). The total cost is an aggregation of the total net present value of the stream of annual costs for each region of the model. It constitutes the objective function (Eq. (2.1)) to be minimized by

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[1] The Integrated MARKAL-EFOM System.

[2] MARKet Allocation model.

[3] In this article, Electric vehicles include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel-cell electric vehicles (FCEVs).

[4] 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

the model in its equilibrium computation. A detailed description of the objective function equations is 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 contained in the objective function, as follows:

- The investment costs incurred for investing into processes;
- Fixed and variable annual costs,
- Costs incurred for exogenous imports and revenues from exogenous exports; However, in the case of the global TIMES incarnation such as TIAM, exogenous imports and exogenous exports are not relevant.
- 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 in the 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

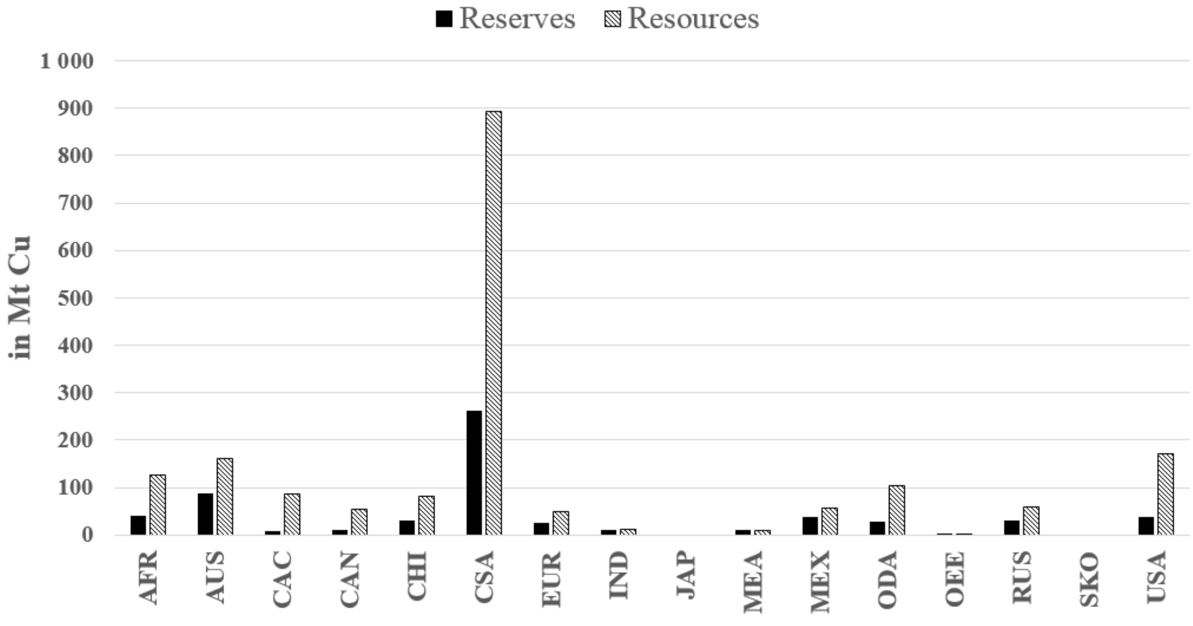
The model includes, for each region, detailed descriptions of numerous technologies , logically interrelated in a Reference Energy System, the chain of processes that transform, transport, distribute and convert energy into services from primary resources and raw materials to the energy services needed by the end-use sectors (See Appendix A for more details of the TIAM-IFPEN model).

2.2. Copper supply and demand modelling in TIAM-IFPEN

2.2.1. The copper supply chain

As explained by Gordon et al. (2007), copper is not uniformly distributed in Earth's crust as observed in the geographical distribution of copper ore reserves and resources (Fig.1)**Fig. 1**.

Fig. 1: Geographical distribution of copper resources and reserves worldwide[5]



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

Nearly half of the world's reserves and resources are located in the region CSA (Central and South America), mainly in Chile and Peru. The copper supply chain has been integrated into the model from ore deposits to its end-use sectors via various transformation processes and trade flows (Fig.2).

Two processes, pyrometallurgy and hydrometallurgy, used for refining copper ores have been implemented in the model. They are related to ore concentrates and leached ores respectively. Regionalized mining CAPEX and OPEX have been done using weighted averages of real projects around the world (Davenport et al., 2002; Boulamanti et al., 2016; Companies reports).

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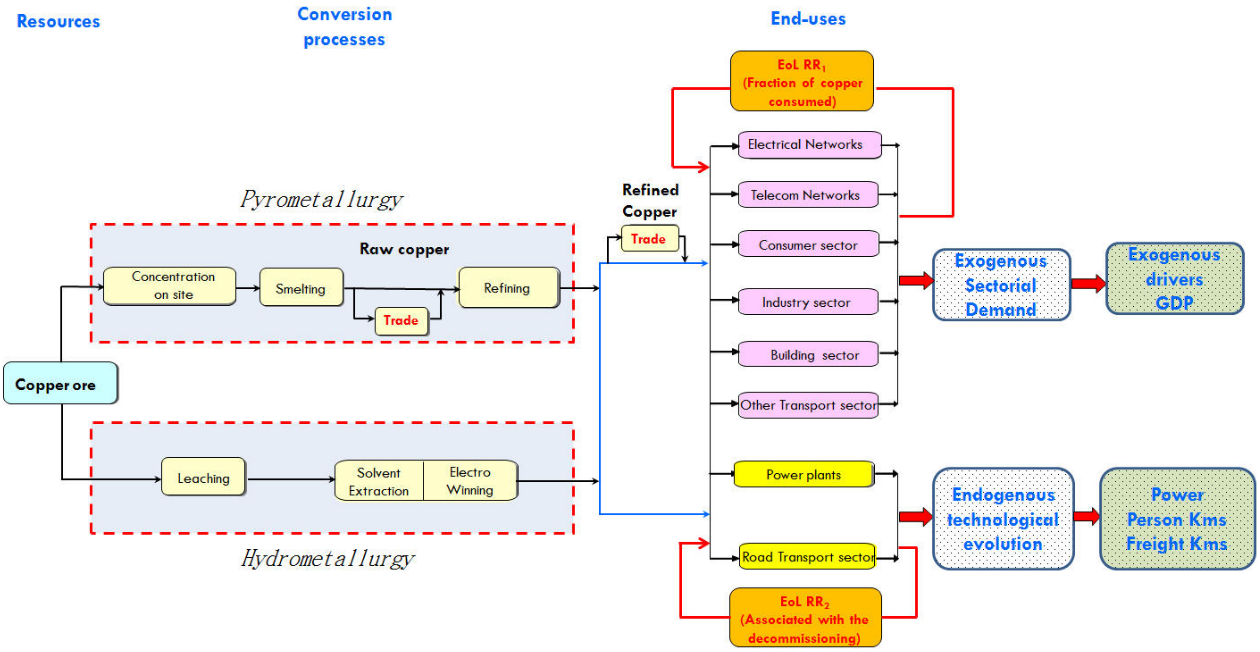
[5] Africa (AFR), Australia-New Zealand (AUS), Central Asia & Caucasia (CAC), Canada (CAN), China (CHI), Central & South America (CSA), European Union 28+ (EUR), India (IND), Japan (JAP), Middle East (MEA), Mexico (MEX), Other Developing Asian countries (ODA), Other Eastern European countries (OEE), Russia (RUS), South Korea (SKO), United States (USA) (See more details on these regions in Appendix A)

Fig. 2: Detailed description of the copper supply chain in each TIAM region



The regional disaggregation of these two refining processes is made using production weights since 1990 as displayed in Table 1. The repartition between concentrates and leached ores has been rather stable over time within a country between 2005 and 2015 due to the geological characteristics of the deposit.

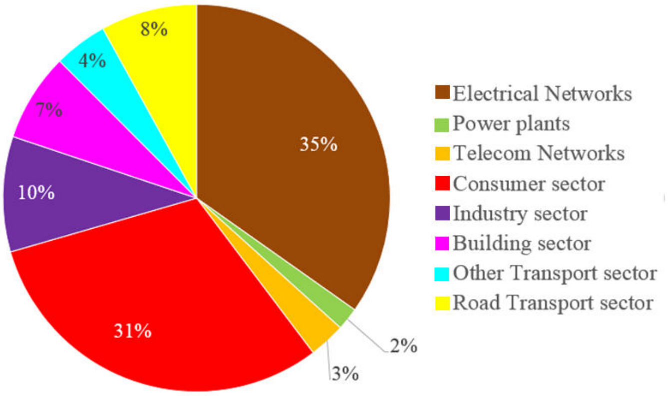
Table 1: Average share of ore concentrates (pyrometallurgy) in the cumulative mine production (in %) over the period 2005-2015 in the main producer countries

	AFR	AUS	CAC	CAN	CHI	CSA	EUR	IND	JAP	MEA	MEX	ODA	OEE	RUS	SKO	USA
Pyro	65	96	95	100	98	71	92	100	100	95	73	89	94	100	100	59

Source: USGS

As displayed in Fig. 2**Fig. 2**, copper is used in many sectors, such as the construction industry (plumbing, roofing, shipbuilding and cladding), the power sector (power plants and electrical infrastructure), the industry sector, the transportation sector and in the final goods sector (the main component of coins for many countries, dwelling accessories, water heaters, etc.).

Fig. 3: End-use consumption of worldwide copper in 2015



Source: IWCC/ICA

“Electrical Networks” which includes power distribution, lightning and connection to ground, is with the “consumer sector”[6] by far the largest copper usages as they consume respectively 35% and 31% of semi-finished copper products in 2015 (Fig. 3). 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 the “consumer” sector pertaining to the manufacturing of final goods that are not related to transport is the most dissipative end-use sectors. Hence a major barrier regarding the reuse of copper is the long period during which it may be stuck in products that are still in use.

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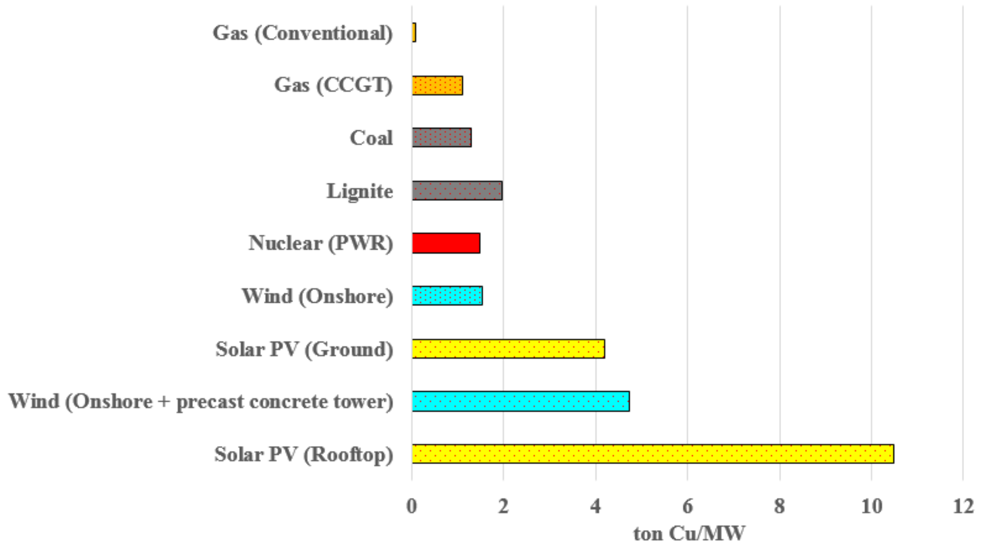
[6] It includes consumer and general products (Appliances, instruments, tools and other), cooling (Air conditioning and refrigeration), electronic (Industrial/ commercial electronics and PCs) and diverse (Ammunition, clothing, coins and other).

In a future driven by more stringent environmental constraints and economic growth, the increasing copper content of all decarbonisation innovations, particularly in the transport and power sectors, could, due to copper resource availability, be a hindrance to the diffusion of these technologies.

Fig. 4: Copper content of different energy means of production (kg/MW) considered in the model TIAM-IFPEN

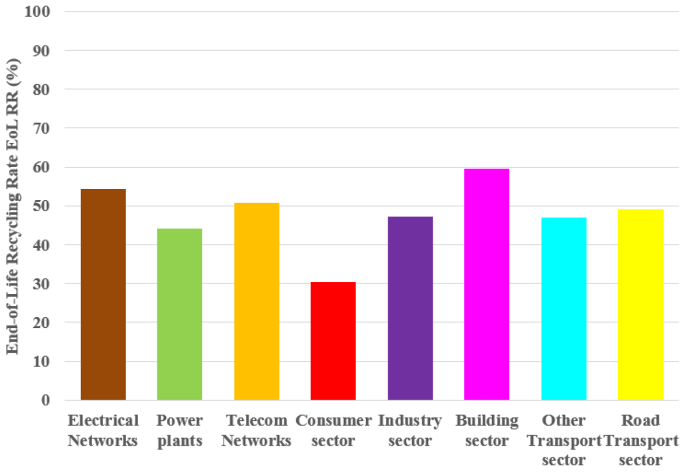


Source: Ecoinvent.

CCGT: Combine Cycle Gas 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 combined cycle gas turbine for example, while it will triple in an onshore wind turbine compared to a nuclear power plant (Fig. 4). The same trend is observed in road transport vehicles. Compared to conventional vehicles, electric vehicles contain three to nine times more copper. Typically, between 96% and 100% of the copper is in the vehicle body, while the copper in the latter falls to 45% due to the battery, much heavier, which contains 55% of the copper (Burnham, 2012). Thus, more emphasis will be placed on the need to increase the recycling efficiency of copper from scrap in all end-use economic sectors. Indeed, Glöser et al. (2013) have discussed several commonly used indicators to measure it at the global level. 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 scrap recycling. This indicator is determined as the fraction of metal contained in end-of-life products that are collected, pretreated and finally recycled back in the anthropogenic cycle (Eurométaux and Eurofer, 2012, cited in Tercero Espinoza and Soulier, 2018).

Fig. 5: 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. (2013) provide global estimates for the 2000-2010 period. The EoL-RR value for the eight copper consuming sectors considered in the model is presented in Fig. 5. The average value for all sectors combined is around 45%. As shown in Fig. 2, we have distinguished two EoL-RR according to the way we implement them. For the copper consuming sectors which have not been represented in detail technologically, i.e. the sectors in pink in **Fig. 2**, we assume the EoL-RR$_1$ as a fraction of the demand which is recycled back. For the transport and power sectors in yellow in **Fig. 2**, it has been provided EoL-RR$_2$ when there is a copper recycled associated with the decommissioning. These two last sectors have indeed a detailed technological representation. Thus, we have taken into account the recycling activity by using the sectorial EoL-RR values. With the lack of evolutive EoL-RR data, we make a conservative hypothesis by assuming they are kept constant in the model over our 2005-2055 time horizon period. Indeed, it is a pessimistic scenario considering that significant efforts would certainly be made to improve copper recycling, for example, in the "consumer sector" due to its dissipative characteristic and its weight in copper consumption. In other words, the EoL-RR implemented in the model (Fig. 5) provides the basis of our pessimistic view of recycling activity (probable minimum values).

Copper is traded in three forms worldwide. The first is copper concentrate that is processed by pyrometallurgy techniques. The second one is refined copper cathodes that are sold by the copper 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 represents a small share of global copper trade. So, for sake of simplification, we consider two types of trade in the model: in **Fig. 2** the first one is the trade of raw copper which encompasses all trades of copper ores and concentrates, copper mattes, copper anodes and unrefined copper. The second type concerns the refined copper. Taking into account the trade capabilities will allow analysing future international copper exchanges and strategies according to each regional needs and growth. This possibility of the model would be very relevant as historical trade analysis pinpointed changes into regions' strategies in response to environmental and economic constraints between 2005 and 2015 (see the example of China in Appendix B). Trade data have been extracted from the Resourcestrade.earth website that uses as a primary source the UN Comtrade database and corrects the missing points.

2.2.2. The copper end-use sectors and their demand evolution

When considering future copper demand, all end-use sectors have to be considered in the modelling exercise as depicted in the copper supply chain in Fig. 2 (in §2.2.1). Two methodologies have been considered. Firstly, the demands for the sectors represented in pink in the aforementioned Fig. 2, Electrical and Telecom networks, Consumer, Industry sector, Building and Other road transport sectors, are linked to the GDP per capita (extracted from the IEA database) 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 of the sectorial copper demands along with the GDP per capita between 1975 and 2015[7] to take into account changing trends in socio-economic growth. Copper end-use demand for future years is 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 copper demand in in power plants and the road transport sector (See Appendix C for more details of their representations in the model), 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 copper requirements according to the new installed capacities of power plants and the vehicle fleet evolution at any period.

2.3. Scenario specifications

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 in our previous lithium criticality study (Hache et al., 2019b) where we considered two climate scenarios[8] 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 2100 expected global average temperature increase to 4°C above pre-industrial levels.

- "Scen 2D" which is a more ambitious scenario, which translates the 2100 climate objectives of limiting global warming to 2°.

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

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

In each climate scenario, different future scenarios of mobility have been assumed and derived from the IEA Mobility Model (MoMo Model). The MoMo model is a techno-economic database spreadsheet and a 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 an 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 transport mobility inputs into our TIAM-IFPEN, there are two mobility scenarios for each climate scenario (More details of the MoMo model in Appendix D):

- A "BAU mobility" scenario equivalent to a continuous increase of the ownership rate, a higher private transit mode share and lower city densities. It is assumed that, at the global scale, urban dispersal will continue to increase and will positively impact demand for mobility and travel; the huge car dependency is expected to continue to grow. As acknowledged by the UN-Habitat (UN-Habitat, 2013), urban dispersal has an undeniable and profound influence on travel because of the fact that spread-out growth increases the use of private motorized vehicles. Nowadays, this "urban sprawl"[9] is increasingly widespread in developing countries and should be considered in transport modelling.

- A "Sustainable mobility" scenario 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 D with the bus and minibus travel demands.

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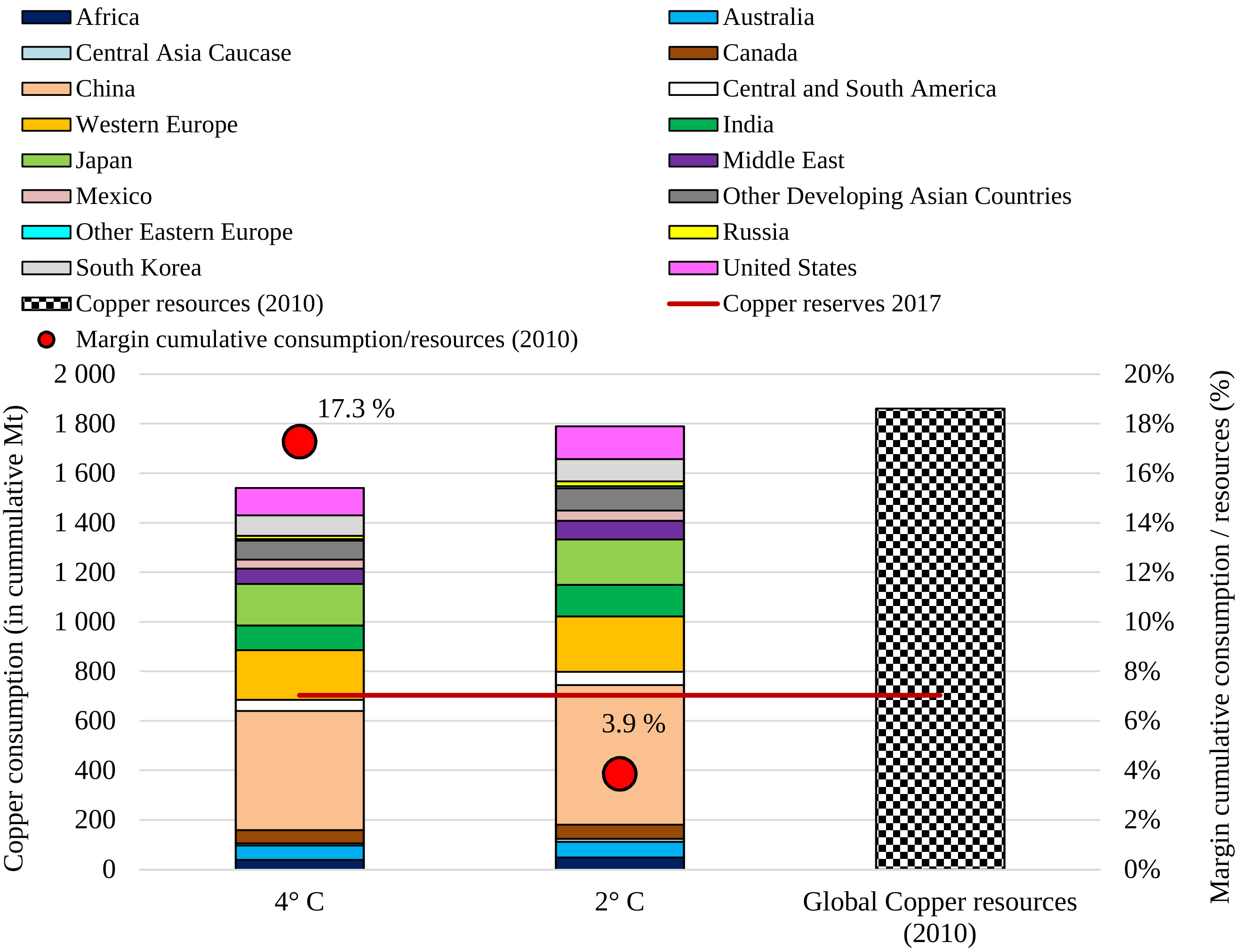
[9] The term "urban sprawl" describes low-density, dispersed, single-use, car-dependent built environments and settlement patterns that, critics charge, waste energy, land and other resources and divide people by race, ethnicity and income/wealth.

III. RESULTS

3.1. The impact of the energy transition on the global copper resources

We aim at quantifying the impact of the energy transition on copper resources. We therefore compare the remaining copper resources in 2055 under the 4°C and 2°C climate scenarios. Both scenarios assume that resources are available for copper mining at current cost. This rather optimistic assumption does not impose any delay in the conversion of resources into reserves. This greatly simplifies the modelling and allows us to avoid any arbitrary assumptions about the timing of future copper reserves development. In addition, assuming that the copper contained in resources is available, the total amount of copper required can be quantified according to our scenarios, as described above. Fig. 6 compares the total cumulative copper consumption from 2010 to 2055 with the world's known copper resources in 2010 under climate scenarios. The two leftmost bars represent the cumulative global consumption in the 4°C and 2°C scenarios, and its distribution across consumer regions. The right bar depicts the world's known copper resources in 2010. On the right axis, we have defined an indicator for a dynamic assessment of copper criticality. This indicator, which could also be called safety margin, is calculated as the ratio of the cumulative copper consumption to the current resources.

Fig. 6: Comparison between cumulative copper extraction from 2010 to 2055 under two climate scenarios and global copper resources in 2010



Source: Authors' result

A first observation is that, in both climate scenarios, copper production capacity will have to increase considerably. To capture the scale of these transformations, the horizontal red line depicts the 2017 world's copper reserves based on USGS data. 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. These results pinpoint the fact that a significant additional effort on the development of copper reserves will be needed. Given the historical developments of copper reserves, such an increase could be achievable. In 1996, the USGS estimated world copper reserves at 310 Mt. In 2015, the institute revised its estimates as it does every year and concluded that copper reserves reached 700 Mt.

This evolution corresponds to a 2.25-fold increase in reserves over 20 years only, which suggests that world copper requirements could probably be met by 2055.

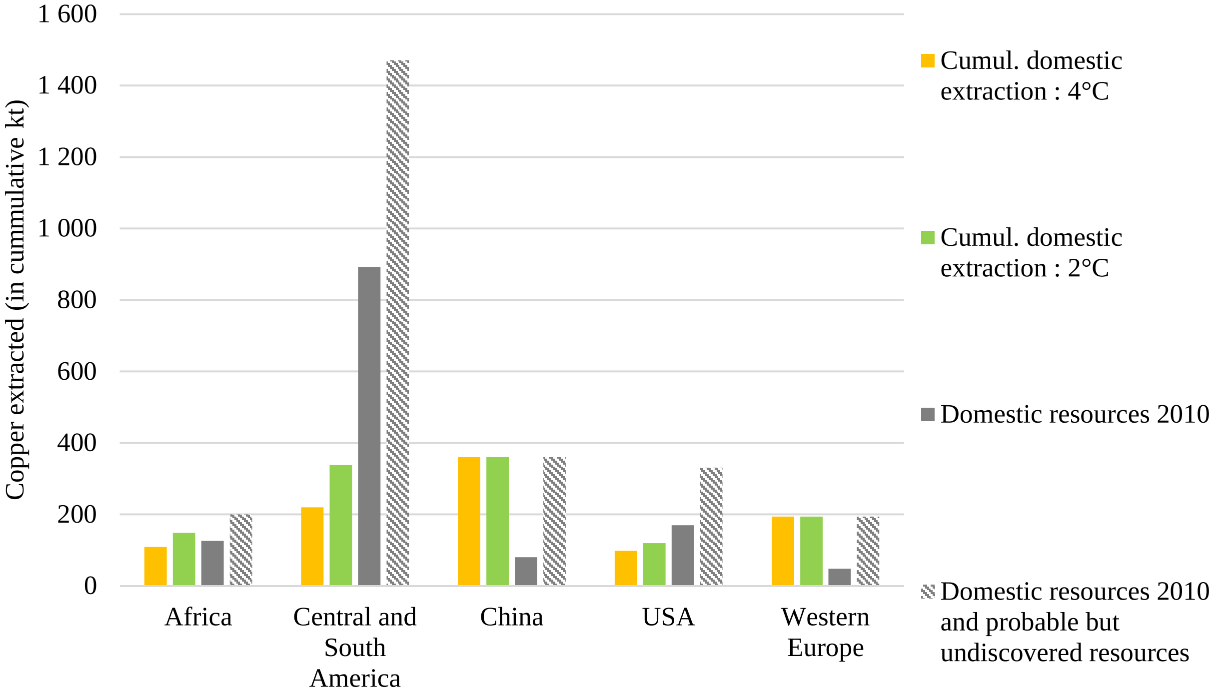
This copper geological scarcity at the global level, in the context of the energy transition, is a first indication that highlights the interdependence between the diffusion of low-carbon technologies and copper resources. However, the stress on the copper resources may greatly vary among the regions of the model.

3.2. Regionalization of the effects of the energy transition on copper

Each region may fulfil its copper needs by recycling, extracting or importing copper. We assess to what extent a region will rely on foreign copper resources by considering a resource 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 regions will not be able to meet their domestic copper needs.

These geographical discrepancies are highlighted in Fig. 7 which emphasises several key regions. For each one, the yellow and green bars represent the cumulative domestic extractions of copper over 2010-2055 period in the two climate scenarios. The grey bars represent the current level of copper resources and the dashed ones these same resources, augmented by the probable but undiscovered resources.

Fig. 7: Cumulative domestic extractions over 2010-2055 period in the two climate scenarios and domestic copper resources (in kt Cu)



Source: USGS, Authors' result

It should be kept in mind that our model minimizes the total cost of the energy system. Due to the existence of transport costs, the model will generally meet the copper needs of a geographical area by focusing on the use of its domestic copper resources before reviewing the opportunities offered by other copper-producing regions. However, this rule is not systematic since the differences in refining costs between geographical areas and the existence of trade in both crude and refined copper can potentially make imports less costly than domestic production.

This feature explains why China and Western Europe, as can be observed in Fig. 7, extract the totality of their existing and probable domestic resources in both climate scenarios. Indeed, the copper needs of these two regions are expected to continue to grow in the next decades, especially in China which continues to have high growth GDP rate projection. To this extent, energy transition will contribute to increasing the dependence of these countries to copper imports. The case of China is striking and raises the specific issues of copper: as a structural metal it is used in many applications so that its availability for the energy transition can be constrained by the dynamics of other sectors. Thus, taking into account USGS estimates of undiscovered resources would increase China's copper resources by a factor of 4.48 from their 2010 level. Assuming that these resources become exploitable by 2055, it can be seen that the projected growth of the Chinese economy and its copper needs are pushing the country to consume all its resources and to import part of the copper it uses. It raises concerns about how this region will manage to deal with this issue.

Three other regions are also represented in Fig. 7 namely Africa, Central and South America and the United States. The latter share the common characteristic of having abundant copper resources that allow them to meet domestic demand in both climate scenarios, while allowing them to export primary copper to other countries. As expected, Latin America could obtain an additional rent from resource extraction in a 2°C scenario. This is the geographical area that records the greatest difference between the two climate scenarios in terms of the quantity of copper extracted. The countries in the region that hold the vast majority of copper resources are Chile and Peru. They could constitute a powerful duopoly in the copper market. However, the Chile/Peru duopoly may face a competitive fringe of smaller copper producers. Indeed, according to our results, Africa, Central Asia and Caucasia, Canada, Mexico, Russia, USA and the Other Developing Asian countries[10] are the regions that have enough copper resources to meet their domestic demand and to export to other regions in both climate scenarios.

The emphasis is now put on regions that are net importers of copper. Indeed, Western Europe for instance imports raw copper, refines it and then exports it; to this extent the region is a net exporter. Consequently, the scarcity of copper is expected to primarily impact European refining sector. On the contrary, several regions are net importers as their copper imports are dedicated to domestic consumption. The reliance of these regions on external copper resources can be measured by expressing net imports as a

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[10] 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).

share of the total consumption of primary copper from these regions over 2010-2055 period. Japan and South Korea do not have any copper resources so in both scenarios they fully rely on external resources. The Middle East and Other Eastern Europe have low copper resources that they extract and meet their residual domestic demand by importing 37.5 % and 29% of their cumulative consumption of primary copper, respectively, in the 4°C scenario by 2055. Their reliance on external resources increases in the 2°C scenario, the shares of imports in their cumulative consumption increasing to 46.5% for the other Eastern European countries, and to 48.6% for Middle East. Two major consumers of copper are also expected to increase their reliance on external resources: China and India. Both are net importers in the 4°C scenario, with 24% and 66% of their domestic consumption met through import for China and India, respectively. In the 2°C scenario, these shares increase to 35% for China and 73.5% for India. This additional import dependence can be a factor that weakens climate policies and hampers the diffusion of low-carbon technologies. To this extent, two policy options have been assessed in the next two subsections.

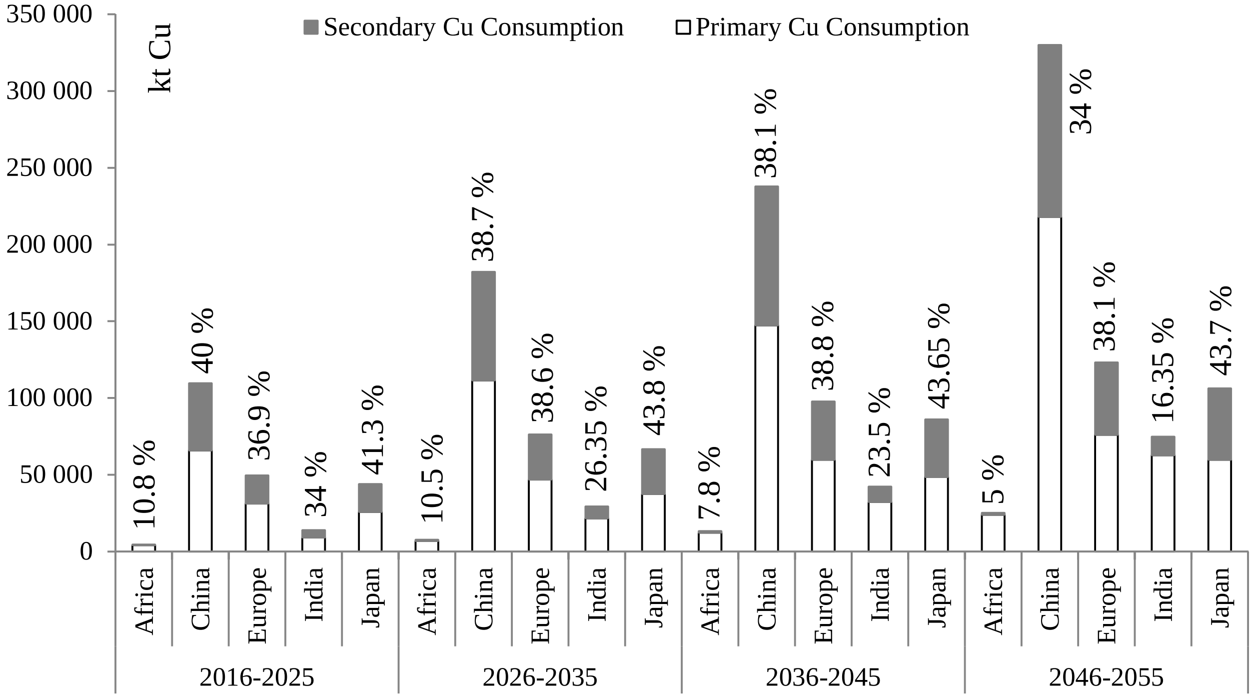
3.3. The time profile of copper recycling

Our results show that the energy transition will require the development of new copper reserves, which allows us to highlight the importance of recycling as a key lever for preserving copper resources.

It is relevant to analyse the evolution of recycling over the coming decades, as it illustrates the mechanisms that can lead to secondary (recycled) copper decreasing as a proportion of total copper consumption over time. Historically, the share of demand covered by recycled copper has decreased (this was the case for instance between 2005 and 2014; Elshkaki et al., 2016). The growth rate of copper demand and its sectoral composition are two crucial elements in understanding the dynamics of recycling. They jointly determine, on the one hand, the composition of copper scraps, which, depending on its source, will be more or less costly to recycle in the future and, on the other hand, the rate at which copper is immobilized in applications with varying lifetime. Thus, a country that experiences a strong growth in copper demand to supply the consumption of dispersive uses runs the risk of seeing the share of its copper demand covered through secondary production decreases over time.

This phenomenon has been quantified by our model and is represented in Fig. 8. It shows the evolution of copper consumption in the 2°C scenario over five decades for several major consuming regions. A distinction is made between the two sources of copper consumed: primary copper and secondary copper from recycling; the weight of recycled copper in consumption is expressed as a percentage on the data labels.

Fig. 8: Evolution and distribution of domestic copper consumption for major consumers (2006-2055)



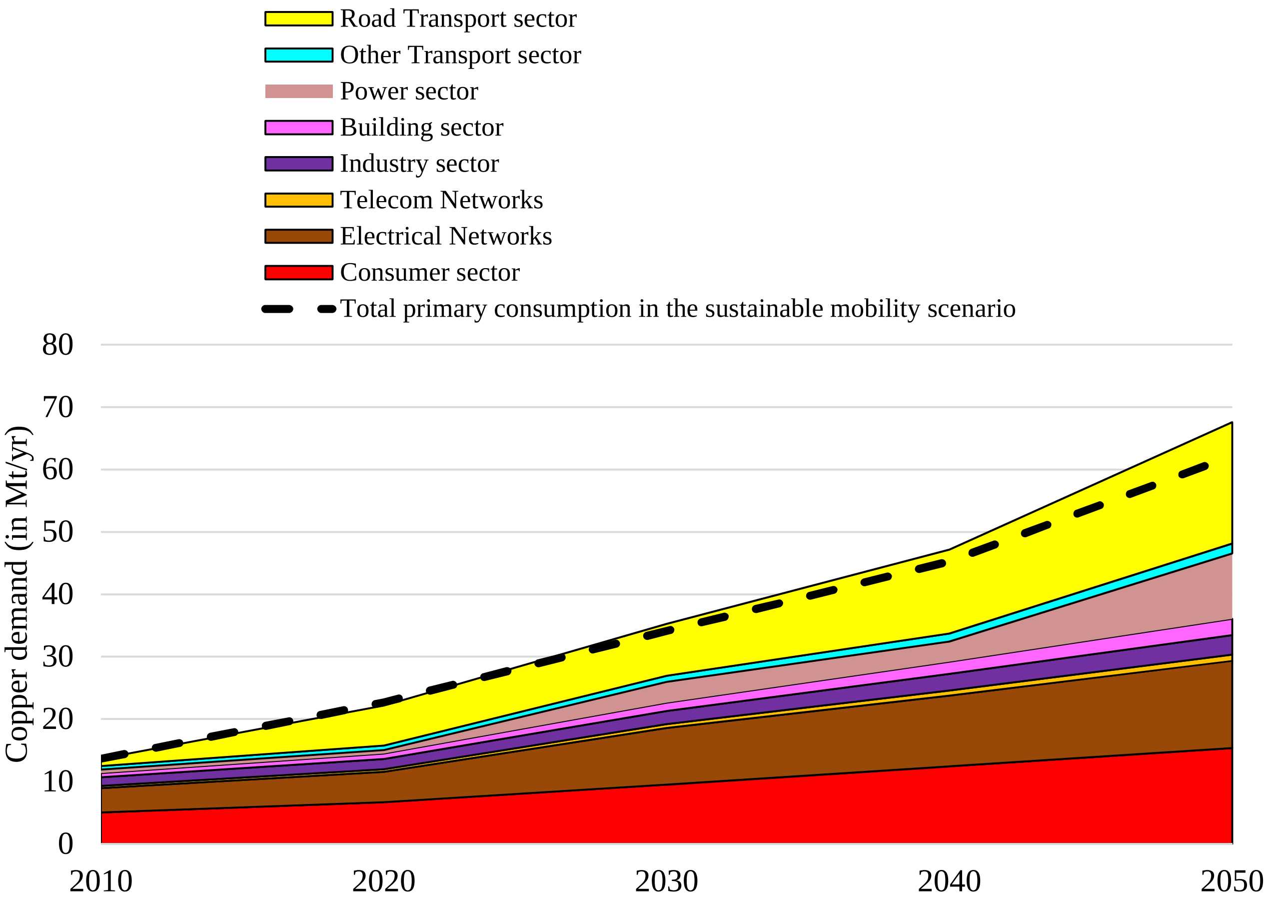
Source: Authors' result

Although recycling practices are calibrated on historical data, the share of recycling in the copper consumption does not remain stable over time because the consumption dynamics of each sector within a country change the available scrap copper stock used for recycling. This is particularly important for countries or regions for which strong economic growth is expected: China and India, and to a lesser extent Africa. Secondary production accounts for the largest share of domestic consumption in these countries during the 2016-2025 decade. Over time, 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 upstream copper recycling sector to reduce their import dependency. Europe and Japan, due to their moderate expected economic growth, are able to maintain relatively stable recycling performance over time, although Europe has a significant margin for improvement compared to Japan in the use of recycled copper.

3.4. Individual vehicles and copper consumption

The transport sector is crucial for the future evolution of copper consumption, as low-carbon vehicles are more copper-intensive than conventional ones. Hence, this sector turns out to be a major emitter of GHGs. The evolution of sectorial consumption has been depicted, all regions combined, in Fig. 9 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 under a more sustainable mobility scenario as defined in detail in §2.3 and in Appendix D. Thus, the area comprised between this dotted line and the upper limit of the copper consumption of the transport sector represents the copper consumption savings achieved through more sustainable mobility.

Fig. 9: Evolution of primary copper consumption in the 2°C scenario, an assessment of the role of road transport

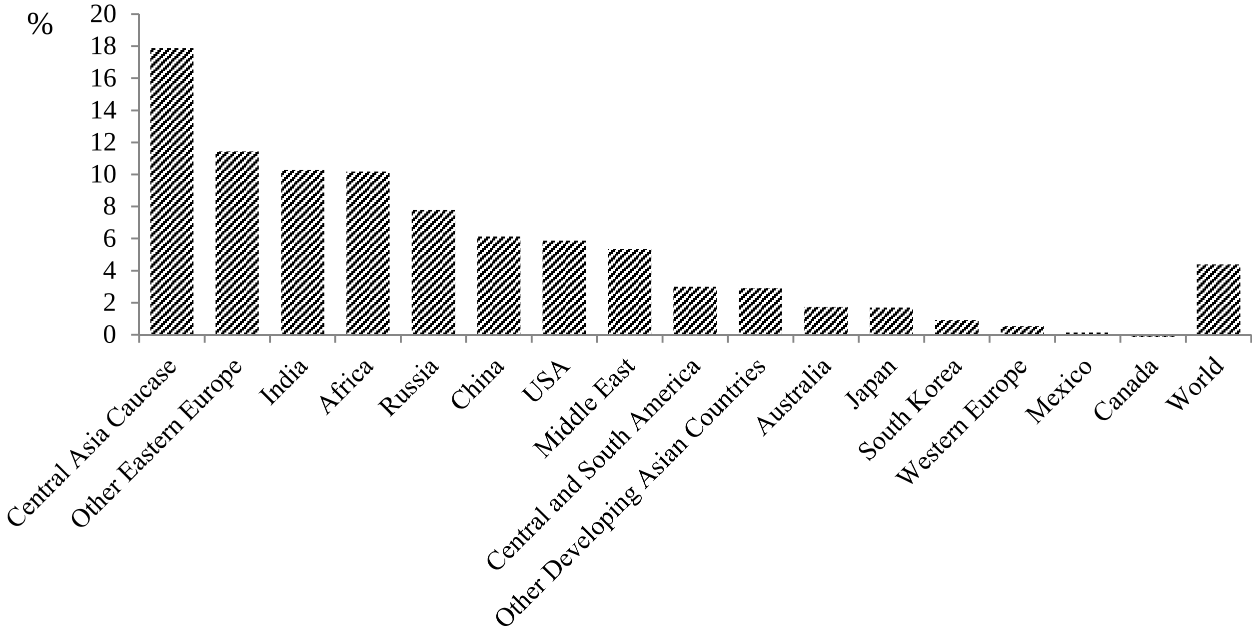


Source: Authors' result

The results indicate that copper consumption will be mainly driven by three sectors: transport, consumer goods and networks. During the period 2040-2050, the impact of power generation sector gets heavier. Of these sectors, only one really is suitable for a public policy strategy that can reduce copper demand 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. Public policies and market forces will in fact make it possible to regulate consumption more effectively than to ration it; the latter being obviously subject to both practical and political limits. Therefore, the road transport sector triggers copper savings: the implementation of sustainable mobility policies would reduce the ecological impacts of mobility while limiting the use of copper resources.

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, the share of reduction in total copper consumption over the period 2010-2055 imputable to sustainable mobility in a 2°C climate scenario when compared to a BAU scenario, has been represented in Fig. 10.

Fig. 10: Share of primary copper consumption avoided through a sustainable mobility scenario (in %), 2010-2055



Source: Authors' result

The results illustrate the impact of a more sustainable mobility policy on the use of copper resources. For most of the countries, it reduces their cumulative copper consumption over the period 2010-2055 by 5% to 18%. Countries for which a sustainable mobility has only a small effect on copper consumption are Western Europe, Mexico, Japan, South Korea, Canada and Australia. This comes from the combined effects of transport policies, socio-economic development along with urban population density evolution. Indeed, most OECD countries around the world have constantly adjusted their transport policies over time through an integrated approach to land use and transport planning, transport pricing (congestion pricing schemes, road tolls), parking restrictions to challenge car attractiveness while providing alternative modes of transport (Hache et al., 2019b). These measures, combined with their (OECD countries) constant urban population density until 2050 have helped reduce car dependency (through, among other indicators, the reduction of the vehicle ownership rate[11]) and therefore, have kept their vehicles stocks constant or slightly declining by switching to other more sustainable modes of transportation. For the other regions, mostly non-OECD, the contrary is observed in the current transport structure. In the case of a BAU mobility scenario they should evolve towards a very high dependence on cars due to a lack of efficient public transport infrastructure. This explains the high share of primary copper consumption saved in these countries for a sustainable mobility scenario. The case of China, India and Other developing Asian countries (ODA) should be highlighted due to the predominance of 2/3-wheelers. Indeed, in a sustainable mobility scenario, a slight switch from cars to this latter mode of transportation will also be observed. Therefore, in the case of China and India for example, due to their importance and combined with more public and non-motorized transport mobility, they can significantly save large quantities of copper. Thus, at the global level, if all regions are implementing policies with the aim of achieving a more sustainable mobility, overall cumulative copper consumption could be reduced by 4.4%.

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[11] The number of vehicles per 1000 inhabitants

IV. DISCUSSION

4.1. Cumulative consumption of copper and the evolving resources and reserves

On the basis of our results, it seems clear that the future growth of the global economy will significantly reduce available copper resources, especially in a low-carbon energy transition scenario. However, predicting the complete depletion of a mineral resource stock is a difficult task that is out of the scope of this article. Indeed, the controversy over the end of mineral resources has generated numerous articles in which two paradigms are opposed (Tilton, 2003; see also Gordon et al., 2006; Tilton and Lagos, 2007; Gordon et al., 2007). The first paradigm is that of geologists using the framework of a fixed stock of resources that decreases with extraction. The criticism of this paradigm is that it is based on data available at time *t*, despite the fact that mineral resource estimates are often revised upwards over the years. This criticism does not concern the method chosen but more specifically the nature of the mineral resource data. The second paradigm which Tilton attributes to economists is that of opportunity cost. He considers that the scarcity of a metal depends on the cost that society is willing to bear to keep on consuming it, and therefore results primarily from the usefulness of that metal. From this perspective, a good indicator of a metal's scarcity is its actual price since it reflects the ability of supply to satisfy demand.[12]

Our approach is halfway between these two paradigms. To our opinion, more than the depletion of resources, it is the risk of a bottleneck in the copper supply chain that matters as it may hamper the deployment of low-carbon technologies. Our results therefore suggest that we should bring our attention to the link between copper resources and the energy transition. A long-term strategy for copper resource management is all the more necessary as market prices do not seem to be able to anticipate the geological scarcity of metals (Henckens et al., 2016). We have also

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[12] Tilton considers, however, that other indicators are useful such as trends in the extraction costs of marginal producers and trends in the user costs (Tilton 2007).

implemented an optimistic scenario for resource development in our analysis. This latter considers that probable but undiscovered resources will be exploitable at current cost. Although very optimistic, this scenario nevertheless it shows that countries, particularly China, will be extremely dependent on imported copper in the years to come (see Fig. 7 and the associated discussion).

4.2. Chile and the growing copper demand risks and opportunities

Our modelling exercise shows that, as in the past, Chile could strengthen its role in copper production by fuelling global demand. In this endeavour, Chile's copper resources are crucial for managing the global energy transition. It would therefore be tempting to conclude that Chile will benefit from accompanying the growing demand for copper. Yet, the copper production sector in Chile is experimenting different natural boundaries of the ecosystem. Thus, the evolution of the Chilean copper sector is directly linked to water resources.

Chile accounted for 27% of world copper mining in 2018 (USGS, 2019). Historically, the country has been a major mining country for many years and this activity has always been associated with significant environmental externalities and, necessarily, a decline in its resources. Figueroa and Calfucura (2003) have quantified the real cost of mining for the Chilean economy by correcting its GDP by: (i) resource depletion and (ii) the associated air pollution. They concluded that the standard GDP calculation overestimates the national income of the mining sector by 31% to 36% over the period 1985-1996. More, the pace of extraction has contributed to reducing the productivity of the copper mining sector in Chile. A study shows that this productivity has decreased over the period 1985-2015 and that 15% of this decrease is attributable to declining ore grades (Villena and Greve, 2018).

However, Chile's macroeconomic situation shows that it is not subject to a resource curse as the development of its mining sector has benefited other sectors, investment, government tax revenues and employment (Medina, 2018). In this context, it is relevant to look at recent developments in the copper sector in Chile and, more particularly, at its impact on water resources. The direction taken by water use legislation indicates Chile's desire to place the evolution of its mining sector on a more sustainable pathway.

Recently the Chilean authority in charge of water management announced a gradual reduction in water extraction permits and a ban on granting new mining licences in areas subjected to some water stress. As an illustration the Escondida mine, the world's largest copper mine, is authorized to pump 1 400 litres per second of water from the ground. Between 2020 and 2030, this extraction rate will have to be reduced to 640 litres per second.[13] In a context of declining ore grades, this reduction is all the more problematic as water is a major resource in ore concentration operations and its use is proportional to the metal content of the extracted ores.[14] In addition, climate change is also a factor that reduces the availability of water resources (Northey et al., 2017). The technical solution chosen to meet the needs of the Chilean mining sector is the use of seawater. Cochilco, the Chilean Copper Commission, which is a government agency, forecasts a 290% increase in the use of seawater between 2016 and 2028 to supply Chilean mines (Cochilco, 2017). Fresh and seawater consumption in the mining industry is expected to almost equalize in 2028. This conversion to seawater of the Chilean mining industry will lead to several challenges. Indeed, Chilean mining sites are generally located in extremely arid areas and at high altitudes. The use of seawater potentially involves its desalination, its transport via pipelines requiring pumping systems, and its integration into mining processes, primarily concentration. A third option is to use partially desalinated water, but this is not yet implemented (Cisternas and Gàlvez, 2018). Indeed, current installations cannot use seawater directly because of its corrosiveness. Desalination would increase the cost due to a higher energy consumption. The direct use of seawater would require adapted facilities which poses new challenges due to the interactions between the chemical elements present in the ore and the seawater. Finally, the cost of using seawater in mines is higher in Chile because of mines' altitude and the higher cost of energy, compared to other mining countries

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[13] https://www.miningweekly.com/article/chile-squeezing-water-rights-for-copper-lithium-miners-in-north-2019-02-21/rep_id:3650

[14] In Chile, 71% of the water used in the copper industry is dedicated to ore concentration operations (Cisternas and Gàlvez, 2018).

(Cisternas and Gàlvez, 2018.). The evolution of the Chilean mining industry is therefore at the heart of a nexus between energy, water and ore grades that could compromise its ability to supply global copper demand at a competitive cost.

4.3. The Chinese strategy on the copper sector

Regarding demand, our results show the importance of China's future copper consumption. The country is heavily dependent on copper imports[15] and our results suggest that this dependence will increase in the coming decades. While the deployment of low-carbon technologies will further increase this dependence, so will the "Made in China 2025" strategy implemented in 2015 by the Chinese Government. It aims at developing the country's production capacities in innovative industries (artificial intelligence, robotics, low-carbon technologies such as solar, wind and storage, new materials, etc.). This strategy illustrates China's desire to develop its export capacities for high-value-added goods

Securing the supply of metals, particularly copper, seems to be a priority for the government. Chinese Foreign Direct Investments (FDI) are highly regulated by the government and generally respond to its strategic priorities (Andreff, 2016). The role of the mining sectors is one of the government's priorities, as illustrated by the fact that in 2004, 53% of Chinese investments abroad targeted these sectors (Pamlin and Baijin, 2007). Between 2005 and 2018, according to the Investment tracker[16] of the American Enterprise Institute, China spent more than 175.55 billion dollars cumulatively in the metals sector (mining and refining), representing more than 9 % of total Chinese investments (Fig. 11). Some recent transactions indicate an expansion of Chinese economic power in the copper sector.

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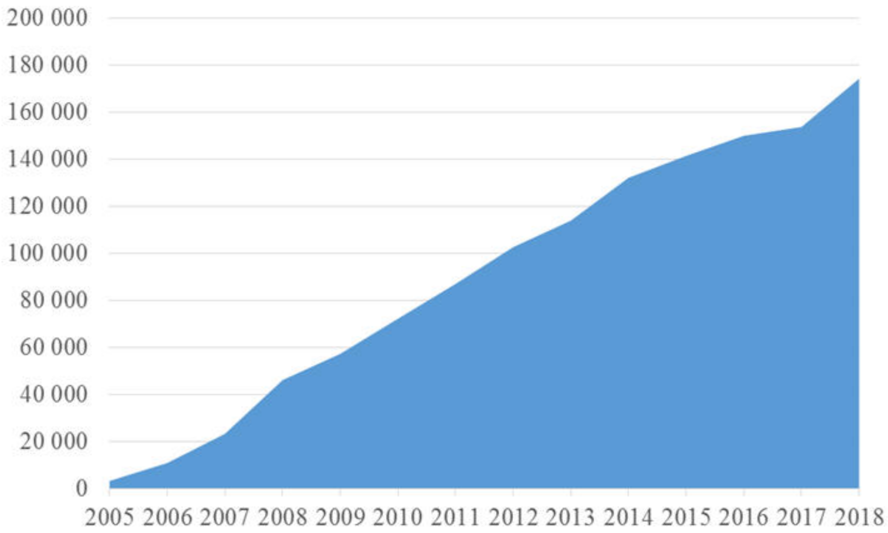
[15] According to the UN Comtrade data, China accounted for 44% of world imports of crude copper and 31% of world imports of refined copper in 2015.
[16] American Enterprise Institute, http://www.aei.org/china-global-investment-tracker/.

Fig. 11: Chinese Investments (in millions US $)



Source: Investment Tracker

This is the case, for example, of the $1.3 billion investment in 2018 to expand the Peruvian Toromocho mine with the objective of increasing its production by 45% by 2020. These investments abroad meet the dual objectives of securing copper supply and reducing domestic pollution related to its production and refining. Indeed, the greening of the mining sector is one of the objectives set out in the government's 13th Five-Year plan and it involves a profound transformation of the Chinese mining sector that will have global consequences because of its status as the largest consumer and refiner of the red metal (Li et al., 2017).

V. CONCLUSION

We assess the criticality risk for copper in the context of the energy transition. For the first time, 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 transport sector. The primary interest of our modelling 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. Our scenarios demonstrate that in 2055, 82.7% of the copper resources known in 2010 will have to be extracted from the ground in a 4°C scenario and 96.1% in a 2°C scenario. These results show that the rate of increase in world copper consumption should pressure the 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 could have an impact on the energy transition process and therefore underlines the importance of policies to smooth future demand trends. China and Europe should become highly dependent on external sources. In addition, Central and South America provide a significant portion of copper production to meet the additional demand resulting from the energy transition. While our scenario shows the importance of the copper resources held by Chile and Peru, it does not eliminate uncertainty about the ability and willingness of these countries to continue to increase their copper production capacities, particularly due to environmental externalities (local pollution) caused by the exploitation of the ore produced. Two public policy options are therefore being considered to reduce the copper demand rate of growth: strengthening recycling capacities and accelerating sustainable mobility policies. With regard to recycling, our results highlight the importance of strengthening copper recycling channels now without waiting for the 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 sectorial 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 could be to implement sustainable mobility policies to reduce the demand for low-carbon and copper-intensive passenger vehicles. It can be supported by strong transport policies aiming at reducing car dependency and promoting the use of alternative modes of transport (walking, cycling, shared mobility and public transport). While at the global level, the copper savings may seem minor, this strategy may be important for some countries. Indeed, several regions of the model such as India, Africa, other East European countries or Central Asia and Caucasia can reduce their cumulative consumption of primary copper by more than 10% over the period 2010-2055.

Other perspectives of our global model as further research on raw materials would be then to implement and analyse the impact of other strategic materials (nonferrous metals such as cobalt, nickel and rare-earth metals such as neodymium, terbium, lanthanum, etc.) either in transport or in the power sector with the increasing deployment, respectively, of Electric Vehicles (EVs) and Renewables Energy Technologies (RETs). Indeed, this new global energy model could be very useful as a good decision-making tool to better understand investments in low-carbon technologies based on future raw material market constraints for better sectorial assessment. ■

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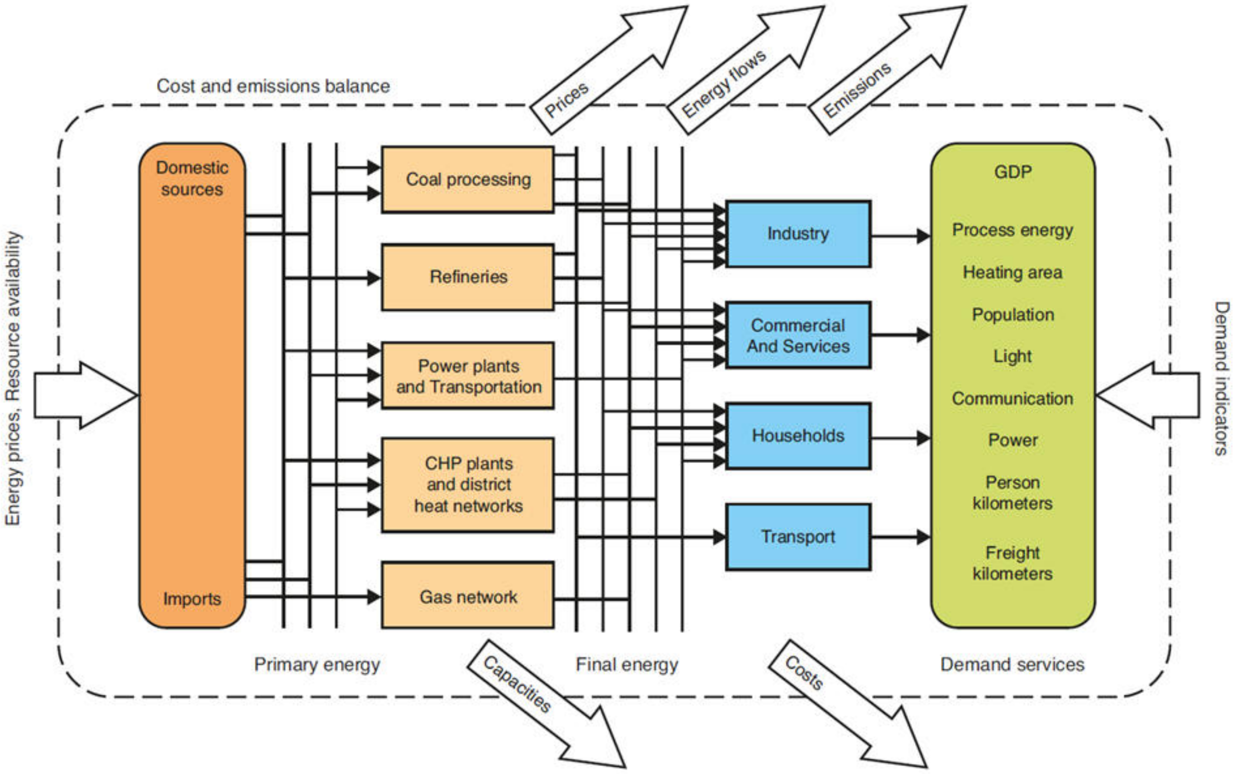
SUPPLEMENTARY MATERIALS

Appendix A: Presentation of the TIAM-IFPEN model

The TIAM-IFPEN offers a detailed representation of the technological structure of the energy system. The existing and future technologies in the sectors ,over a given time horizon, are associated 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 (**Fig. 12**) divided in 16 regions (**Table 2**). Each region can carry out exchanges of fossil resources, biomass or materials. The long-distance trade between the regions has been endogenously modelled 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. 12: Simplified view of the TIAM's Reference Energy System



Source: Remme and Jussi, 2001

All energy services demand projections have been done considering macroeconomic drivers such as the GDP, the population growth, etc. (Statistics/outlook of the IMF results from GEMINI-E3 or GEM-E3 macroeconomic models). All assumptions related to regional fossil fuel reserves and trade capacities have also been implemented along with the regional renewable energy potential (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 (see Hache et al., 2019b for more details). 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[17], long-term investigation for large-scale low-GHG energy diffusion in Africa using TIAM-ECN[18] (Van der Zwaan et al, 2018) or the decarbonisation of road transport using TIAM-UCL[19] (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 2: 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

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

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

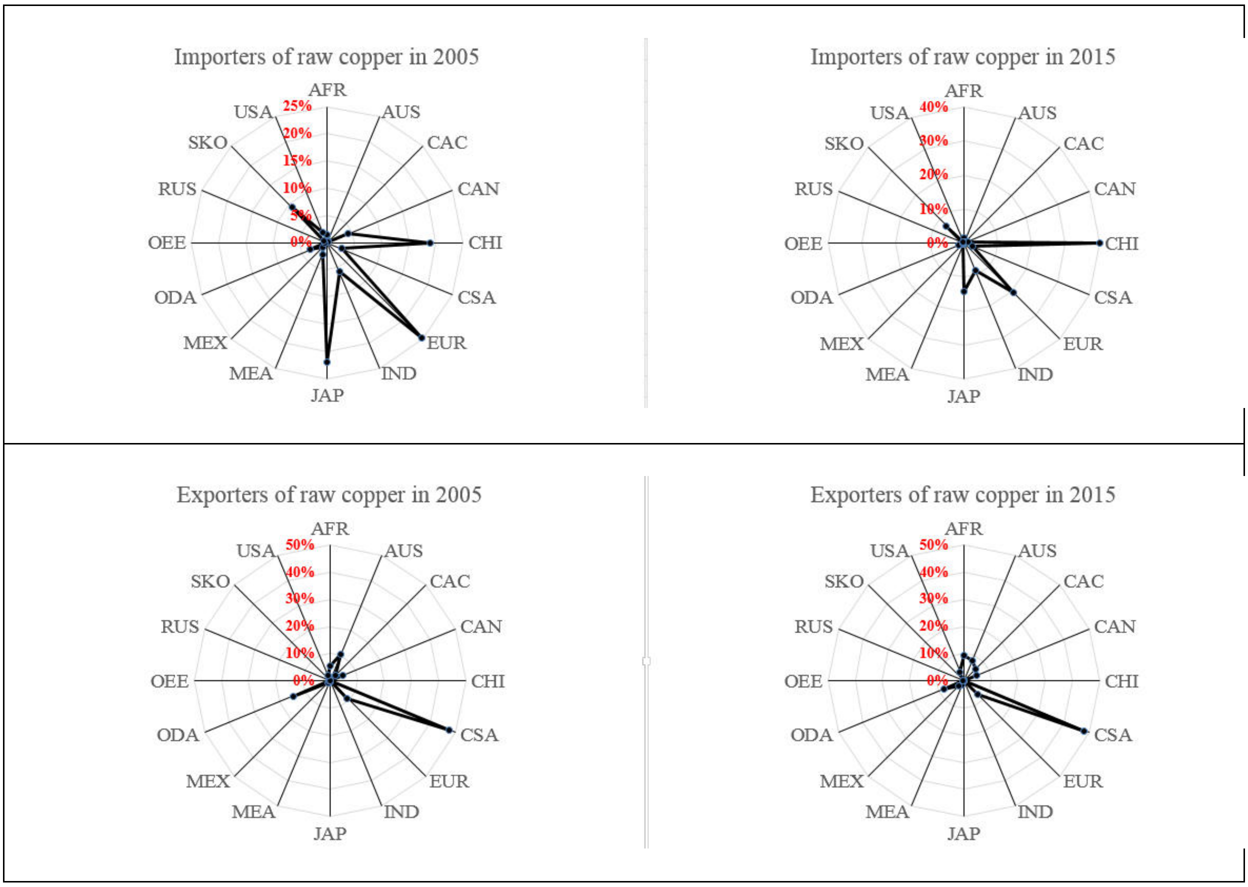
[19] This version of TIAM has been developed at the University College of London (UCL) through the UK Energy Research Centre (UKERC).

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)

Appendix B: international trade of copper

The evolution of raw copper trade between 2005 and 2015 is depicted in **Fig. 13**. 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 and Peru) dominates the exports of raw copper, reflecting its high reserves of copper.

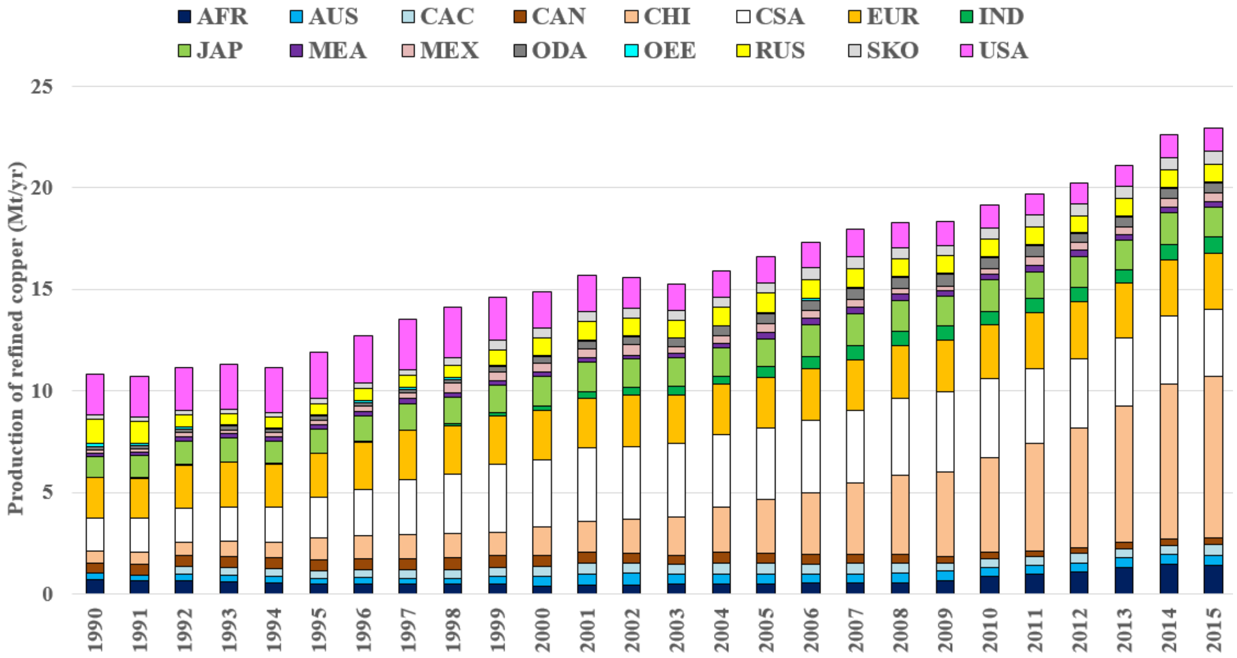
Fig. 13: Distribution of raw copper imports and exports (in % of the global monetary value) for the years 2005 and 2015



Source: Resourcetrade.earth

The annual production of refined copper disaggregated by region over the 1990-2015 period is represented on the **Fig. 14**. 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.

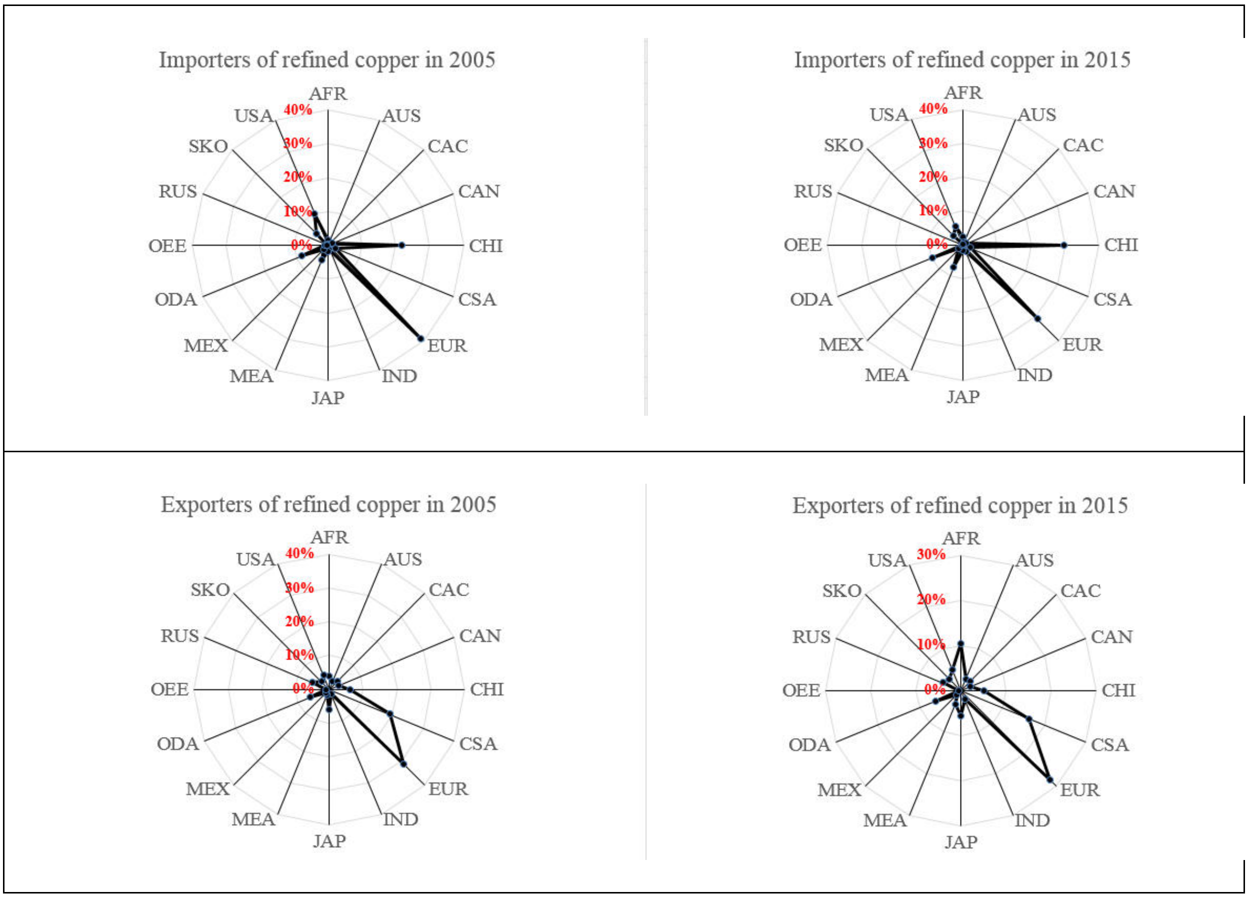
Fig. 14: Production of refined copper (Mt/yr)



Source: 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 in **Fig. 15**. 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. 15: Distribution of refined copper imports and exports (in % of the global monetary value) for the years 2005 and 2015



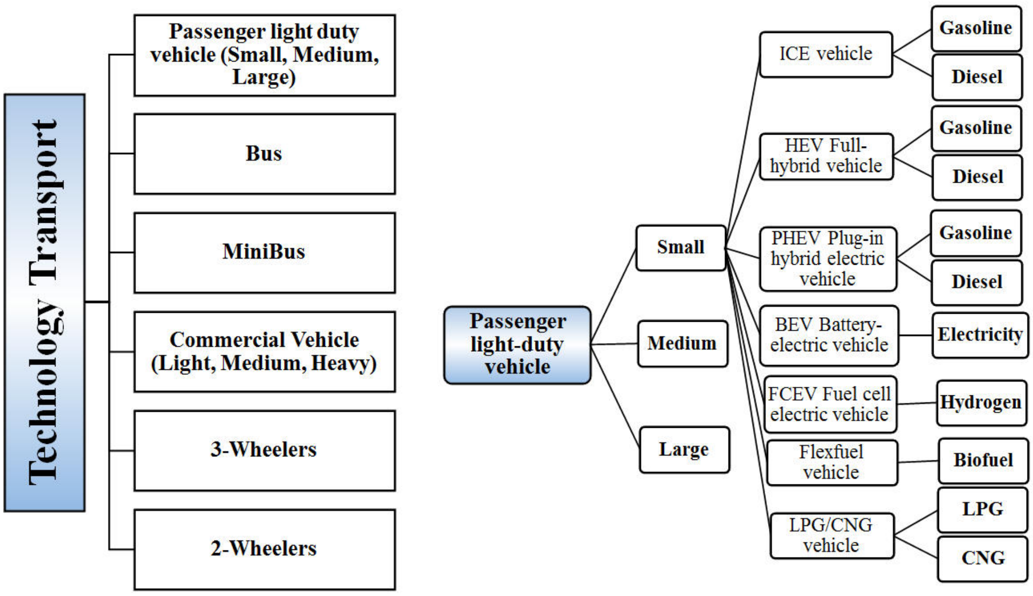
Source: UN Comtrade

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 extent, 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 C: presentation of the road transport

The road transport sector has been disaggregated in passenger light-duty vehicles (PLDV) (small, medium and large size), buses, minibuses, commercial vehicles (CV) (light, heavy and medium trucks) and 2/3-wheelers (**Fig. 16**). The existing and future vehicles have been implemented with their techno-economical parameters. For all technologies across the 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[20] and FSIM[21] models developed by IFPEN. The copper content has been implemented in each technology segment.

Fig. 16: Overview of the road transport technologies in TIAM-IFPEN model



In the power sector (**Fig. 17**), a wide range of fossil-based and renewable 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

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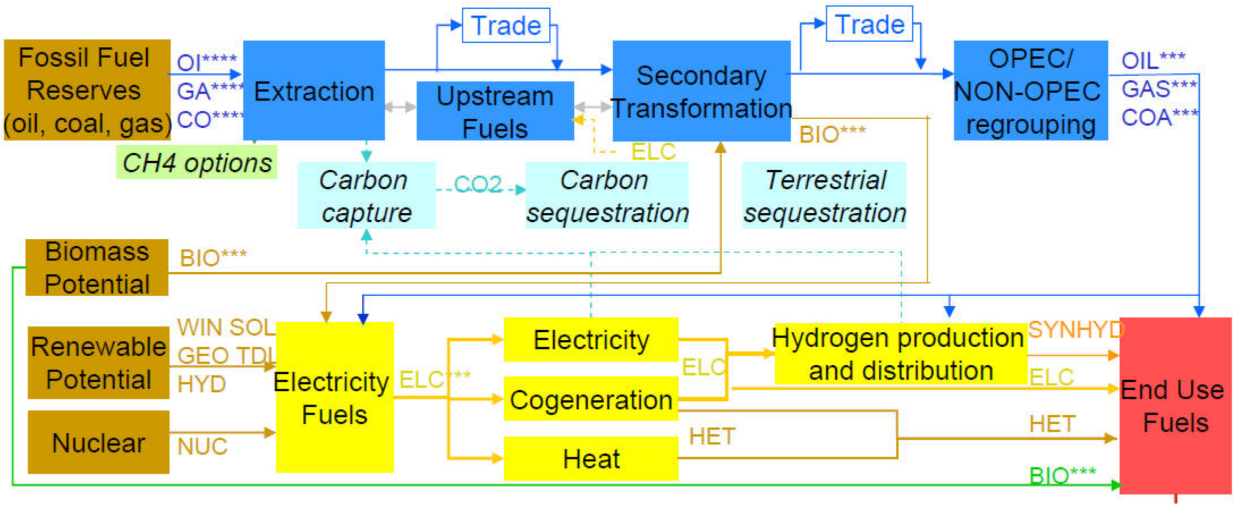
[20] BEAVeR (Economic and Life-Cycle Assessment of road vehicles) model is a TCO model which allows calculation and comparison of ownership and usage costs for various road vehicles, whether private vehicles, utility vehicles, buses or heavy trucks

[21] 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

taken from the World Energy Outlook 2018 (IEA, 2018), IRENA (IRENA, 2018) and the European Commission database. Electricity grids are not explicitly modelled 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 of America and Canada) to consider this in further development of the model.

Fig. 17: Overview of the power sector in TIAM-IFPEN model



Source : Loulou et Labriet, 2008

Appendix D[22] : Mobility scenarios

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).

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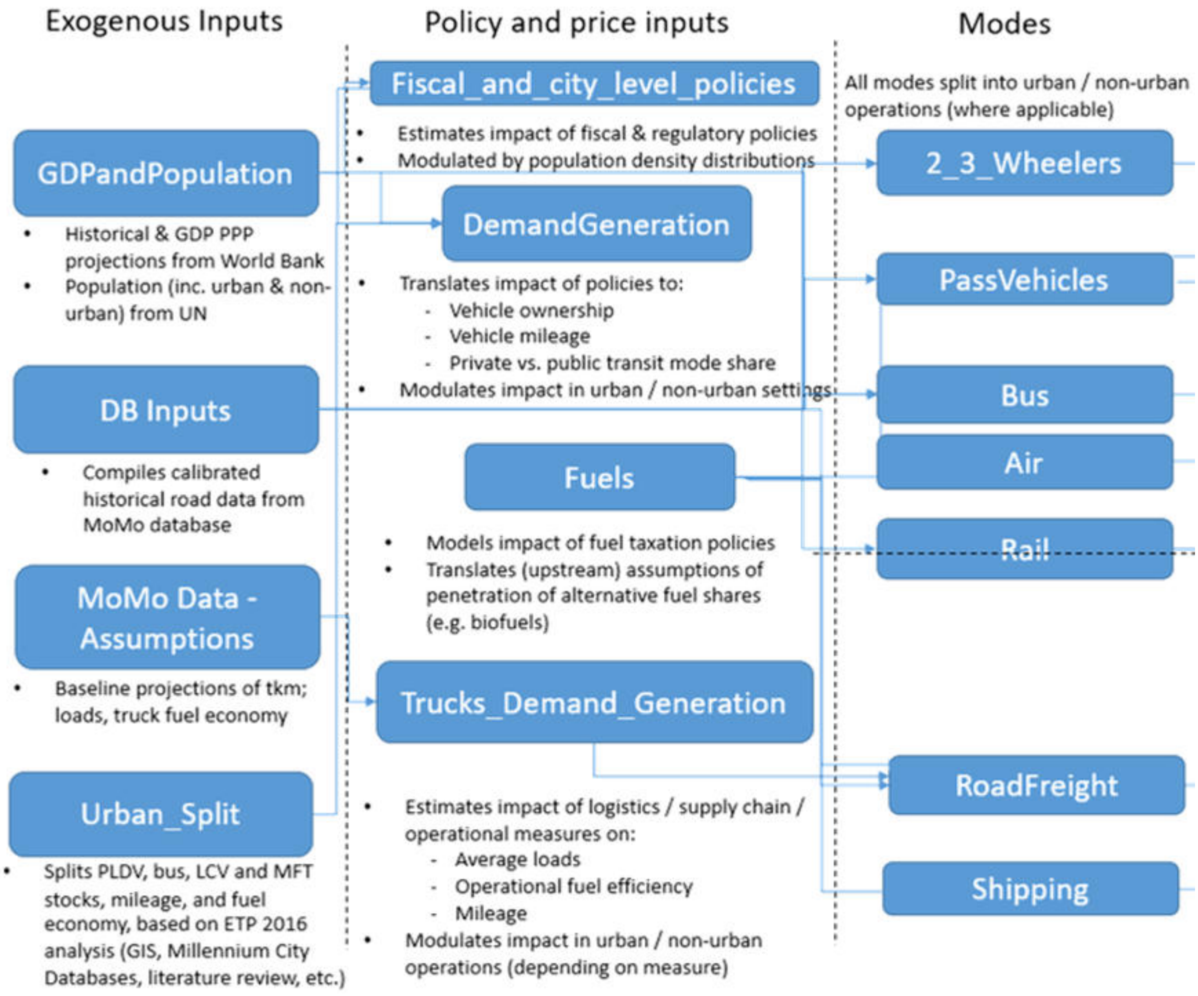
[22] Hache et al., 2019b

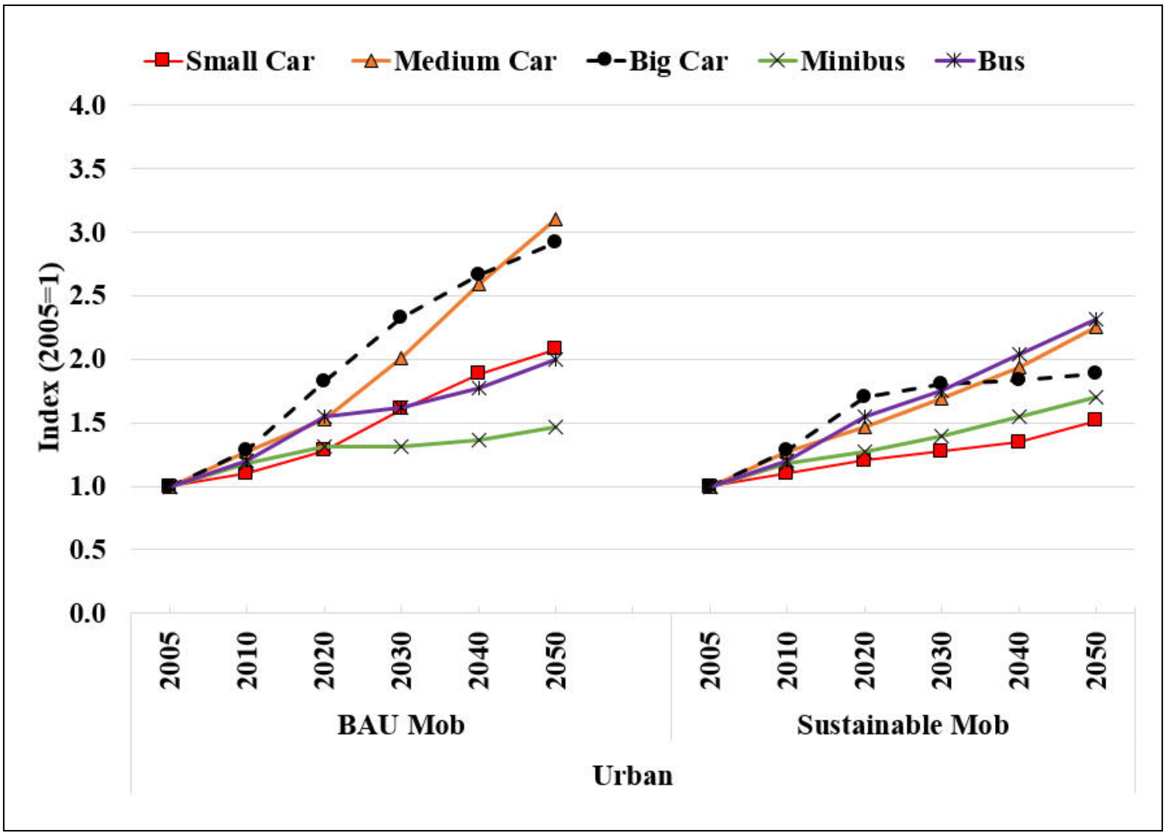
Fig. 18 : The network of spreadsheets of the IEA Mobility Model (MoMo model)

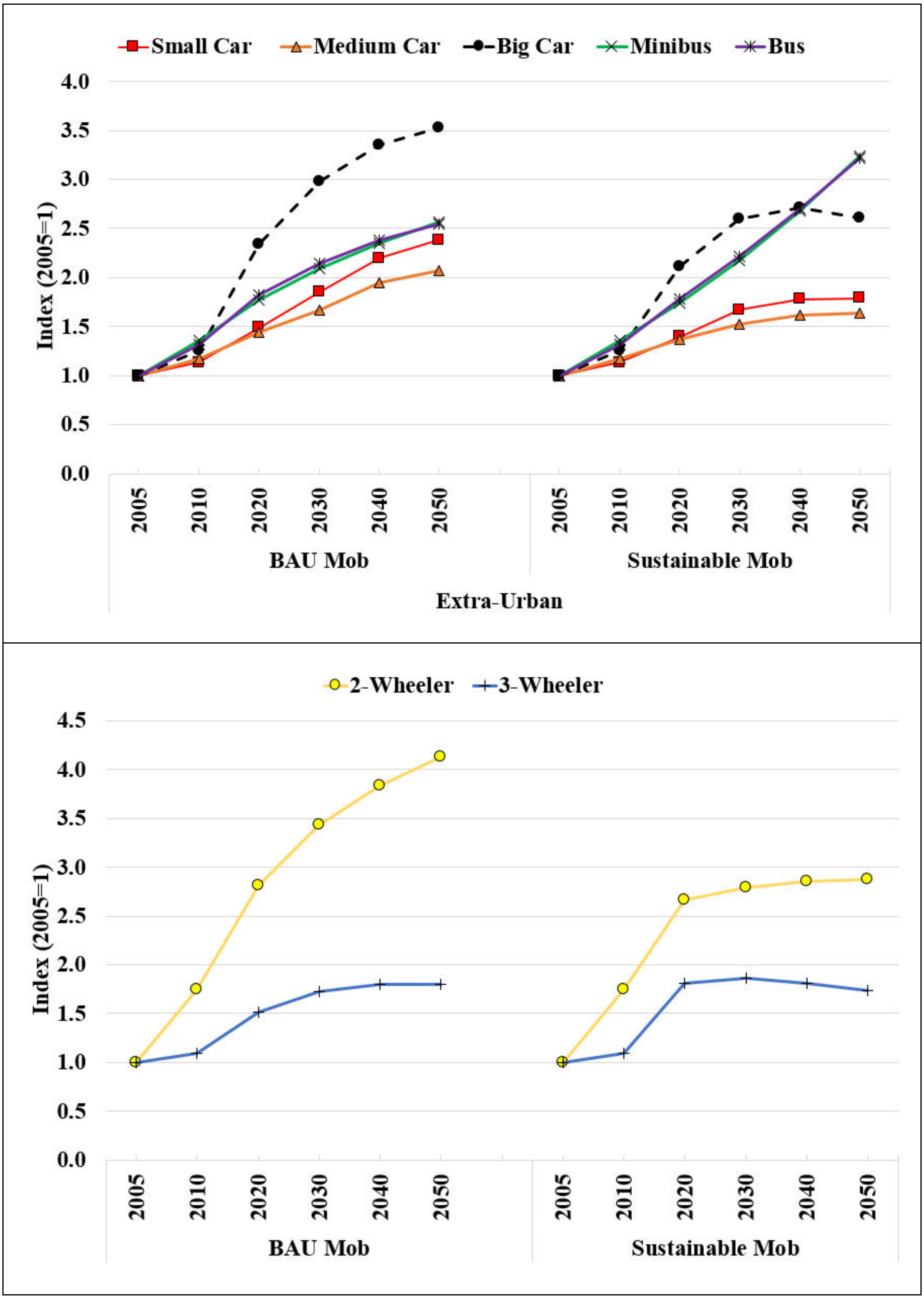


Source: IEA Mobility model

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. 18. As seen in Fig. 19, 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 aims to contribute to the transport policy literature by modelling the implications of different forms of mobility along with climate constraints, firstly on car fleet evolution and secondly on the regional copper needs in regard to the resource availability in the future.

Fig. 19 : Evolution of the two different shapes of mobility (BAU and Sustainable) with the travel mode (urban and extra-urban)





Source: IEA Mobility model

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