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Copper at the crossroads: Assessment of the interactions between low-carbon energy transition and supply limitations[☆]

Dr. Gondia Sokhna Seck^{a,*}, Dr. Emmanuel Hache^{a,b,c}, Dr. Clément Bonnet^a,
Marine Simoën^a, Samuel Carcanague^b

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Abstract

This article aims to assess the impact of copper availability on the energy transition and to determine whether copper could become critical due to the high copper content of low-carbon technologies compared to conventional technologies. In order to assess copper availability through to 2050, we rely on our linear programming world energy-transport model, TIAM-IFPEN. We examine two climate scenarios (2°C and 4°C) with two mobility shape, 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) is likely to significantly increase copper demand by 2050. In order to investigate how tension over copper resources can be reduced in the energy transition context, we consider two public policy drivers: sustainable mobility and recycling practices. Results show that in the most stringent scenario, the cumulative primary copper demand between 2010 and 2050 is found to be 89.4% of the copper resources known in 2010. They also pinpoint the importance of China and Chile in the future evolution of the copper market.

Keywords: Copper; Bottom-up modelling; Energy transition; Transport sector; Power sector; Recycling

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 67 49.

E-mail address: gondia-sokhna.seck@ifpen.fr

32

33 1. Introduction

34 The issue of mineral resource dependency is a relevant illustration of the challenges the world is
35 likely to face in the energy transition process. Many studies [1][2][3]underline the need to take
36 these constraints into account in the dynamics of the global energy transition, and especially the
37 location of resources, the organization of industrial markets, and actors' strategies. As Kolotzek
38 et al. [4] pointed out, criticality assessments are intended to cover many dimensions of interest,
39 which are usually vulnerability and supply risk based on economic concerns [5][6], geopolitical
40 concerns (the case of the rare earth elements (REE) production concentrated in China is a perfect
41 illustration), geological or technical concerns [7][8] sometimes extended to cope with
42 environmental impacts [9][10] or social implications [11][12]. This can be even more complex as
43 it can also depend on the scale of the analysis (i.e. the micro level (industrial sector or enterprise),
44 the macro level (countries) or the global level), on the chosen geographical scale (lithium is
45 considered critical in the US but not in the European Commission's list of critical materials), on
46 the time scale i.e. how long or short-term the assessment is made over (chromium was critical for
47 the European Commission in 2014 but not in 2017) [13].

48 Whereas economic literature generally focuses on lithium [14][15][16][17], cobalt [18]and rare
49 earths [19][20][21]to illustrate the systemic impacts of the energy transition on raw materials, this
50 shift will also potentially impact the major non-ferrous metal markets (copper, nickel, zinc, etc.),
51 as well as steel, cement, aggregates and water sectors [22]. Several economists and geologists
52 have focused on copper, as evidenced by articles and responses by Tilton[23][24], Gordon et al.
53 [25], Tilton and Lagos [26], Gordon et al. [27] and more recently Vidal [28] on the subject of
54 copper criticality. According to the International Copper Association [29] around 35% of copper
55 has been used for electrical power & power utility in 2017 and this share could increase with the

56 deployment of renewable energy technologies. In the context of the energy transition, and
57 because copper is used in many applications in the transport and power sectors, this raw material
58 appears to be an interesting case study on criticality issues. Therefore, it is necessary to integrate
59 raw material supply chain in long-term energy models in order to take into account the supply
60 limitations on resources for low-carbon technologies needed to shape future energy transition.

61 The current dearth of diversity in the raw material supply chain along with the rapid deployment
62 of all decarbonisation and digital innovations required in the short to medium term, to meet more
63 stringent environmental constraints and economic growth, raises concerns about the feasibility of
64 meeting short-term roll-out targets [30]. Since many important countries (such as China) are less
65 and less interested in exporting strategic raw material and more and more constrained by their
66 internal consumption [31], many importing countries have considered resource supply limitations
67 as a priority by formulating raw material strategies (Europe is a perfect illustration
68 [32][33][34][35]. Raw materials supply risk and criticality have been widely discussed over the
69 last two decades as said Hache et al.[17], although the concept of “raw material criticality” has
70 been firstly introduced in 1939 by the US government for common defence, industrial demands,
71 and military commitments within a geopolitical context to analyse uncertainty on relevant
72 materials availability [36]. They found more than 2000 articles published on the issue of material
73 criticality with nearly 80% of which since 2010. Moreover, an extensive part of the first literature
74 was devoted to rare-earth elements (REEs) criticality, although in recent years an increasing
75 number of metals have been studied.

76 With the multiple alternative pathways which are under studies to achieve the objectives of the
77 Paris agreement, it is also necessary and valuable to assess the growing need for raw material in
78 low-carbon technologies, as well as their impacts on the environment. Therefore, long-term

79 energy analyses may not be relevant or may have to be re-evaluated if possible future constraints
80 on material supply are not taken into account by energy modellers and policymakers.

81 According to the review literature, the existing approaches or methods related to the analysis of
82 raw material demand could be gathered into two categories.

83 1.1. The first category of existing approaches or methods based on past analysis of raw
84 material flows

85 On the one hand, the first category relies on the detailed analysis of past raw material flows to
86 identify historical patterns or snapshot analysis within material flow analysis (MFA) or life cycle
87 analysis (LCA) to quantify the environmental sustainability. Material flow analysis (MFA) is a
88 common analytical tool to characterize material stocks and flows within national, regional, and
89 global boundaries. At a city scale, Sörme et al. [37] and Zhang et al. [38] described and estimated
90 the copper-in-use stocks in 1995 in Stockholm and in 2009 in Nanjing, respectively, while van
91 Beers and Graedel [39] conducted the same approach at Inner Sydney, Sydney Metro, all
92 Australian states/territories, and Australia itself at the beginning of the century. At the contrary of
93 a "snapshot" of a system in time as in previous articles, many authors have described the
94 behaviour of a system over a time interval using the dynamic material flow analysis (D-MFA). It
95 has been also used to estimate the amount of copper in-use stocks or scrap generation at different
96 spatial scales. This approach has been conducted at a national and regional scales e.g. China
97 [40][41][42], North America [43][44][45][46], Europe [47][48], or at a global scale [49]. A time-
98 series Life Cycle Assessment (LCA) approach to examine the historical environmental impacts
99 associated with copper mining and smelting in the five largest Australian copper mines from
100 1940 to 2008 has been done by Memary et al. [50]. They explored the usefulness of LCA for
101 assessing the impacts of the mining and minerals processing industry over 70 years by
102 incorporating changes in ore grade and differences in technologies and regional energy sources.

103 Song et al. [51] and Jingjing et al. [52] have conducted comparative analysis on copper based on
104 LCA approach in Norway and China. The former assessed the environmental impacts of a
105 Norwegian copper ore mine and identify significant environmental hotspots at the plant level, and
106 then to compare the impacts of alternative energy and tailings management options in relation to
107 the overall environmental performance of the mine. These studies have provided valuable
108 information for scientific literature in exploring the historical patterns of the copper in-use stocks
109 which is useful for extrapolating future stocks. They have been helpful to better understand
110 copper supply chain and prepare long-term criticality mitigation strategies.

111 1.2. The second category of existing approaches or methods based on prospective analyses of
112 raw material demand

113 On the other hand, the second category relies on prospective analyses of raw material demand i.e.
114 the assessment of possible future growth of raw material along with energy transition. It could be
115 subdivided into four main sub-categories.

116 The approach of the first sub-category is based on the analysis of possible future evolution
117 considering past trends or assuming expected growth rates based on experts' opinion. Few
118 decades ago, there have been studies on the long-term demand for copper, such as Fisher et al.
119 [53], Rohatgi and Weiss [54] to estimate the future demand of copper in 1980 and 1990 using an
120 econometric model. Schipper et al. [55] employed and compared two methods to estimate future
121 copper demand by 2100: a regression-based method where the future trend is extrapolated from
122 the estimated relationship on the basis of empirical data from the past, and a stock-dynamics-
123 based method which starts from the stock of applications, and calculates demand as a derivative.
124 In the same vein, Halada et al. [56] also developed a model of per capita correlations of the state
125 of decoupling of various metals (e.g. copper) to estimated growth of so-called BRICs (Brazil,
126 Russia, India, China) and the original G6 countries (Japan, USA, UK, France, Germany, Italy) to

127 estimate the consumption of these metals until the year 2050. Elshkaki et al. [57] also analysed
128 the demand, supply, and energy implications related to copper production and use over the period
129 2010–2050 from the analysis of the historical demand for copper from 1980 to 2010 using
130 regression analysis with per capita GDP, the level of urbanization, and time as explanatory
131 variables. After modelling the dynamics of copper production with a prey-predator approach
132 linking the evolution of reserves to that of industrial wealth, Vidal et al. [58] simulated the future
133 demand by 2200 based on assumed evolutions of world population and gross domestic product
134 per capita. Through a dynamic material flow analysis, Zhang et al. [59][60] extrapolated future
135 stock and demand of China by 2050 based on past patterns of the copper in-use stocks. Habib et
136 al. [61] analysed the geopolitical supply risk and the geographical transition trend of global
137 primary production of REE in 86 different countries from 1994 to 2013, and further projected this
138 transition in future i.e., 2050 by using the global distribution of current known geological
139 reserves (2014) of metals as representative of their global primary production share by countries
140 in 2050. On the contrary, in order to identify vulnerabilities for REE-consumers and to propose
141 ways to address the environmental impacts of REE mining, Dutta et al. [62] assessed the future of
142 REE supply chains up to 2020 reflecting an anticipated growth in demand of 5%. Their
143 assumption followed Roskill's estimates of global trends in supply and demand for rare earths
144 found in Rollat et al. [63], who also assumed a similar trend in forecasting demand for rare earths
145 in Europe by 2020.

146 The second sub-category gathers studies which use prediction models for exhaustible resource
147 production such as bell-shaped curve-fitting models. Among them, the Hubbert model and the
148 generalized Weng model are the most influential, as they have been widely used in the field of
149 exhaustible resource peak production prediction [64]. Wang et al. [64] and Wang et al. [65] used
150 the Hubbert model and the generalized Weng model, respectively, to predict long-term rare earth

151 production, although they only focused on China. Roper [66] used empirical Hubbert-like
152 functions for assessing copper, zinc and lead mining rates and estimated when the production
153 would peak as also done by Laherrere [67] for copper. On the other hand, Wang et al. [68]
154 analyse the global rare earth production in the long term using the Richards model which has
155 similarities with the two previous models.

156 The two last sub-categories, in contrast, rely more on the assessment of future raw material
157 demand using long-term energy models. In other words, the interaction can be seen as a multi-
158 model, where a group of models co-evolve and interact with each another in a dynamic
159 environment [69]. Indeed, the third sub-category is based on using the outputs from a long-term
160 energy model or specific road mapping process as inputs into dynamic raw material demand
161 assessment. Several studies have been done using this approach in line with the prospective
162 scenario generated by energy system models or government's goals. Kuipers et al. [70] conducted
163 a Life Cycle Sustainability Assessment (LCSA) methodology for assessing potential
164 environmental implications related to global copper demand scenarios by combining a life cycle
165 approach with metal demand scenarios for the period 2010–2050. They considered the
166 International Energy Agency (IEA) World Energy Outlook (2012) energy scenarios and
167 incorporated them into the LCA model to account for developments in the background energy
168 supply mix from 2010 to 2050. Hertwich et al. [71] developed an integrated hybrid LCA model to
169 estimate the future copper requirements by 2050 of the wide-scale global deployment of different
170 low-carbon electricity generation technologies as foreseen in the International Energy Agency's
171 (IEA) BLUE Map scenarios (IEA, 2010). Likewise, McLellan et al. [72] estimated the potential
172 future copper production and potential for both secondary (recycling) and primary production
173 expansion by defining extrapolated expansion rates of clean energy technologies from 2010 to
174 2050 from the analyses of IEA data. Their study just focused on three clean energy technologies

175 (PV, wind and fuel cells), and not all available technologies. Kalvig and Machacek [73] assessed
176 whether the global REE supply can keep pace with the REE demand for the expanding offshore
177 wind energy sector through demand scenarios based on the estimates of GWEC up to 2030 while
178 Imholte et al. [74] did the same work by assessing the U.S. REE availability for supporting the
179 U.S. wind energy growth targets based on annual U.S. wind installation targets up to 2030
180 established by the US Department of Energy. Other articles were more focused on raw material
181 demand driven by future transport electrification or residential buildings. Among them, Habib et
182 al. [75] estimated the future global demand of copper for passenger vehicles regarding growth of
183 transport electrification which have been taken from three different scenarios run through the
184 Integrated Model to Assess the Greenhouse Effect (IMAGE) , while Deetman et al. [76] and
185 Marinova et al. [77] focused on the in-use stock of raw material (Steel, Concrete, Wood, Copper,
186 Aluminium, Glass) in residential and service buildings towards 2050 by translating material
187 intensities per square meter into material stock using the total useful floor area specified for 26
188 world regions, as projected by the IMAGE model.

189 For the last and fourth sub-category where the raw material supply chain and LCI metrics have
190 been integrated as inputs and constraints into prospective energy models, it has been noticed that
191 fewer studies have been found in scientific literature. Some recent studies considered this
192 approach; however, they were in majority covering rare-earth elements and their environmental
193 implications, and few on other raw materials. Schandl et al. [78] analysed whether well-designed
194 policies can reduce global material and energy use, and carbon emissions, with only minimal
195 impacts on improvements in living standards. Their analysis are based on a novel modelling
196 architecture employing a soft-link between three models as one: a top-down integrated climate
197 and economy model (GIAM) [79], a global, multi-regional technology-based physical stocks and
198 flows model (MEFISTO) [80], and a global multi-regional input–output model (Eora) [81].

199 Alonso et al. [82] presented a top-down analysis of rare earth flows in order to identify the
200 conditions where REEs may experience unprecedented demand growth, and assess the
201 implications of co-mining on rare earth availability under rapid demand growth in specific
202 industries. In particular, resource requirements for electric vehicles (EVs)¹ and wind turbines
203 were estimated from performance specifications and vehicle sales or turbine deployment
204 projections. Still, at a country level, Wang et al. [83] construct a computable general equilibrium
205 (CGE) model to investigate the market impacts of environmental regulation on the production of
206 rare earths in China. Likewise, Ge et al. [84] constructed a dynamic computable general
207 equilibrium (DCGE) model to forecast the production, domestic supply, and export of China's
208 rare earths in 2025. These studies considered this approach, notwithstanding they were only top-
209 down models. This type of models describes the interactions between different agents (e.g.,
210 households, producers, and the government), representing flows of goods and services in a
211 market-based economy [85]. The use of production functions and no explicit representation of the
212 different technologies limit the detailed technological study. Moreover, technical progress is
213 isolated from innovations in the energy sector. However, we can also pinpoint the work done by
214 Northey et al. [86] where they modelled mined copper production using the 'Geologic Resources
215 Supply – Demand Model' (GeRS-DeMo) [87]. By listing all mines, including their ultimate
216 recoverable resource and production and applying supply-demand parameters, GeRS-DeMo
217 models the cumulative production over time [88]. Nevertheless, the authors pinpointed one of the
218 limitations in applying this kind of supply focused model like the geRS-DeMo is their myopic
219 insights into the future available options to meet the cu demand, and thus the need for coupling

¹ Electric vehicles include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel-cell electric vehicles (FCEVs). In this article, our transport module covers passenger light duty vehicles (PLDVs), Light, Medium and Heavy Commercial Vehicles (LCVs, MCVs and HCVs), Buses, Minibuses and two- and three-wheelers.

220 with material flow analysis. Currently to the best of our knowledge, no paper has been found in
221 future raw material demand with an approach using a bottom-up long-term energy system
222 optimization models. In this context, this article contributes filling the gap identified in the
223 scientific literature on energy system optimization models by implementing raw material supply
224 chain and material intensities of technologies in the different sectors of the economy in a bottom-
225 up integrated assessment model. In this paper, we have developed the first bottom-up long-term
226 energy model TIAM-IFPEN (TIMES Integrated Assessment Model) with an endogenous copper
227 supply chain from the resources to the end-use sectors, the availability constraints on resources
228 and the trade balances. Given the recent attention given to concepts such as urban mining and
229 recycling, this model could be helpful to provide unique insights in this area.

230 We present in this paper the main findings related to an endogenous representation of the copper
231 supply chain in order to assess its dynamic criticality, along with technological changes through
232 to 2050. It is crucial to understand whether the limited availability of copper can hinder the
233 deployment of low-carbon technologies or conventional ones in the economy as a whole. This
234 would be valuable for any energy analyses to examine the geological risk, geopolitical risk,
235 production risk, etc. related to raw material supply availabilities and how they could impede the
236 energy transition. In order to assess copper availability through to 2050, two climate scenarios
237 (2°C and 4°C) have been analysed with two different mobility scenarios each. Recycling has
238 been also implemented into all these scenarios. The rest of the article is organized as follows.
239 Section 2 describes the methodology, the overall structure of the TIAM-IFPEN model, and the
240 specific features and assumptions considered for a detailed analysis of copper criticality. Section
241 3 presents our main results and related analyses on the copper supply chain at global and regional
242 levels, copper resource availability and the implications of regionalized recycling policies and
243 more sustainable road transport mobility. Finally, Section 4 summarizes the main conclusions.

244 2. Methodology

245 We have developed the first global bottom-up energy system optimization model with an
246 endogenous representation of raw material supply chains in the TIAM-IFPEN (TIMES²
247 Integrated Assessment Model) model using a MARKAL³-TIMES framework [89][90][91] .
248 TIAM-IFPEN is able to assess a dynamic raw material's criticality in a global energy prospective
249 exercise subject to different climate and sectorial constraints through to 2050. However, contrary
250 to our previous article [17] based on assessing future risks related solely to the lithium supply
251 chain with fast roll-out of electric vehicles⁴ in the coming years; we add a complete copper
252 supply chain as an additional raw material constraint to the energy transition. The model will
253 therefore allow analysing the dynamic criticality of copper through to 2050 based on current
254 known resources, urban mining and resource availability.

255 2.1. Overview of the TIAM-IFPEN model

256 TIAM-IFPEN is a multiregional and intertemporal partial equilibrium model of the entire world
257 energy system, based on the TIMES model generator [92]. It is a version of the TIAM-WORLD
258 developed, maintained and used by the Kanlo team and is the global incarnation of the TIMES
259 generator. A complete description of the TIMES equations appears in the ETSAP⁵
260 documentation. It is a bottom-up techno-economic model that estimates energy dynamics by
261 minimizing the total discounted cost of the system over the selected multi-period time horizon
262 through powerful linear programming optimizers. The components of the system cost are
263 expressed on an annual basis while the constraints and variables are linked to a period. Special

² The Integrated MARKAL-EFOM System.

³ MARKet Allocation model.

⁴ Electric vehicles (EVs) include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel-cell electric vehicles (FCEVs).

⁵ 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>

264 care is taken to precisely track cash flows related to process investments and dismantling in each
 265 year of the horizon. Different investment tracking cases have been considered in the model in
 266 order to help guarantee a smooth trajectory and a more realistic representation [92]. The total cost
 267 is an aggregation of the total net present value of the stream of annual costs for each of the
 268 model's regions. It constitutes the objective function (Eq. 1) to be minimized by the model in its
 269 equilibrium computation. A detailed description of the objective function equations is provided in
 270 Part II, section 6.2 of the TIMES documentation [91]. We limit our description to giving general
 271 indications on the annual cost elements contained in the objective function:

- 272 - Investment costs incurred for processes;
- 273 - Fixed and variable annual costs,
- 274 - Costs incurred for exogenous imports and revenues from exogenous exports;
- 275 however, in a global TIMES incarnation such as TIAM, exogenous imports
- 276 and exogenous exports are not relevant;
- 277 - Delivery costs for required commodities consumed by processes;
- 278 - Taxes and subsidies associated with commodity flows and process activities
- 279 or investments;

280 TIAM-IFPEN represents the global energy system divided into 16 regions⁶ (See Table 10 in
 281 Appendix C). It is set up to explore the development of the world energy system from 2005
 282 through to 2050 and is calibrated to the 2005 data provided by energy statistics of the
 283 International Energy Agency:

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

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

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

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

⁶ The regions represent either individual countries, such as the People's Republic of China (China) or India, or aggregates of several countries, such as the Central and South America countries (CSA).

289 **REFYR** is the reference year for discounting;

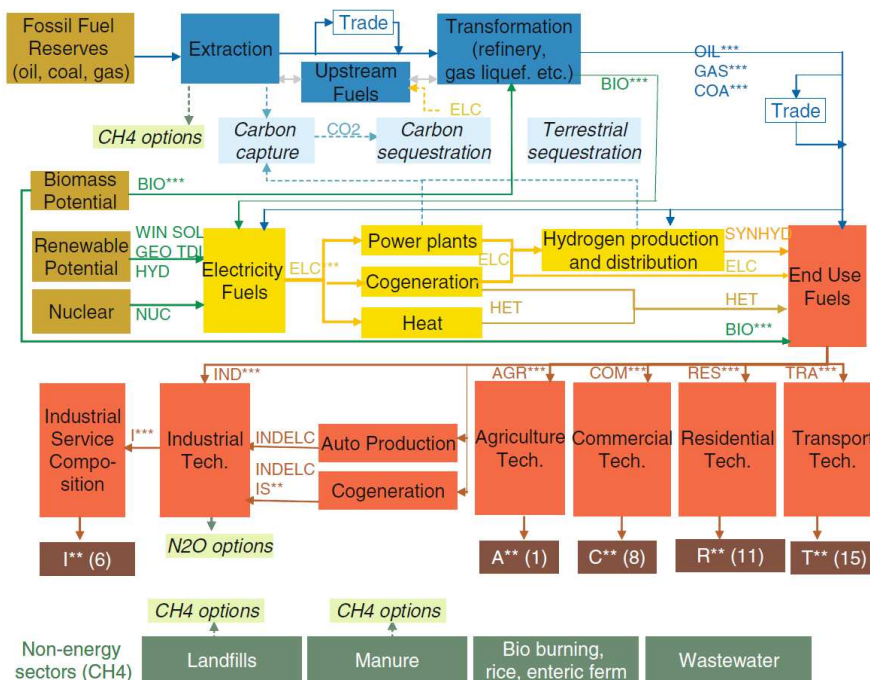
290 **YEARS** is the set of years for which there are costs, including all years in the horizon,
 291 plus past years (before the initial period) if costs have been defined for past
 292 investments, plus a number of years after EOH where some investment and
 293 dismantling costs are still being incurred,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

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

295 TIAM model is data driven, its parameterisation refers to technology characteristics, resource
 296 data, projections of energy service demands, policy measures etc. It means that the model varies
 297 according to the data inputs while providing results such as the shape of investments, technology
 298 pathways or the evolution of trade flows for policy recommendations [17].

299 For each region, the model includes detailed descriptions of numerous technologies, logically
 300 interrelated in a Reference Energy System (Fig. 1) – the chain of processes that transform,
 301 transport, distribute and convert energy into services from primary resources and raw materials to
 302 the energy services needed by end-use sectors (See [17] for more details of the TIAM-IPEN
 303 model).

304 **Fig. 1: TIAM model's Reference Energy System [92]**



305 The model is driven by a set of demands for energy services in all sectors: agriculture, residential,
 306 commercial, industry and transport. Each element in the network (Fig. 1) is characterized by
 307 several input parameters. The construction of the exogenous demands for energy services has
 308 been done via general equilibrium models such as the global General Equilibrium model GEM-
 309 E3⁷ or GEMINI-E3⁸, which provide a set of coherent drivers for each region and for the World as
 310 a whole, such as population, households, GDP, sectors outputs, and technical progress. These
 311 drivers provided the growth rates for each demands for energy services through to 2050
 312 following (Eq. 2):

$$D_t = D_{t-1} * (1 + \left(\frac{DRIVER_t}{DRIVER_{t-1}} - 1\right) * decoupling_factor) \quad (\text{Eq.2})$$

313 The decoupling factors account for phenomena such as saturation (factor is then less than 1) and
 314 suppressed markets (factor is then larger than 1), and are in part empirically based. Most demands
 315 have economic growth as their driver.

316 **Table 1: Energy service demands and their drivers/input sources**

DEMAND	DRIVER	Via other model outputs
Transportation	All regions	All regions
PLDV		IEA MoMo model ⁹
Bus and Minibus		IEA MoMo model
Commercial vehicle travel		IEA MoMo model
2 & 3 wheelers		IEA MoMo model
Rail passenger travel	POP	

⁷ GEM-E3 (General Equilibrium Model for Economy-Energy-Environment interactions) is a recursive dynamic computable general equilibrium model that covers the interactions between the economy, the energy system and the environment. (please refer to the GEM-E3 documentation for more details <https://ec.europa.eu/jrc/en/publication/euro-scientific-and-technical-research-reports/gem-e3-model-documentation>)

⁸ GEMINI-E3 (General Equilibrium Model of International -National Interactions between Economy , Energy and the Environment) is a multi-country, multi-sector, recursive computable general equilibrium model

⁹ The MoMo model is a techno-economic database spreadsheet and simulation model that enables detailed projections of transport activity based on user-defined policy scenarios through to 2100. The model covers 29 countries and regions with an urban/non-urban split, offering the potential for municipal-level policies to reduce transport energy use ([93], <https://www.iea.org/etp/etpmodel/transport/>).

Domestic aviation travel	GDP		
International Aviation travel	GDP		
Fret rail	GDP		
Domestic Navigation	GDP		
Bunkers	GDP		
Residential	All regions after 2050 + Non-OECD before 2050	OECD regions before 2050	
Space heating	HOU	HOU	
Space Cooling	HOU	GDPP	
Water Heating	POP	POP	
Lighting	GDPP	GDPP	
Cooking	POP	POP	
Refrigeration and Freezing	HOU	GDPP	
Washers	HOU	GDPP	
Dryers	HOU	GDPP	
Dish washers	HOU	GDPP	
Other appliances	GDPP	GDPP	
Other	HOU	GDPP	
Commercial	All regions		
Space heating	SPROD-Services		
Space Cooling	SPROD-Services		
Water Heating	SPROD-Services		
Lighting	SPROD-Services		
Cooking	SPROD-Services		
Refrigeration and Freezing	SPROD-Services		
Other electric demands	SPROD-Services		
Other	SPROD-Services		
Agriculture	SPROD-Agriculture		
Industry	SPROD-X		

317 Source: [94]
318 PLDV: Passenger Light-duty vehicle; CV: Commercial vehicle; HOU: Households; POP: Population; GDP: Gross
319 domestic product; GDPP: GDP per capita; SPROD-X: Industrial outputs of sector X
320 Technologies are described by means of technical data (e.g., capacity, efficiency), environmental
321 emission coefficients (e.g., CO₂, CH₄, N₂O), and economic values (e.g., capital cost, date of
322 commercialization). Possible future developments of the system are driven by reference demands

323 for energy services (e.g. commercial lighting, residential space heating, air conditioning, mobility
324 and many others), the supply curves of the resources (e.g., amount available at each price level),
325 along with environmental or other constraints (e.g. greenhouse gas emission constraints,
326 efficiency standards, energy portfolio, etc.), which are provided as exogenous inputs to the model
327 [93].

328 TIAM-IFPEN also includes a climate module which per se is directly inspired by the Nordhaus-
329 Boyer model [95]. It consists of three sets of equations, calculating the atmospheric
330 concentrations of the three gases CO₂, CH₄ and N₂O, the atmospheric radiative forcing of these
331 three gases and of Kyoto GHG's that are not explicitly modelled in TIAM-WORLD (i.e. CFC's,
332 HFC's, SF₆), and finally the yearly change in mean global temperature. It includes two recursive
333 formulas that calculate temperature changes in two layers (upper ocean + atmosphere layer, and
334 lower ocean layer), as in Nordhaus and Boyer [95], recalibrated for TIAM-IFPEN and adapted to
335 periods with variable length.

336 Although various recent studies have been already conducted using the TIAM model, such as the
337 effects of global GHG reduction on bioenergy sector expansion [96] and carbon capture and
338 storage in power supply [97] using TIAM-FR¹⁰, long-term investigation for large-scale low-GHG
339 energy technology diffusion in Africa using TIAM-ECN¹¹ [98], and the decarbonisation of road
340 transport using TIAM-UCL¹² [99], none has yet examined raw material supply chains in a TIAM
341 model within energy transition analysis as far as we know.

342 2.2. Copper supply and demand modelling in TIAM-IFPEN

¹⁰ TIAM-FR is a version of TIAM adapted at the Mines ParisTech Centre of Applied Mathematics in Sophia-Antipolis (France).

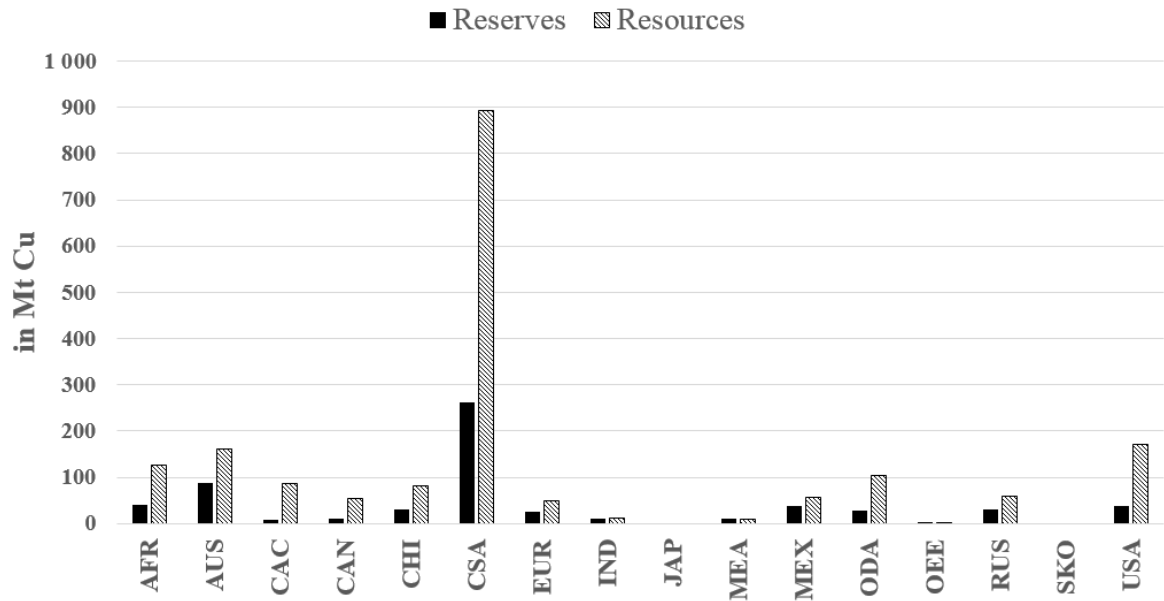
¹¹ TIAM-ECN is the version of TIAM developed at the Energy Research Centre of the Netherlands (ECN).

¹² This version of TIAM was developed at University College London (UCL) through the UK Energy Research Centre (UKERC).

343 2.2.1. The copper supply chain

344 As explained by Gordon et al. [27], copper is not uniformly distributed in the Earth's crust, as
345 observed in the geographical distribution of copper ore reserves and resources (Fig. 2).

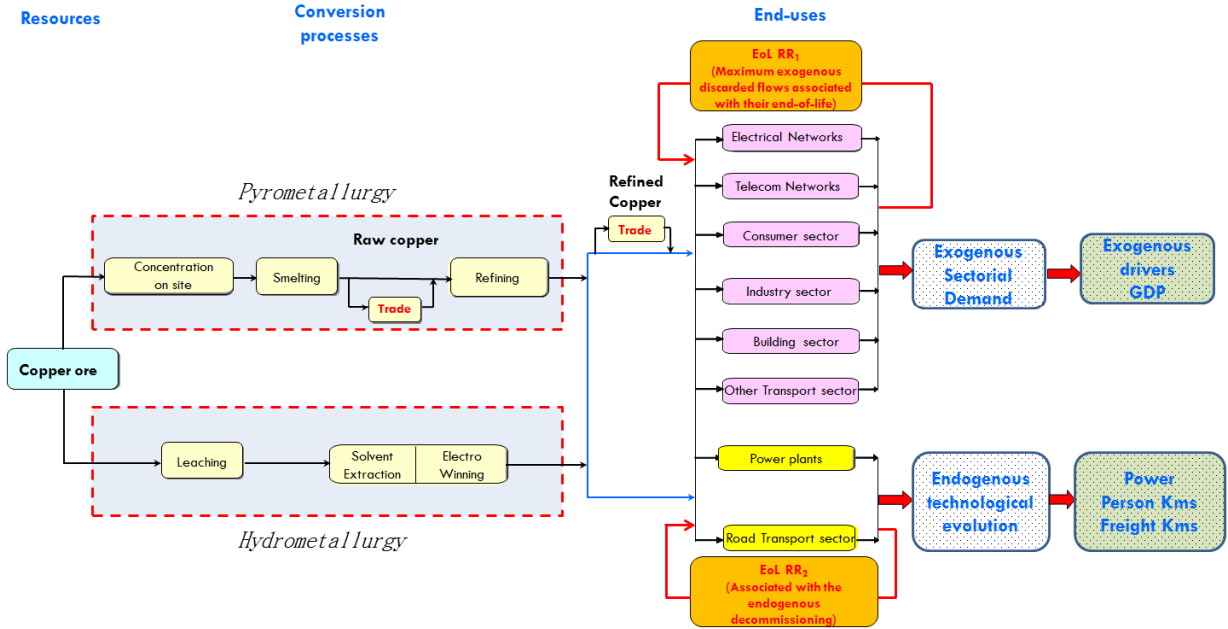
346 **Fig. 2: Geographical distribution of copper resources and reserves worldwide**



347 Source: USGS, [61], [100]

348 Nearly half of the world's reserves and resources are located in the CSA region (Central and
349 South America), mainly in Chile and Peru. The copper supply chain has been implemented into
350 the model from ore deposits to its end-use sectors via various transformation processes and trade
351 flows (Fig. 3).

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



353 Regionalized mining CAPEX and OPEX have been done using weighted averages of real
 354 projects around the world ([101], [102], companies’ reports) (See Appendix B Table 11).

355 Two processes used for refining copper ores, pyrometallurgy and hydrometallurgy, have been
 356 implemented in the model. They concern ore concentrates and leached ores respectively. The
 357 regional disaggregation of these two refining processes is made using production weights since
 358 1990, as displayed in Table 2. The shares of concentrates and leached ores have been rather
 359 stable over time within a country between 2005 and 2015 due to the geological characteristics of
 360 the deposit.

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

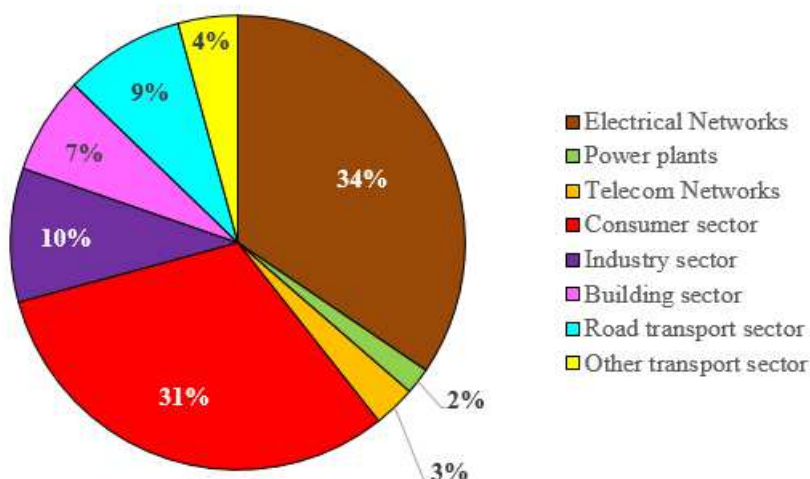
	AFR	AUS	CAC	CAN	CHI	CSA	EUR	IND	JAP	MEA	MEX	ODA	OEE	RUS	SKO	USA
Pyro	65	96	95	100	98	71	92	100	100	95	73	89	94	100	100	59

Source: USGS

364 As displayed in Fig. 4, copper is used in many sectors, such as the construction industry
 365 (plumbing, roofing, shipbuilding and cladding), the power sector (power plants and electrical

366 infrastructures), the industry sector, the transport sector and in the final goods sector (the main
367 component of coins for many countries, home accessories, water heaters, etc.).

368 **Fig. 4: End-use consumption of copper worldwide in 2018**



369 Source: [29]

370 “Electrical Networks”, which include power distribution, lighting and earthing connection, are,
371 alongside the “consumer sector”¹³, by far the largest copper users as they consume respectively
372 34% and 31% of semi-finished copper products in 2017. These two sectors illustrate a general
373 fact about copper: it is widely used in long-lived applications with useful life-spans that can last
374 several decades. It is estimated that two thirds of the copper produced since 1900 was still in use
375 in 2010 [103]. Moreover, it appears that the “consumer” sector, pertaining to the manufacturing
376 of final goods that are not related to transport, is the most dissipative end-use sector. A major
377 barrier to the reuse of copper is therefore the long period during which it may be trapped in
378 products that are still in use.

379 2.2.2. The technology copper content

¹³ This includes consumer and general products (appliances, instruments, tools and other), cooling (air conditioning and refrigeration), electronics (industrial/commercial electronics and PCs) and miscellaneous items (ammunition, clothing, coins, etc.).

380 In a future driven by more stringent environmental constraints and economic growth, the
 381 increasing copper content of all decarbonisation innovations, particularly in the transport and
 382 power sectors, could, due to limited copper resource availability, hinder the diffusion of these
 383 technologies. The variability of technologies and their rapid evolution make it difficult to
 384 quantify the full requirements for energy raw materials (Table 3).

385 **Table 3: Variation of the copper content for power generation technologies in the literature**

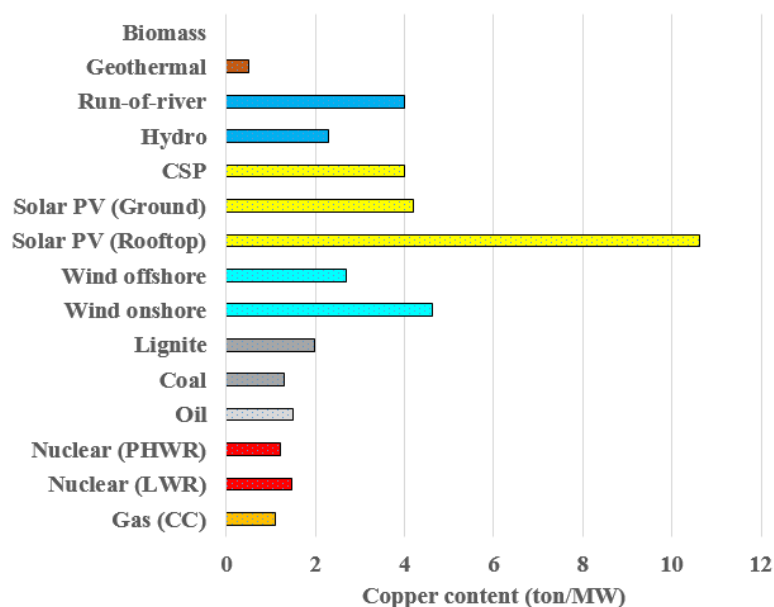
Copper content (kt/GW)	Literature data	
	Min.	Max.
Gas	0.5	1.5
Nuclear	0.06	1.5
Oil	1.5	1.5
Coal	0.3	2
Wind onshore	1.6	20.1
Wind offshore	0.9	11.7
Solar PV (Rooftop)	0.02	11.4
Solar PV (Ground)	3	7.5
CSP	0.4	12.4
Hydro.	0.1	11.4
Run-of-river	3.5	4
Geothermal	0	0.5
Biomass	0	0

386 Source: [2], [104]

387 For some technologies such as nuclear, coal, gas and oil plants, the average copper content are
 388 almost identical between for example Ecoinvent and literature data ([71], [104]). However, large
 389 discrepancies are observed for the RETs. According to Ecoinvent, copper content per unit
 390 capacity is ten times higher in a solar PV rooftop compared to a gas plant for example, while it
 391 triples in an onshore wind turbine compared to a nuclear power plant (Fig. 5). On the other hand,
 392 Vidal [104] assumed a copper content up to six times higher for an onshore wind compared to
 393 nuclear, while solar PV rooftop is only four times higher compared to a gas plant. In addition,
 394 concentrated solar plant (CSP) is for example not referenced in Ecoinvent while it could have
 395 different values for the same authors according to the year of publication. Vidal considered a

396 copper content for CSP of 2.3 kt/GW in 2013 [105] while it almost doubled in 2018 to reach 4
 397 kt/GW [104]. There are relatively few validated studies that give an exhaustive account of
 398 material intensities (in tonnes per unit of capacity), and most often they are limited to production
 399 infrastructure isolated from other equipment (transformers, connections, foundations, etc.)[104].
 400 In this article, we have considered the copper contents which have been reported in Ecoinvent
 401 and we fill the missing technologies such as CSP with literature data (Fig. 5).

402 **Fig. 5: Copper content of different means of energy production (kg/MW) considered in the model**
 403 **TIAM-IFPEN**

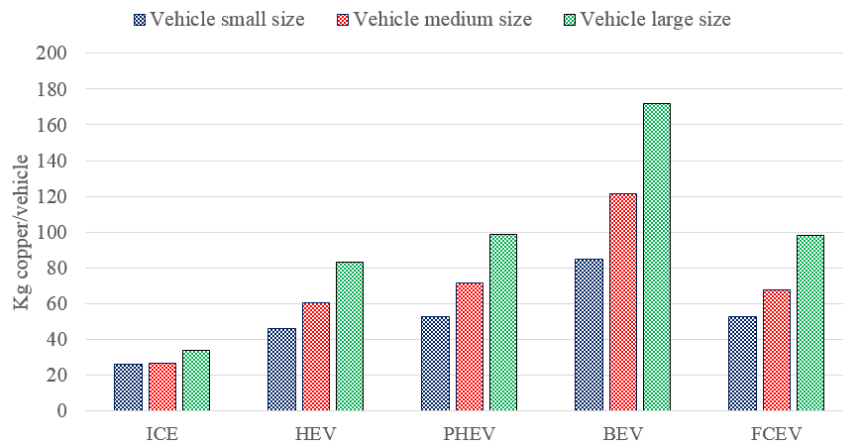


404
 405 Source: Ecoinvent.
 406 CC: Combined Cycle; LWR: Light Water reactor which encompasses the PWR (pressurized water reactor), the
 407 boiling water reactor (BWR), PHWR: Pressurized heavy Water Reactor; PV: Photovoltaic; CSP: Concentrated Solar
 408 Plant

409 The same trend is observed in road transport vehicles. Compared to their inherent conventional
 410 vehicles, electric vehicles contain two to more than five times more copper (Fig. 6 and Table 4).
 411 The copper content has been accounted for in each technology segment (Table 4).

412

Fig. 6: Copper content in passenger light duty vehicles per size



413

Source: [106], See Table 4 in Appendix C for more details

414 Typically, between 96% and 100% of the copper is in the vehicle (for wiring), while in electric
 415 vehicles, the copper in the latter falls to 45% due to the much heavier battery, which contains
 416 55% of the copper [104]. More emphasis will therefore be placed on the need to increase the
 417 recycling efficiency of copper from scrap in all end-use economic sectors.

418

Table 4: Copper content in road transport according to the weight (kg/vehicle)

		ICE	HEV	PHEV	BEV	FCEV
Passenger light duty vehicles	Small	25.9	46.2	52.8	84.9	52.8
	Medium	26.4	60.6	71.3	121.3	67.6
	Large	33.5	83.0	98.5	172.0	97.9
Bus		90.5	224.0	265.8	369.0	210.1
Minibus		54.9	136.0	161.4	224.0	127.5
Commercial vehicles	Light	39.1	96.8	114.9	200.6	114.2
	Medium	57.2	141.5	167.9	233.1	132.7
	Heavy	190.5	471.6	559.7	776.8	442.2
2-wheelers		0.6			2.9	
3-wheelers		3.9			20.1	

419

Source: [106], ECI/CA¹⁴, Authors

420 Copper is traded in three forms worldwide. The first is the copper concentrate which have been
 421 processed by pyrometallurgy techniques. The second is refined copper cathodes, sold by copper
 422 refineries. This is the purest form of copper and is used to produce wires, sheets and strips, for
 423 example. The last traded product is blister copper. Custom refineries process blister copper to

¹⁴ European Copper Institute/Copper Alliance, <https://copperalliance.eu/e-mobility-european-copper-market/>

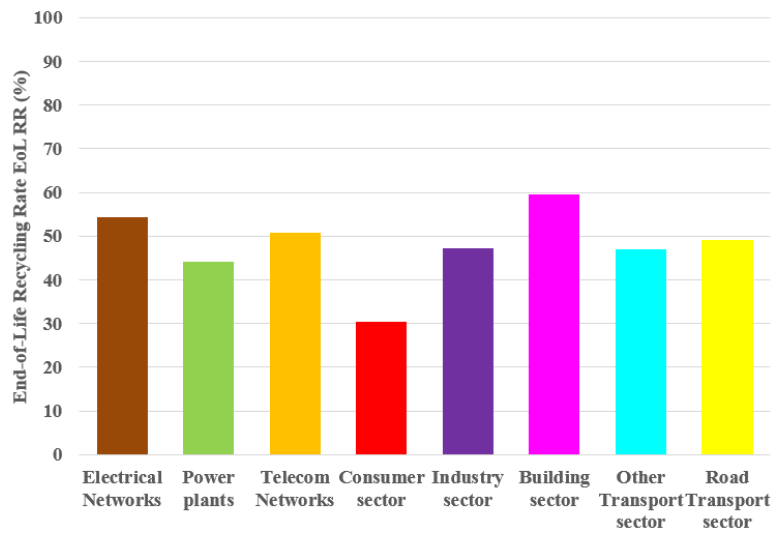
424 produce cathode; however, this represents a small share of the global copper trade. So, for
425 simplification's sake, we consider two types of trade in the model. In Fig. 3, the first is trade in
426 raw copper, encompassing all trade in copper ores and concentrates, copper mattes, copper
427 anodes and unrefined copper. The second is refined copper. Taking into account trade capabilities
428 enables analysis of future international copper trade and strategies based on each region's needs
429 and growth. This use of the model would be very relevant, as historical trade analysis pinpoints
430 changes in regions' strategies in response to environmental and economic constraints between
431 2005 and 2015 (see the example of China in Appendix A). Trade data were extracted from the
432 resourcetrade.earth website, which uses the UN Comtrade database as a primary source and
433 corrects missing points.

434 2.2.3. The recovery and recycling of copper in the TIAM-IFPEN

435 Strong growth in emerging economies over the past decade, together with the rapid deployment
436 of innovative copper-intensive technologies, has led to a sharp increase in copper demand. The
437 recovery and recycling of copper helps to satisfy this demand and to build a sustainable future.
438 Glöser et al. [107] discussed several commonly used indicators to measure it at the global level.
439 In this paper, we implement the End-of-Life Recycling Rate (EoL-RR) indicator in our TIAM-
440 IFPEN model in order to take into account the efficiency of scrap recycling. This indicator is
441 determined as the fraction of metal contained in end-of-life products that is collected, pre-treated
442 and ultimately recycled back in the anthropogenic cycle (Eurométaux and Eurofer 2012 cited in
443 [108]).

444

Fig. 7: End-of-life recycling rate (EoL-RR) by end-use sector in the TIAM-IFPEN model



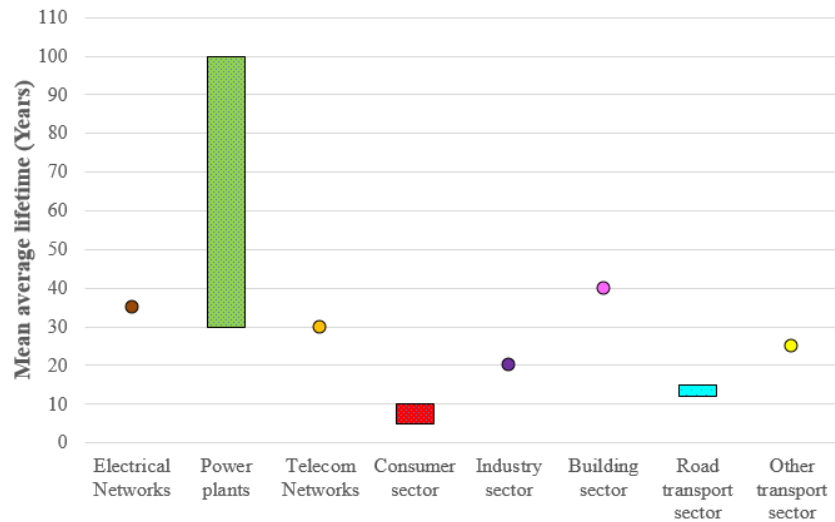
445

Source: [107]

446 There is a lack of data on recycling activity in copper-consuming sectors, but Glöser et al. [107]
447 provided global estimates for the 2000-2010 period. The EoL-RR value for the eight copper-
448 consuming sectors considered in the model is presented in Fig. 7. The average value for all
449 sectors combined is around 45%. In each end-use sector, different lifetime distributions have
450 been implemented in order to take into account their end-of-life. Estimated mean average lifetime
451 values have been extracted from Glöser et al. [107] and are shown in Fig. 8, for the lifetimes of
452 power plants and road transport, we relied on the IEA-ETSAP and IFPEN databases.

453

Fig. 8: Mean average lifetimes by end-use sector in the TIAM-IPFEN model



454

Source: [107], Authors

455 For the copper-consuming sectors not represented in detail technologically, i.e. the sectors in pink
456 boxes shown before in Fig. 3, the estimated $EoL-RR_1$ will allow calculating exogenously the
457 maximum discarded flows which could be recycled according to the historical data and the mean
458 average lifetimes considered in the model. For the road transport and power sectors in yellow in
459 Fig. 3 which have a detailed technological representation, the $EoL-RR_2$ value is provided and the
460 model will calculate endogenously the maximum discarded flows associated with their inherent
461 technology decommissioning. Given the lack of scalable $EoL-RR$ data, we make a conservative
462 hypothesis, assuming they are kept constant in the model over our 2005-2050 time horizon
463 periods. This is a pessimistic scenario considering that significant efforts would certainly be
464 made to improve copper recycling, such as in the “consumer sector”, due to its dissipative
465 characteristics and weight in copper consumption. In other words, the sectorial $EoL-RR$
466 implemented in the model provides the basis of our pessimistic view of recycling activity
467 (probable minimum values).

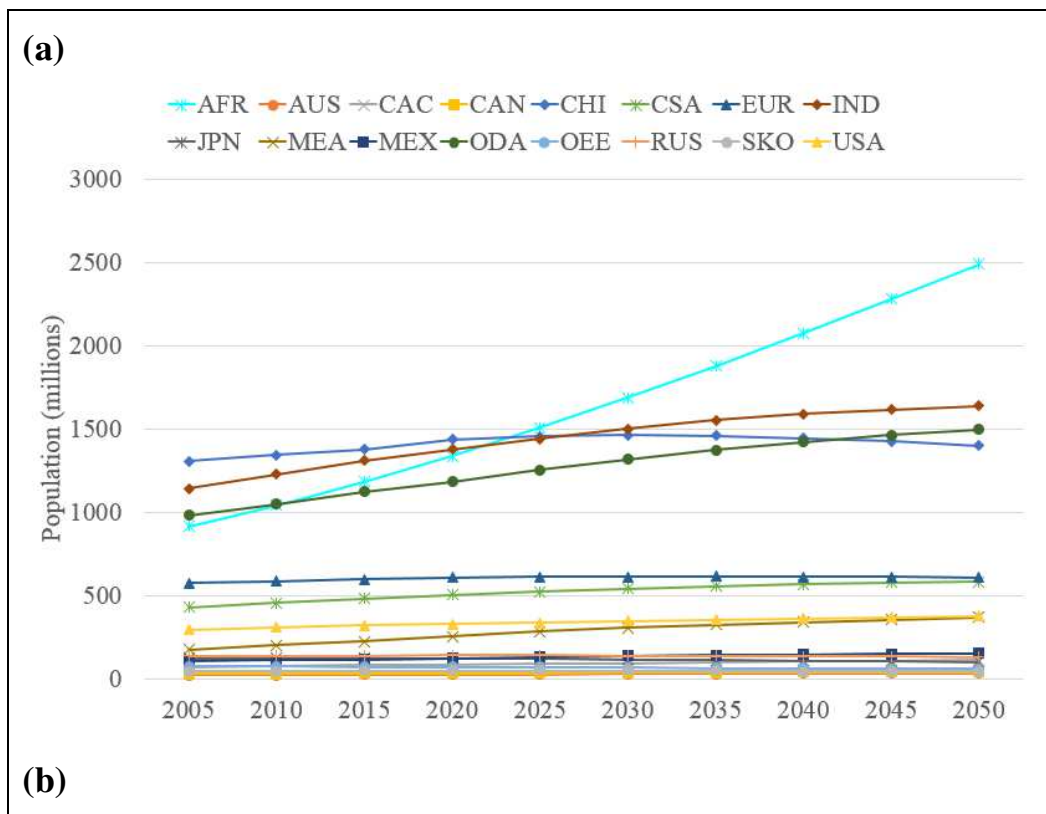
468

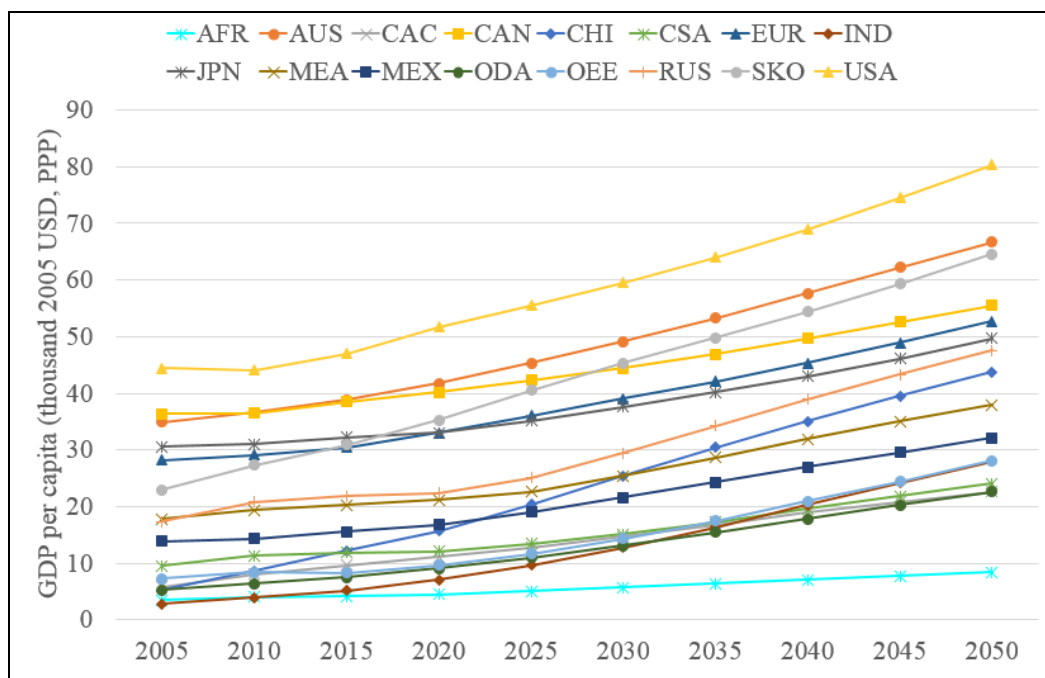
2.3. Macro-economic assumptions and scenarios specifications

469 2.3.1. GDP and population scenarios

470 The GDP per capita evolution has been derived from the assumed evolutions of population and
 471 GDP (Fig. 9). The UN released a revision in 2019 of the foreseen growth of all countries in the
 472 world [109]. The world population has increased from 7.4 billion to around 9.7 billion inhabitants
 473 in 2050 in the median scenario. On the other hand, the IEA assumed in their IEA Mobility Model
 474 (MoMo Model) an increase of the world GDP (ppp) from around 67 912 billion US\$ 2005 in
 475 2005 to 283 500 billion US\$ 2005 in 2050. Thus, the world GDP per capita (ppp) is assumed to
 476 increase from 10 430 US\$ 2005 in 2005 to around 29 200 US\$2005 in 2050.

477 **Fig. 9: (a) Evolution of population, (b) Evolution of the GDP per capita**





Source: IEA MoMo 2019, [109]

478

479

2.3.2. Copper end-use sectors and the evolution of their demand

480

All end-use sectors have to be considered in the modelling exercise to consider future copper

481

demand, as depicted in the copper supply chain in Fig. 3 in §2.2.1. Two methodologies have been

482

assumed. Firstly, the copper demands for the sectors not represented in detail technologically,

483

Electrical and Telecom networks, Consumer, Industry sector, Building and Other Road Transport

484

sectors, are exogenous and calculated according to the GDP per capita (ppp¹⁵) projection via

485

decoupling factors. The decoupling factor series represents the sensitivity of each end-use

486

demand to one unit change in its driver – which here is GDP per capita (GDPP). They have been

487

derived from the analysis of the sectorial copper demands along with GDP per capita between

488

1975 and 2018¹⁶ (Fig. 10), taking into account changing trends in socio-economic growth (Table

¹⁵ Purchasing Power Parity

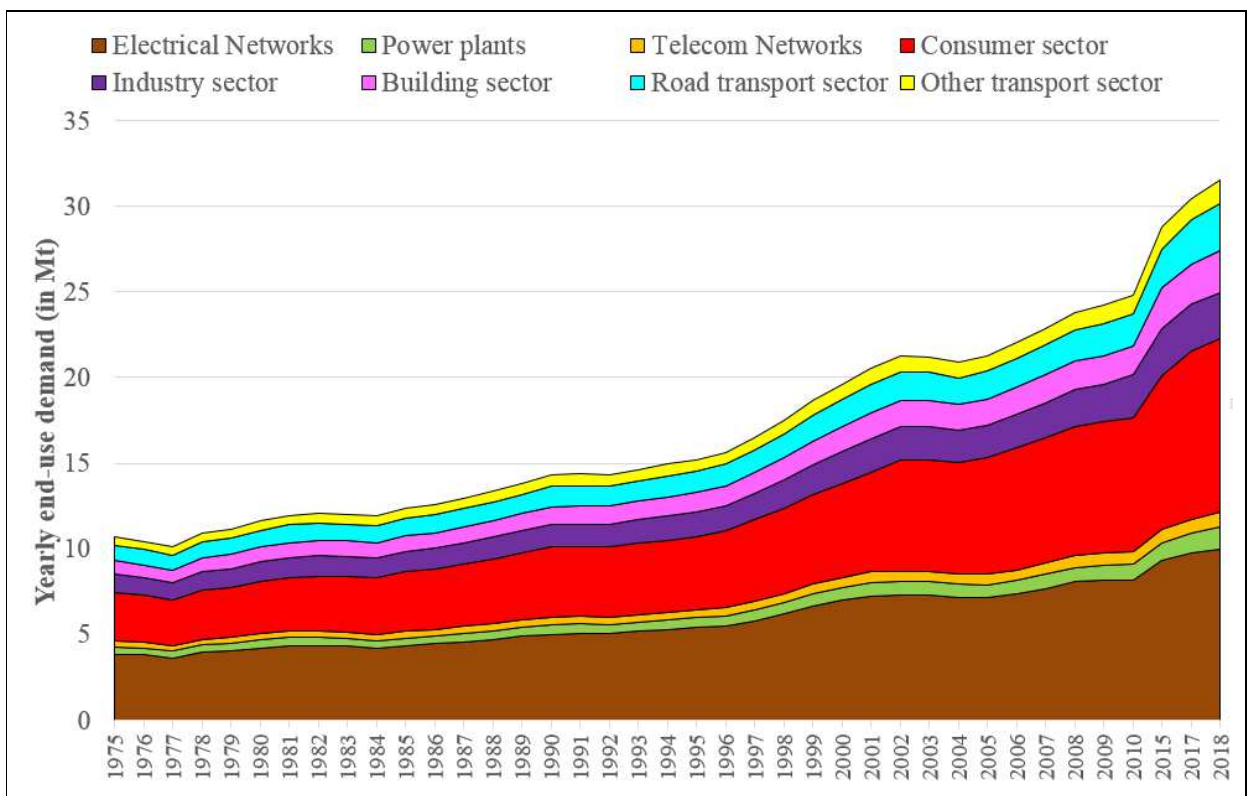
¹⁶ Annual data have been extracted and calculated from the International Copper Study Group (ICSG), Copper Council and Copper Alliance between 1975 and 2018, <https://www.icsg.org/index.php/component/jdownloads/viewdownload/170/2965>, <http://www.coppercouncil.org/wp-content/uploads/2019/08/End-Use-Summary.pdf>, <https://copperalliance.org/trends-and-innovations/data-set/>

489 5). As mentioned before, these decoupling factors account for phenomena such as saturation
 490 (factor is then less than 1) and suppressed markets (factor is then larger than 1). Copper end-use
 491 demand for future years is projected using the equation (Eq.3):

$$D_{i,t} = D_{i,t-1} * \left(1 + \left(\frac{GDPP_t}{GDPP_{t-1}} - 1\right) * decoupling_factor\right) \quad (\text{Eq.3})$$

492 Where $D_{i,t}$ is the copper demand for the end-use i at the year t

493 **Fig. 10: Global copper demand by end-uses**



494 Source: ICSG, Copper Council, Copper Alliance

495 **Table 5: Estimated decoupling factors**

	Electrical Networks	Telecom Networks	Consumer sector	Industry sector	Building sector	Other transport sector
Estimated sensitivity to GDP per capita	1.21	1.21	1.65	0.95	1.67	1.17

496 Secondly, for copper demand in power plants and the road transport sector (See Appendix C for
497 more details of their representation in the model); an endogenous technological evolution will be
498 derived by the model while satisfying electricity needs and mobility demand respectively. TIAM-
499 IFPEN will assess copper requirements based on new installed capacities of power plants and
500 vehicle fleet evolution at any period.

501 2.3.3. Scenario specifications

502 Several scenarios have been defined in order to analyse the evolution of copper demand and
503 assess its criticality in response to more stringent environmental constraints or sustainable
504 behaviour requirements. We run four scenarios for copper, two climate scenarios with two
505 different mobility shapes each:

- 506 - “Scen 4D”, which is consistent with limiting the 2100 expected global average
507 temperature increase to 4°C above pre-industrial levels.
- 508 - “Scen 2D”, which is a more ambitious scenario, corresponding to the 2100 climate
509 objectives of limiting global warming to 2°C.

510 In each climate scenario, two different future scenarios of mobility have been assumed and
511 derived from the IEA Mobility Model (MoMo Model). In this paper, we incorporate outputs from
512 the MoMo model as transport mobility inputs into our TIAM-IFPEN model. The two mobility
513 scenarios for each climate scenario are (See Appendix C for more details of transport mobility
514 evolution):

- 515 - A “BAU mobility” scenario equivalent to a continuous increase of the ownership rate and
516 a higher car-dependency.
- 517 - A “Sustainable mobility” scenario where the idea of a sustainable mobility is assumed to
518 underpin an integrated approach to urban land-use and transport planning and investment,

519 and gives priority to sustainable modes of mobility such as public and non-motorized
520 transport.

521 Dealing with uncertainty in modelling is a complex endeavour that may be accomplished and in
522 the case of TIMES-MARKAL family model, stochastic programming and parametric analysis
523 (also known as sensitivity analysis) are two available features. By defining series of scenarios
524 through the variation of the values of some important exogenous assumptions (sectorial
525 demands...etc.), sensitivity analysis feature has been performed in this article. Within this
526 approach, a sequence of instances is solved and each assuming different values of the uncertain
527 parameters. For further research, the stochastic mode could be considered.

528 3. Results and discussions

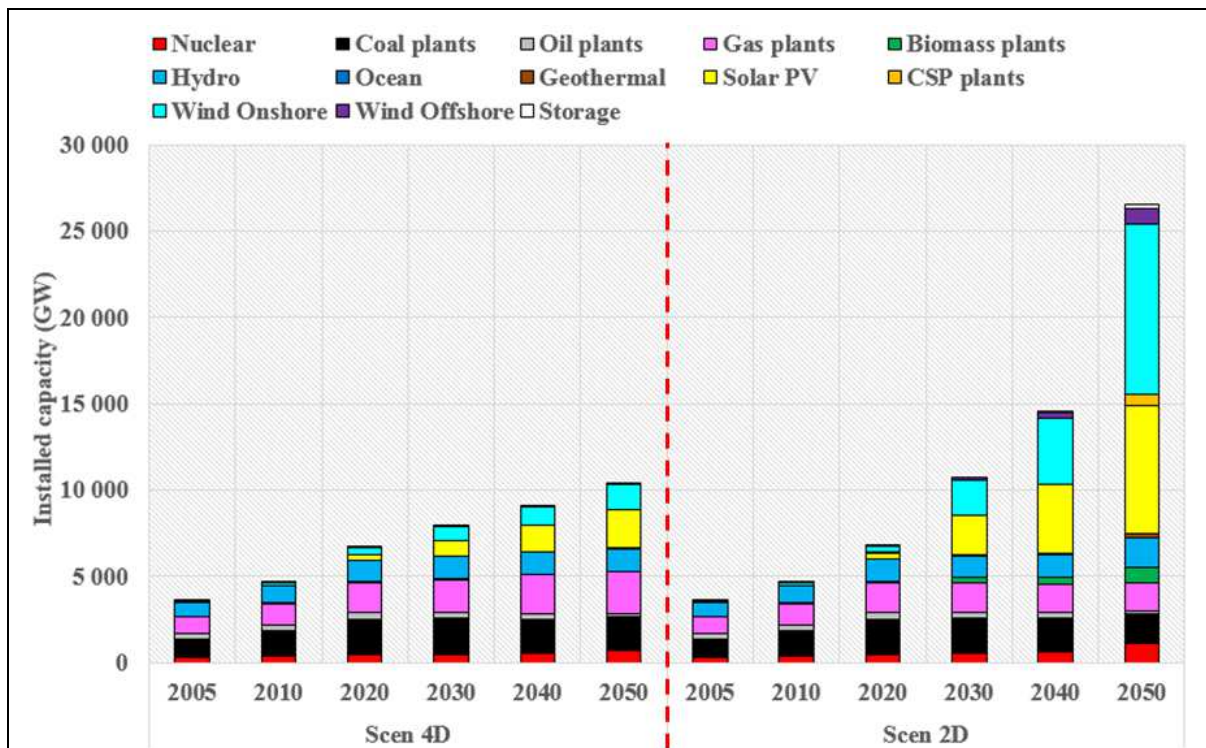
529 3.1. Pathways to achieve the 2°C goal

530 3.1.1. Outlook for power sector

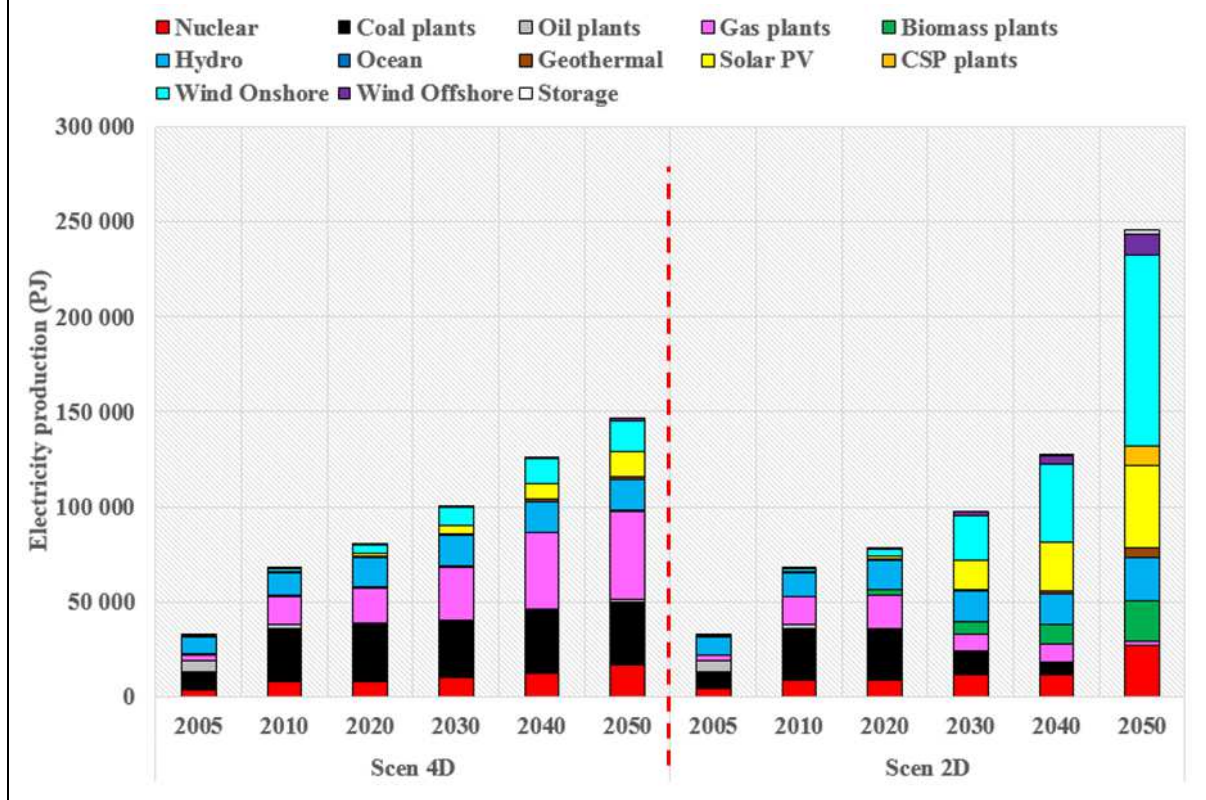
531 The fast shift to the low carbon technologies, which are very copper-intensive (see Fig. 5 in
532 §2.2.1), is observed in the power sector in order to achieve the climate objectives of limiting
533 global warming to 2°C by 2100 (Fig. 11). The total installed capacity by 2050 in the 4°C
534 scenario, which is 10.5 TW, will be multiplied by around 2.5 in the 2°C scenario. The Variable
535 Renewable Energy sources (VREs) (wind and solar) represented around 35% by 2050 in 4°C
536 while it is reaching more than 69% in the 2°C scenario in terms of installed capacity.

537 **Fig. 11: (a) Evolution of World power installed capacity with climate constraints (b) Evolution of**
538 **the world power production with climate constraints**

(a)



(b)



540 Fossil-based plants (coal, gas and oil) remains the main source of power production in the world
 541 in the 4°C scenario with around 55% of overall production while it drop to 0.8% in the more
 542 stringent scenario (2°C scenario). In the other hand, the Variable Renewable Energy sources
 543 (VREs) (wind and solar) has the inverse trend, they represented around 21 % by 2050 in the 4°C
 544 while it is reaching more than 67% in the more stringent scenario, namely 2°C scenario. The total
 545 power production reached in the 4°C scenario is almost 147 EJ (around 40 800 TWh) while it is
 546 almost 246 EJ (or 68 330 TWh). As a comparison, in the WEO 2019 of the IEA [110], the global
 547 power generation is expected to be 38 713 TWh in the Sustainable Development scenario¹⁷
 548 (SDS) by 2040 while in our model it is expected to be around 127.243 EJ, i.e. 35 345 TWh by
 549 2040 (Fig. 11 (b) and Table 6 for more details).

550 **Table 6: Comparison of our modeling results in electricity generation (in TWh) in 2040 with recent**
 551 **literature**

	Our results		IEA WEO 2019 ¹⁸ [110]		
	4°C Scenario	2°C Scenario	Current Policies scenario	Stated Policies scenario ¹⁹	Sustainable Development scenario
2040	35 115	35 345	42 824	41 373	38 713

552 Achieving a high share of renewables, mainly dominated by VREs, would thus require substitute
 553 or additional plants to provide extra inertia to the system. These options might include other
 554 means of production or storage devices, or renewable energy technologies (RETs) capable of
 555 providing such inertia (see Fig. 11 (a)) [111]. With higher VREs penetration by the 2050 horizon,

¹⁷ The Sustainable Development Scenario is constructed on the basis of limiting the temperature rise to below 1.8 °C with a 66% probability without the implied reliance on global net-negative CO2 emissions, or 1.65 °C with a 50% probability [110]

¹⁸ The Current Policies scenario shows what happens if the world continues along its present path, without any additional changes in policy, The Stated Policies Scenario previously named New Policies scenario, by contrast, incorporates today's policy intentions and targets. And the Sustainable Development Scenario maps out a way to meet sustainable energy goals in full, requiring rapid and widespread changes across all parts of the energy system.

¹⁹ This scenario is consistent with limiting the temperature increase to below 2.7 °C above pre-industrial averages with a 50% probability (or below 3.2 °C with 66% probability).

556 nuclear energy combined with more biomass or hydro to ensure the reliability of the grid with a
557 minimum share of dispatchable electricity in the grid. Wind is expected to be the dominant
558 energy as observed in Fig. 11 (b). The system begins to introduce flexible options, such as
559 storage devices from 2040 onwards in the 2°C scenario, despite the fact that this introduction of
560 storage is quite low, which is more or less visible in the graphs.

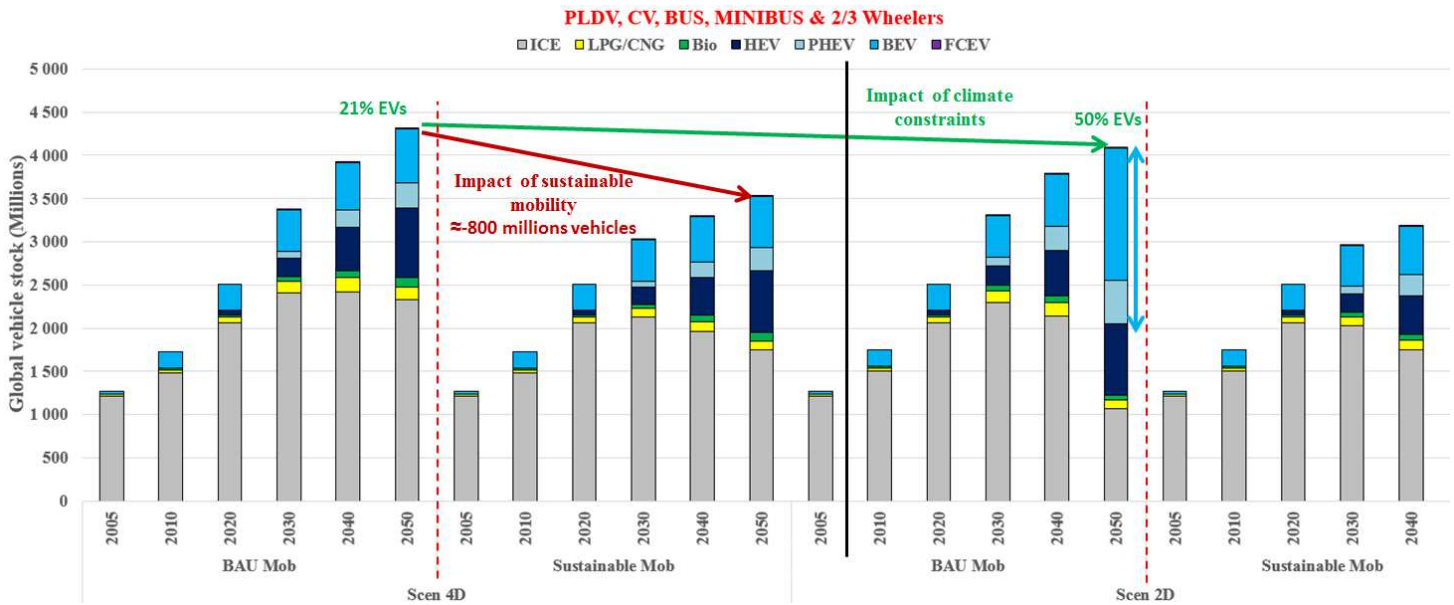
561 3.1.2. Outlook for road transport sector

562 The high level of the transport electrification achieved in the 2°C scenario will have an impact on
563 the copper demand (Fig. 12). Indeed, according to literature [104], electric vehicles contain two
564 to more than five times more copper than the conventional vehicles according to their size (Fig.
565 6). 50% of the global fleet would be electric vehicles in the 2°C scenario while it is only 21% by
566 2050. We should pinpoint that around 1/3 of the world fleet are 2/3-wheelers (mostly in China
567 and India) and around 50% of the electric fleet. Therefore, EV fleet is mostly located in Asian
568 countries (China, India and Other developing countries in Asia) due to the large presence of these
569 2/3-wheelers.

570 With a sustainable mobility, the worldwide fleet achieves 3.5 and 3.4 billion vehicles in the 4°C
571 and the 2°C scenarios by 2050, respectively, while it is more than 4.3 and 4.1 billion in a
572 “Business-As-Usual” mobility. The impact of the mobility shift will allow a reduction of around
573 700-800 million vehicle due to the reduction of the mobility activity with the development of
574 sustainable modes of mobility such as public and non-motorized transport.

575 The world fleet is dominated by the internal combustion engine (ICE) vehicles between 2005-
576 2050 (except in the scenario 2°C from 2040 onward) (Fig. 12).

Fig. 12: Evolution of the global vehicle stock between 2005-2050

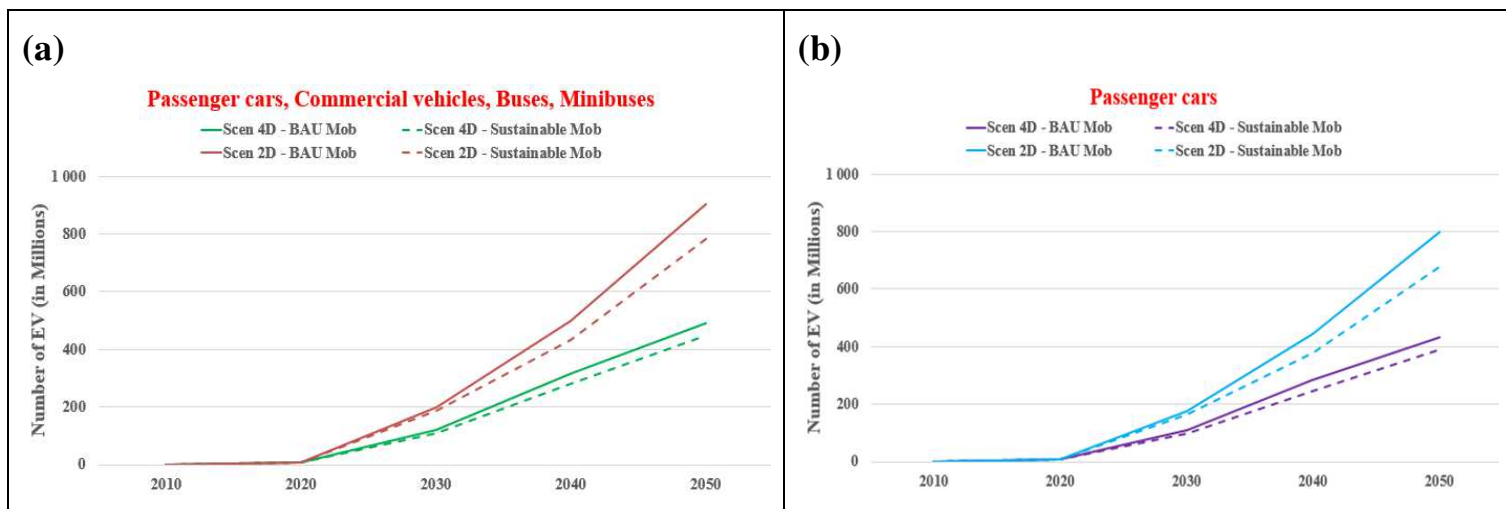


578 ICE: Internal combustion engine; HEV: Full hybrid vehicle; PHEV: Plug-in hybrid vehicle; BEV: Battery-powered
 579 electric vehicle; FCEV: Fuel cell electric vehicle; EVs=BEVs+PHEVs+FCEVs
 580

581 According to Fig. 13 (a), the global fleet of EV (two and three-wheelers excluded) should reach
 582 between 450 and 500 million units by 2050 in the 4°C scenarios, while it could be as high as 785-
 583 900 million units in the 2° scenarios. When considering passenger light-duty vehicles (PLDVs:
 584 small, medium and large cars) alone, they should reach 390 and 435 million units in circulation
 585 by 2050 in the 4°C scenarios with the sustainable and BAU mobility, respectively, while it would
 586 be more than 675 and less than 800 million in Sustainable mobility and BAU hypothesis in the
 587 2°C scenario (Fig. 13 (b)).

588
589

Fig. 13: (a) Evolution of the global electric vehicle fleet (b) Evolution of the electric vehicles in passenger light-duty vehicles



590

591 Our model gives a global EV fleet (2/3-wheelers excluded) between 7.798 and 7.821 million
592 vehicles in 2020. The existing EV worldwide fleet has been counted to be approximately 6.655
593 million vehicles worldwide in 2019 according to MarkLines. Therefore, it could be considered
594 that our results are in fair agreement if considering that the estimated new EV sales would
595 certainly decrease after a 4% decline in sales in 2019, following the slowdown in global
596 economic growth and the implementation of new regulations in Europe and China due to the
597 Covid-19 pandemic. Analysing these graphs, we could acknowledge that our forecasts in the 4°C
598 and 2°C scenarios with the “Business-As-Usual” mobility, 110 and 180 million units by 2030,
599 respectively, are similar in scope to the IEA’s forecasts in the Global EV Outlook (GEVO) 2019,
600 which estimates the number of EV at between 130 and 250 million by 2030 in the New Policies
601 Scenario²⁰ and EV30@30 scenario²¹ (Table 7)[112].

²⁰ The New Policies Scenario has been renamed The Stated Policies Scenario, by contrast, incorporates today’s policy intentions and targets to underline that it considers only specific policy initiatives that have already been announced. The aim is to hold up a mirror to the plans of today’s policy makers and illustrate their consequences, not to guess how these policy preferences may change in the future. This trajectory is consistent with limiting the temperature increase to below 2.7 °C above pre-industrial averages with a 50% probability (or below 3.2 °C with 66% probability)[110].

602 **Table 7: Comparison of our modeling results in future global EV stock in 2030 with recent**
 603 **literature**

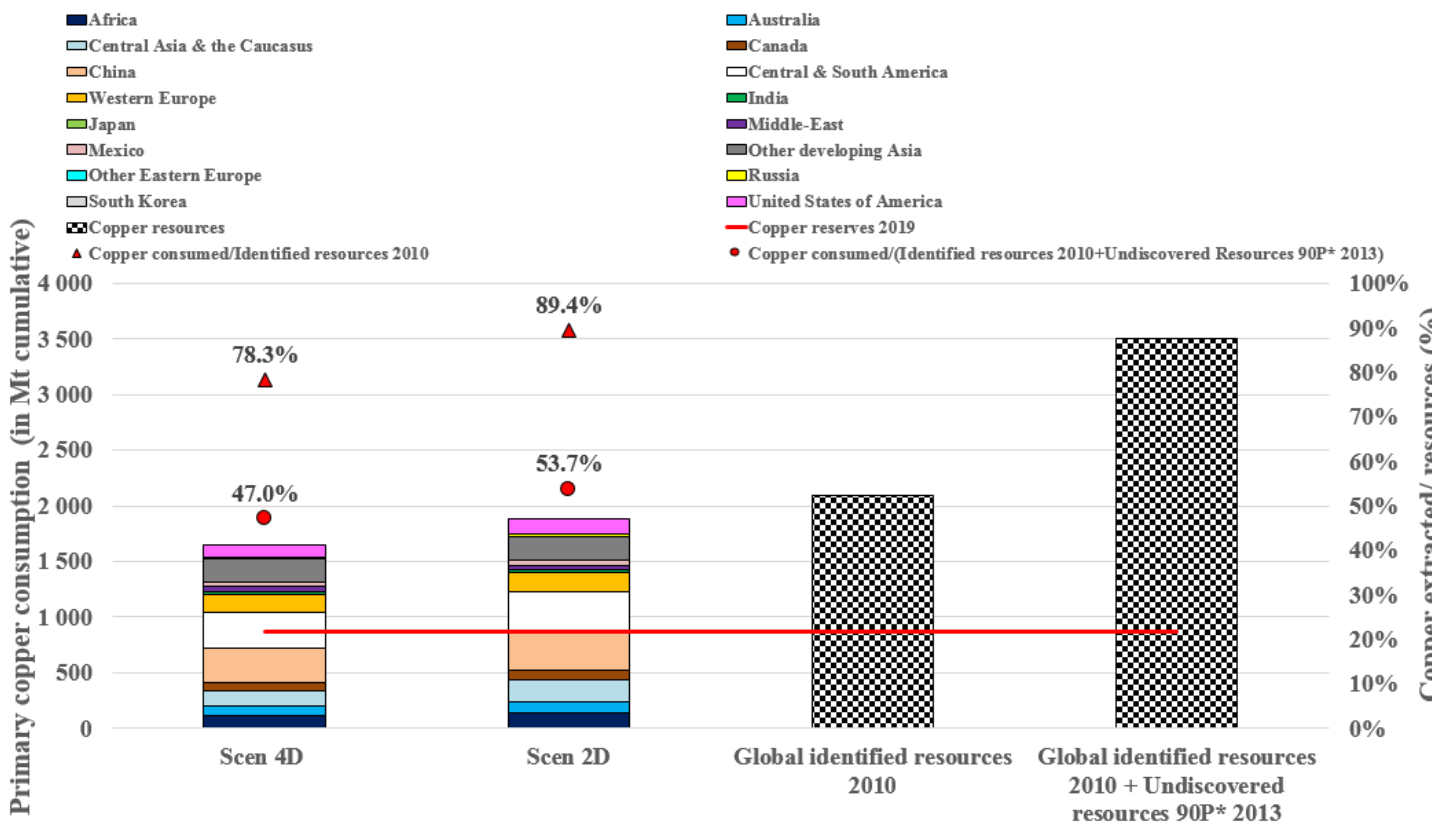
	Our results		IEA GEVO 2019 [112]	
	4°C Scenario	2°C Scenario	Stated Policies scenario	EV30@30 scenario
2030	110 million	180 million	130 million	250 million

604 3.2. The impact of the energy transition on global copper demand
 605 We aim to quantify the impact of the energy transition on copper resources. We therefore
 606 compare the remaining copper resources in 2050 under the most stringent 4°C and 2°C climate
 607 scenarios, i.e. with the “Business-As-Usual” mobility. Both scenarios assume that resources are
 608 available for copper mining at current cost. This rather optimistic assumption does not impose
 609 any delay in the conversion of resources into reserves. This simplifies the modelling and allows
 610 us to avoid any arbitrary assumptions about the timing of future copper reserves development. In
 611 addition, assuming that the copper contained in resources is available, the total amount of copper
 612 required can be quantified based on our scenarios, as described above. Fig. 14 and Fig. 15
 613 compare total cumulative copper extracted from the mines and the total cumulative copper
 614 consumed, respectively, between 2010 and 2050 with the global identified copper resources in
 615 2010 [100], and the global identified copper resources in 2010 plus the estimated undiscovered
 616 resources in 2013 [113] under climate scenarios. According to the graphs, the two leftmost bars
 617 represent cumulative global extraction/or consumption of copper in the 4°C and 2°C scenarios,
 618 and its distribution among the producing/or consuming regions. The two rightmost bars depict the
 619 global identified copper resources in 2010, and the global identified copper resources plus the
 620 estimated undiscovered copper resources at 90% chance assessed in 2013. The global reserves in

²¹ The EV30@30 Scenario takes into account the pledges of the Electric Vehicle Initiative’s EV30@30 Campaign to reach a 30% market share for EVs in all modes except two-wheelers by 2030 [112].

621 2019 according to the USGS are represented by the horizontal red line in both graphs. On the
 622 right axis, we have defined an indicator for a dynamic assessment of copper criticality either the
 623 copper extraction or the copper consumption as a reference. This indicator, which could be also
 624 called the safety margin, is calculated as the ratio of cumulative copper extracted/ or consumed to
 625 the resources.

626 **Fig. 14: Comparison between cumulative primary copper production through to 2050 under two**
 627 **climate scenarios and the identified and undiscovered copper worldwide in 2013**



628 Source: USGS, Authors' results
 629 "90P" indicates a 90-percent chance of at least the amount shown, with other percentiles similarly defined
 630

631 According to the Fig. 14, between 2010 and 2050, 78.3% and 89.4% of the global identified
 632 copper resources will be extracted in the 4°C and 2°C scenarios, respectively. These latter
 633 criticalities in copper mining will fall to 47% and 53.7%, respectively, if the undiscovered copper
 634 resources estimated at a 90% chance, as assumed by the USGS, are also available. In comparison,
 635 the current copper reserves in 2019, which is 870 Mt, would not be sufficient after 2035 or 2040

636 to satisfy the copper extraction evolution in average in the 2°C and 4°C scenarios, respectively.
 637 However, it should be noted that our cumulative primary copper demand is around 1600-1900 Mt
 638 between 2015 and 2050 with a recycling rate of 45% while it is estimated around 800-1000 Mt in
 639 Schipper et al. [55] for the SSP1, SSP2 and SSP5 scenarios, with each 70% and 90% recycling
 640 rates. In addition, they reminded that recycling rates of 70 and 90% are extremely speculative,
 641 they are used to represent an ideal situation regarding recycling. Reaching 70–90% recycling rate
 642 of copper would require significant changes in the way products are designed, and would be
 643 difficulty to acquire in short term. Elshkaki et al. [56] have obtained cumulative primary copper
 644 production between 1500 and 1900 Mt depending on the scenario. These conclusions from this
 645 recent scientific literature are found to be in agreement with our primary copper evolution by
 646 2050 in Fig. 14 (Table 8).

647 **Table 8: Comparison of our modeling results in cumulative primary copper demand between 2015**
 648 **and 2050 with recent literature**

	Our results		Schipper et al. (2018) [55]	Elshkaki et al. (2016) [57]
	4°C scenario	2°C scenario	SSP1, SSP2 and SSP5 scenarios	EF, SF, PF and MF scenarios ²²
Cumulative primary copper demand	1600 Mt	1900 Mt	800 – 1000 Mt	1500 – 1900 Mt
Average recycling rate considered	45%		70% and 90% for each scenario	45%

649

²² These are the four “storylines” of the UNEP GEO-4 foundational scenarios:

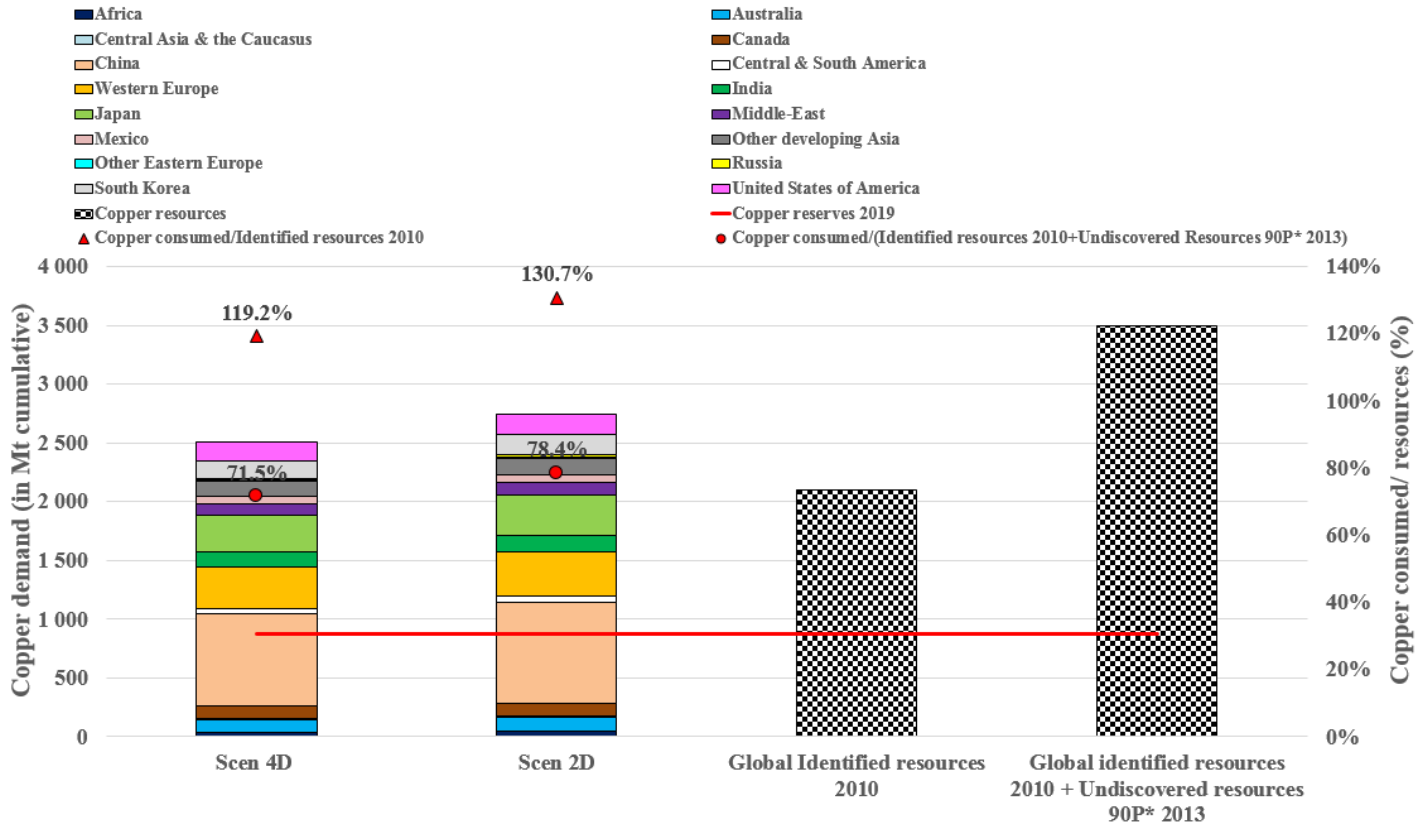
Market First (MF). A market-driven world in which demographic, economic, environmental, and technological trends unfold without major surprise relative to currently unfolding trends.

Policy First (PF). A world in which strong actions are undertaken by governments in an attempt to reach specific social and environmental goals, especially as pertains to renewable energy.

Security First (SF). A world of great disparities where inequality and conflict prevail, brought about by socio-economic and environmental stresses.

Equitability First (EF). A world in which a new development paradigm emerges in response to the challenge of sustainability, supported by new, more equitable values and institutions.

650 Fig. 15: Comparison between cumulative copper consumption through to 2050 under two climate
 651 scenarios and the identified and undiscovered copper worldwide in 2014



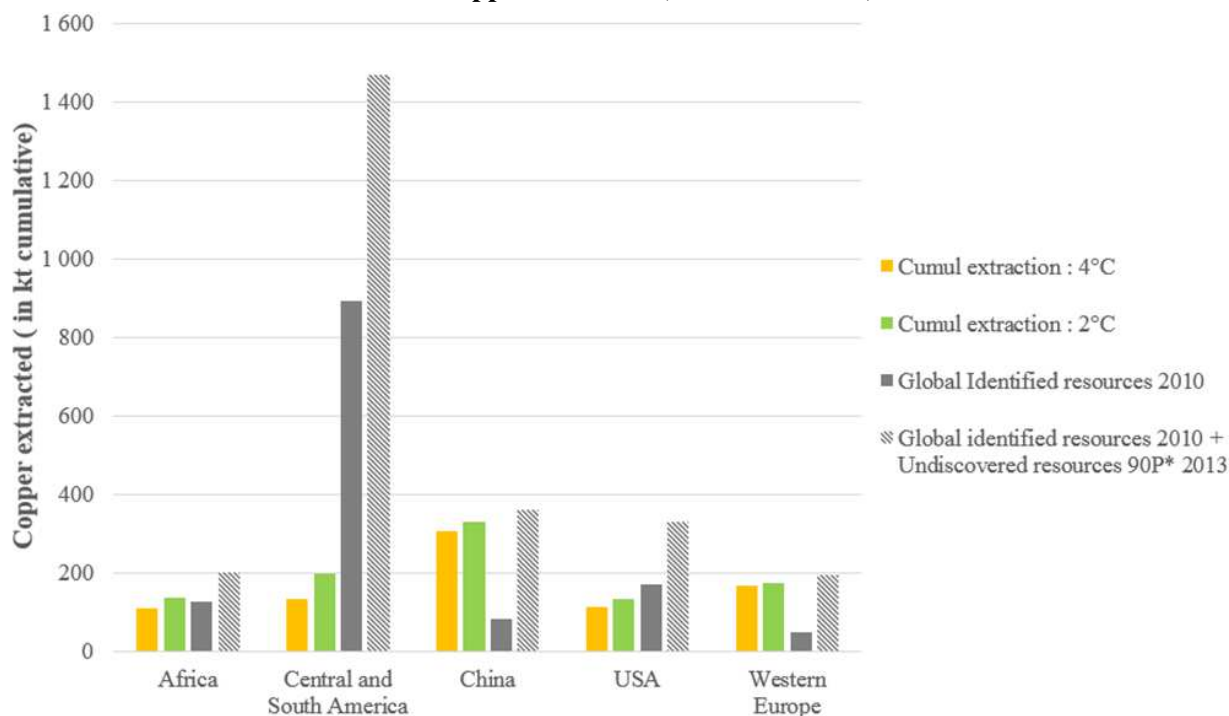
652 Source: USGS, Authors' results
 653 "90P" indicates a 90-percent chance of at least the amount shown, with other percentiles similarly defined

654 Considering copper consumption as a reference in the definition of criticality, the results in Fig.
 655 15, combined with the ones in Fig. 14, show the importance of the secondary production in the
 656 copper demand. Indeed, observing Fig. 15, it can be pinpointed that without any secondary
 657 production, the total cumulative copper consumption between 2010 and 2050 would have been
 658 119.2% and 130.7% of the world's known resources in the 4°C and 2°C scenarios, respectively.

659 These two graphs also highlight the regions which are the most producing, consuming ones or
 660 both. China, Western Europe, Japan and United States of America represent almost 65% of the
 661 total cumulative copper consumption (averaging 31%, 14%, 13% and 6%, respectively) between
 662 2010 and 2050 in the 4°C or 2°C scenarios. While around 60 % of the total cumulative copper

663 mined between 2010 and 2050 was done in only four regions: Central and South America, China,
 664 Other developing Asian countries and Western Europe (averaging 20%, 18%, 13% and 9%,
 665 respectively) in the 4°C and 2°C scenarios.

666 **Fig. 16: Cumulative domestic extractions over the 2010-2050 period in the two climate scenarios and**
 667 **domestic copper resources (in cumulative kt)**



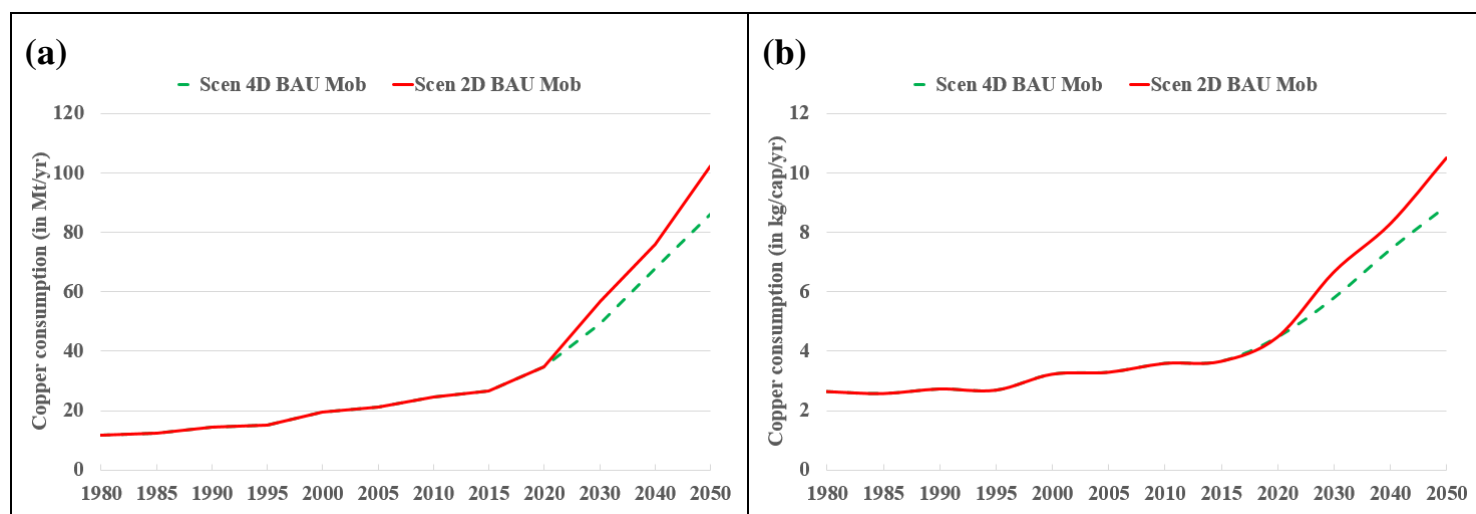
668
 669 Source: USGS, Authors' results

670 China and Western Europe, as can be observed in Fig. 16, extract more than the totality of their
 671 identified domestic resources in both climate scenarios. Taking into account USGS estimates of
 672 undiscovered resources would increase China's copper resources by a factor of 4.48 from their
 673 2010 level. Assuming these resources become exploitable by 2050, we can see that the projected
 674 growth of the Chinese economy and its copper needs are pushing the country to consume all its
 675 resources and to import part of the copper it uses.

676 Three other regions are also represented in Fig. 16: Africa, Central & South America and the
 677 United States of America (USA). They share the characteristic of having abundant copper

678 resources, allowing them to meet domestic demand in both climate scenarios while exporting
 679 primary copper. As expected, Central & South America will obtain an additional rent from
 680 resource extraction in the 4°C and 2°C scenario. This is the geographical area that shows the
 681 greatest difference in the two climate scenarios in terms of copper quantities extracted and
 682 domestic copper consumption (Fig. 14 & Fig. 15). However, the Latin America monopoly may
 683 face a competitive fringe of smaller copper producers. Indeed, according to our results, Africa,
 684 Central Asia & the Caucasus, Canada, Mexico, Russia, the USA and the Other Developing Asian
 685 countries are regions with enough copper resources to meet domestic demand and export to other
 686 regions in both climate scenarios.

687 **Fig. 17: (a) Evolution of the yearly copper consumption (b) Evolution of yearly copper consumption**
 688 **per capita**



689
 690 The yearly copper consumption increases with the growing GDP per capita and will vary from
 691 around 27 Mt in 2015 to around 86 Mt and 102 Mt in 2050 in the 4°C and 2°C scenarios,
 692 respectively (Fig. 17 (a)). These values combined with the evolution of the world population
 693 given by the UN population, the average consumption of copper per inhabitant per year is
 694 calculated to increase from 3.6 kg/cap/yr in 2015 for a GDP per capita (ppp) of 13 102.7 US\$

695 2005 to 8.9 and 10.5 kg/cap/yr in 2050 for a GDP per capita of around 29 200 US\$2005 in the
696 4°C and 2°C scenarios, respectively. According to our results, our global copper demand in 2050
697 is therefore about double or more the value found by Vidal et al. [57] of 45 Mt and the same trend
698 is observed on the copper intensity per capita in 2050. However, Halada et al.[56] estimated the
699 copper consumption of only 10 countries (so-called BRICs (Brazil, Russia, India, China) and the
700 original G6 countries of Japan, USA, UK, France, Germany, and Italy) and they found around 45
701 Mt by 2050. We found our global copper demand to be also in line with the values from top-
702 down method (regressions) or bottom-up stock dynamics method in the three scenarios SSP1,
703 SSP2 and SSP5 estimated by Schipper et al. [55] by 2050 (Table 9).

704 **Table 9: Comparison of our modeling results in global copper demand in 2050 with recent literature**

	Our results		Vidal et al. (2019) [58]	Schipper et al. (2018) [55]	Elshkaki et al. (2016) [57]	Halada et al. (2008) [56]
	4°C scenario	2°C scenario	Main scenario	SSP1, SSP2 and SSP5 scenarios	EF, SF, PF and MF scenarios	Scenario for only 10 countries (BRICS and G6)
Global copper demand in 2050	86 Mt	102 Mt	45 Mt	70 -125 Mt	40 – 70 Mt	45 Mt

705
706 These results pinpoint the fact that the demand for copper will exceed the current reserves as well
707 as ruining almost the global identified resources by 2050. The development of the copper
708 recycling sector would play an important role in the future. It may exist a risk that this geological
709 criticality could hamper the diffusion of low-carbon technologies. To this extent, two policy
710 options have been assessed in the next section.

711

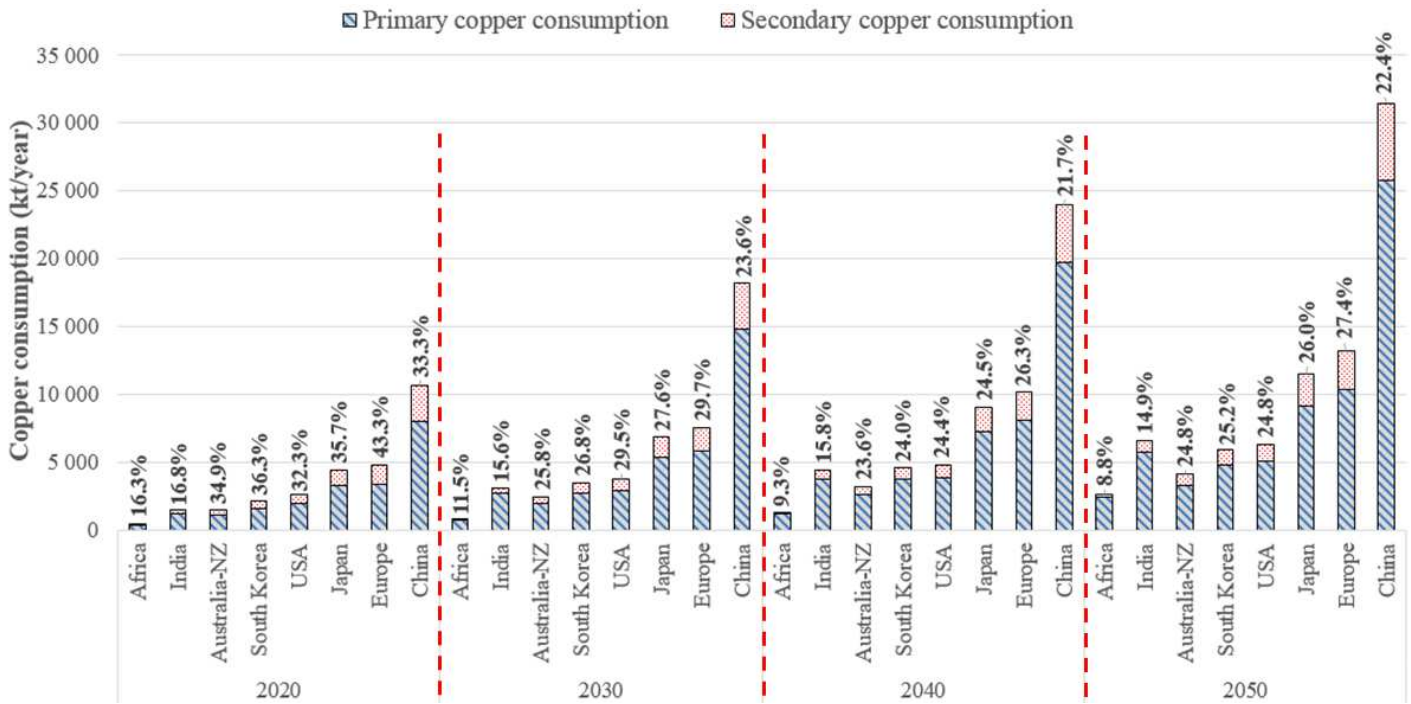
712 3.3. The impact of public policies aimed at reducing world copper demand

713 3.3.1. The regionalized impact of sectorial copper recycling capacities

714 Our results show that the energy transition will require the development of new copper reserves,
715 highlighting the importance of recycling as a key lever for a more efficient use of copper
716 resources. It is relevant to analyse the evolution of recycling over the coming decades, as it
717 illustrates the mechanisms that can lead to secondary (recycled) copper decreasing as a
718 proportion of total copper consumption over time. The growth rate of copper demand and its
719 sectorial composition are two crucial elements in understanding the dynamics of recycling. They
720 jointly determine both the composition of copper scrap, which, depending on its source, will be
721 more or less costly to recycle in the future, and the rate at which copper is immobilized in
722 applications with varying lifetimes. A country that experiences strong growth in copper demand
723 to supply the consumption of dispersive uses therefore runs the risk of seeing the share of its
724 copper demand covered through secondary production decrease over time.

725 This phenomenon has been quantified by our model and is represented in Fig. 18. It shows the
726 evolution of copper consumption in the 2°C scenario over five decades for several major
727 consumer regions. A distinction is made between the two sources of copper consumed: primary
728 copper, and secondary copper from recycling. The share of recycled copper in consumption is
729 expressed as a percentage on the data labels.

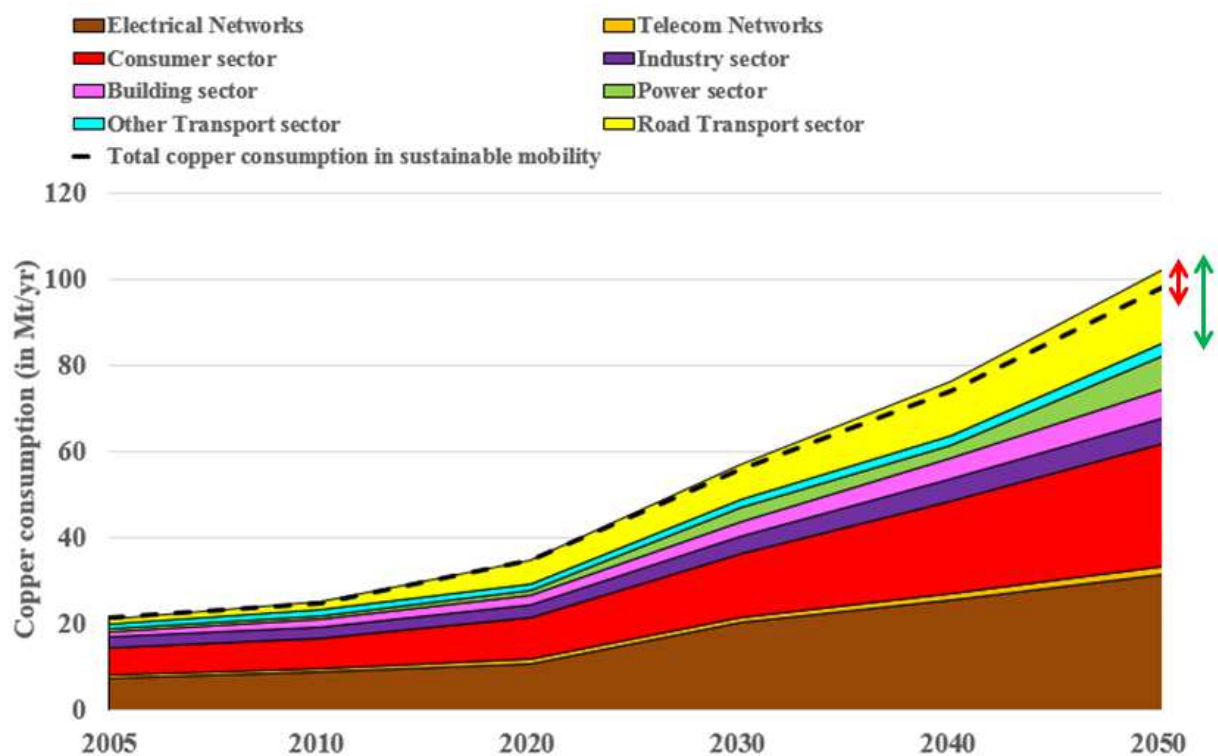
730 **Fig. 18: Evolution and distribution of domestic copper consumption for major consumers (2006-**
 731 **2050) (in kt copper)**



732
 733 Although recycling practices are calibrated on historical data [107], the share of secondary
 734 copper in total copper demand does not remain stable over time because the dynamic speed of the
 735 copper demand and the available scrap copper stock used for recycling are different. This is
 736 particularly important for countries or regions where strong economic growth is expected, such as
 737 Africa, India, and to a lesser extent China. Secondary production accounts for the largest share of
 738 domestic consumption in these countries in 2020. Over time, the acceleration in consumption
 739 outweighs the rate of accumulation of copper scrap available for recycling and demand for
 740 copper is increasingly met through primary production. This result demonstrates the importance
 741 for countries experiencing strong economic growth of developing an efficient upstream copper
 742 recycling sector to reduce import dependency. Europe, Japan, USA and South Korea, due to their
 743 moderate expected economic growth, can maintain relatively stable secondary production share
 744 over time after 2030.

745 3.3.2. The regionalized development of a sustainable mobility in road transport sector
 746 The road transport sector is crucial for the future evolution of copper consumption, as low-carbon
 747 vehicles are more copper-intensive than conventional ones. This sector is a major emitter of
 748 greenhouse gases. The evolution of sectorial consumption is depicted, all regions combined, in
 749 Fig. 19, in a 2°C scenario where road transport mobility is considered to evolve. In this graph, we
 750 represented the results of the 2°C scenario within a “Business-As-Usual” and “Sustainable”
 751 mobility.

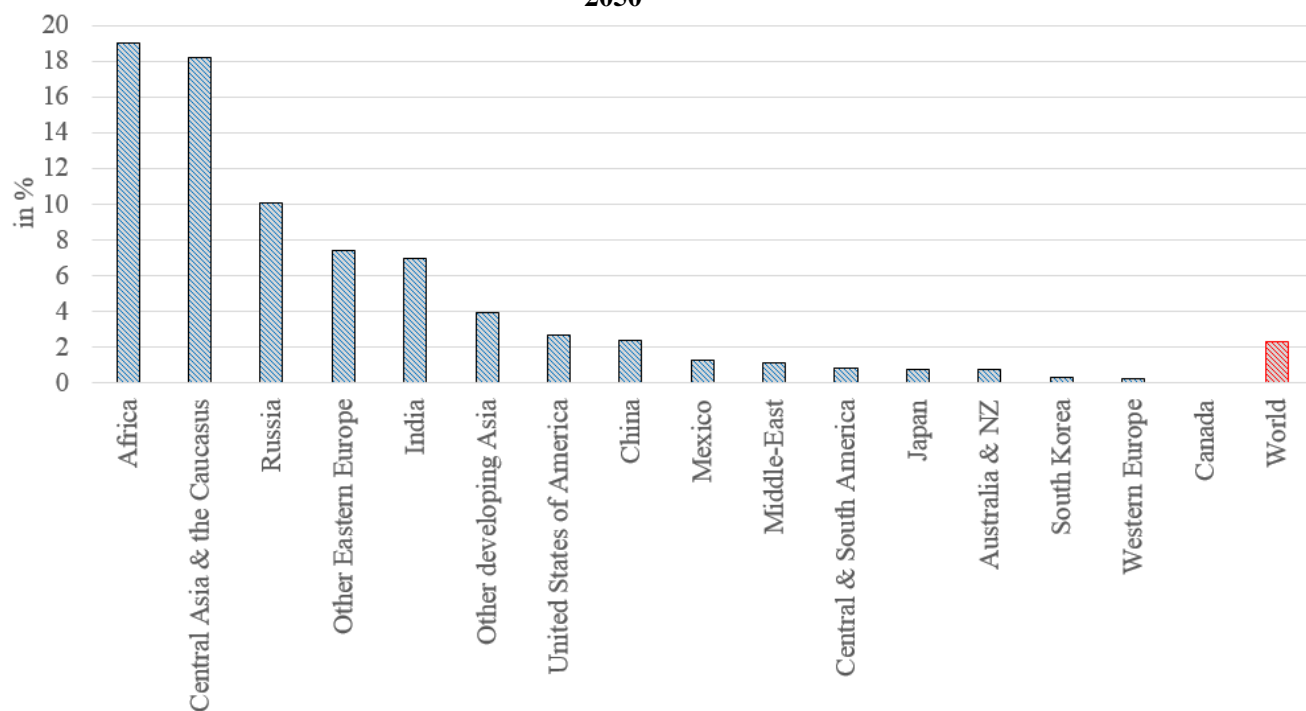
752 **Fig. 19: Evolution of the copper consumption in the 2°C scenario: an assessment of the impact of the**
 753 **transport mobility shift**



754
 755 The dotted line represents the evolution of total copper consumption under a sustainable transport
 756 mobility hypothesis, as detailed in §2.3.3. The area between this dotted line and the upper limit of
 757 the copper consumption of the road transport sector (red arrow) represents the copper
 758 consumption savings achieved through a more sustainable transport mobility. The results in Fig.

759 19 indicate that copper consumption will be driven mainly by three sectors: road transport (green
760 arrow), consumer goods and networks. During the period 2040-2050, the impact of the power
761 generation sector increases due to the fast roll-out of RETs to limit the global temperature rise to
762 2°C as already seen in Fig. 11. Energy transport and telecommunication networks enable the
763 deployment of smart grids and make energy demand more flexible. The consumer goods sector is
764 a highly diverse group of goods. Public policies and market forces will help regulate consumption
765 more effectively than rationing, which obviously has practical and political limits. The road
766 transport sector thus triggers copper savings: the implementation of sustainable mobility policies
767 would reduce the ecological impacts of mobility while limiting use of copper resources.
768 Here, we focus on the consequences of more sustainable mobility on copper consumption. It
769 varies significantly across the model's regions. To account for these differences, the share of
770 reduction in total copper consumption over the period 2010-2050 attributable to a sustainable
771 transport mobility in a 2°C climate scenario is represented in Fig. 20.

772 **Fig. 20: Share of copper consumption avoided through a sustainable mobility scenario (in %), 2010-**
 773 **2050**



774
 775 For most countries, these reduce cumulative copper consumption over the period 2010-2050 are
 776 between 2% to 20%. Countries and regions where sustainable mobility has only a small effect on
 777 copper consumption are Canada, Western Europe, South Korea, Australia-NZ, and Japan. This
 778 results from the combined effects of transport policies, socio-economic development and urban
 779 population density evolution. Indeed, most OECD worldwide have constantly adjusted their
 780 transport policies over time through an integrated approach to land use and transport planning,
 781 transport pricing (congestion pricing schemes, road tolls) and parking restrictions to challenge car
 782 attractiveness, while providing alternative modes of transport [17]. These measures, combined
 783 with these (OECD) countries' constant urban population density through to 2050, have helped
 784 reduce car dependency (including, among other indicators, a reduced vehicle ownership rate²³),
 785 therefore keeping vehicle stocks constant or slightly down, through switches to more sustainable

²³ The number of vehicles per 1000 inhabitants.

786 modes of transport. The case of the United States of America and Canada should be noticed here
787 due to their high car dependency. As expected in Canada, the development of modes of mobility
788 such as public and non-motorized transport will be more difficult due to the country
789 configuration while in the USA this transport shift will have higher impact than in other OECD
790 countries. For other regions, mostly non-OECD, the contrary is observed in the current transport
791 structure. In the case of a BAU mobility scenario, they are likely to evolve towards a very high
792 dependence on cars due to a lack of efficient public transport infrastructure. This explains the
793 high share of primary copper consumption saved in these countries under a sustainable mobility
794 scenario. The case of China, India and Other Developing Asian countries (ODA) should be
795 highlighted due to the predominance of 2/3-wheelers. In a sustainable mobility scenario, a slight
796 switch from cars to this mode of transport will also be observed. In the case of China and India
797 for example, due to their scale and combined with more public and non-motorized mobility,
798 significant quantities of copper can be saved. At the global level, if all regions implement policies
799 aimed at achieving more sustainable mobility, overall cumulative copper consumption could be
800 reduced by 2.3%.

801 4. Conclusion

802 We assess the criticality risk for copper in the context of the energy transition. For the first time,
803 an energy system optimization model has been developed to integrate both a detailed
804 representation of the copper supply chain and the copper content of the technologies available in
805 two major sectors of the energy transition: power and transport.

- 806 • The first interest of our modelling approach is to link the diffusion of low-carbon
807 technologies to copper resources. The technological mix and its evolution therefore
808 interact directly with the rate of copper-resource depletion. Our scenarios demonstrate
809 that 78.3% of the copper resources known in 2010 will have to be extracted from the

810 ground between 2010 and 2050 in a 4°C scenario, and 89.4% in a 2°C scenario. China
811 and Europe are set to become highly dependent on external sources, and Central and
812 South America will provide a significant portion of copper production to meet the
813 additional demand resulting from the energy transition although other regions such as
814 Africa, Central Asia & the Caucasus, Canada, Mexico, Russia, the USA and the Other
815 Developing Asian countries with enough copper resources to meet domestic demand and
816 export to other regions in both climate scenarios. When considering the final copper
817 consumption, the global identified resources will have not be sufficient if recycling would
818 have not been considered. Indeed, the cumulative final copper consumption between 2010
819 and 2050 is found to be at around 119.2% and 130.7% of the global copper resources
820 known in 2010 for the 4°C and 2°C scenarios, respectively. These results show that the
821 rate of increase in world copper consumption is likely to put pressure on existing copper
822 production capacity. In this context, there rapid increase in copper consumption should be
823 followed by the development of copper recycling sectors or demand management policies
824 in order to not hamper the energy transition process. Our results therefore underline the
825 importance of policies to smooth future demand trends.

826 • Two public policy options have also been considered in these analyses in order to reduce
827 the rate of growth of copper demand: strengthening recycling capacities and accelerating
828 sustainable mobility policies.

829 ✓ With regard to recycling, our results highlight the importance of
830 strengthening copper recycling channels now, particularly in countries with
831 strong growth prospects. The rate of deployment of copper-intensive and
832 long-life technologies is the highest in these countries. This changes the
833 sectorial composition of the copper scrap flow available for recycling each

834 year and, ultimately, can reduce the share of secondary copper in total
835 copper consumption.

836 ✓ Another option could be to implement a sustainable transport mobility
837 policy in order to reduce demand for low-carbon and copper-intensive
838 vehicles. This could be supported by strong transport policies aimed at
839 reducing car dependency and promoting the use of alternative modes of
840 transport (walking, cycling, shared mobility, and public transport). While
841 copper savings may seem minor at global level, this strategy may be
842 important for some countries. Indeed, several of the model's regions,
843 including Africa, Central Asia and the Caucasus, Russia, Other Eastern
844 European countries, India, and Other Developing Asian countries could
845 reduce their cumulative consumption of copper consumption by more than
846 5% over the period 2010-2050.

847 • While our scenarios show the importance of the copper resources held by the region
848 Central and South America (Chile and Peru). This region does not eliminate uncertainty
849 about the ability and willingness of its producing countries to continue increasing copper
850 production capacities, particularly due to environmental externalities (local pollution and
851 water resource availability) caused by the exploitation of the ore produced.

852 Other perspectives of our global model for further research on copper, in particular, would be to
853 analyse the impact of an increasing recycling rate, while also in general, it would be relevant to
854 implement and analyse the impact of water resource availability on some major raw material
855 production, therefore on the energy transition. The integration of other strategic materials such as
856 cobalt, nickel and rare-earth metals (neodymium, terbium, lanthanum among others) would be
857 very valuable with the increasing deployment of Electric Vehicles (EVs) and Renewable Energy

858 Technologies (RETs). This new global energy model could be very useful as a decision-making
859 tool to better understand investments in low-carbon technologies based on future raw material
860 resource constraints for better sectorial assessment.

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868 5. References

- 869 [1] Alliance Nationale de Coordination de la Recherche pour l'Energie (ANCRE), 2015,
870 Rapport Ressources minérales et énergie, 75p. [https://www.allianceenergie.fr/wp-](https://www.allianceenergie.fr/wp-content/uploads/2017/06/Ancre_Rapport_2015-Ressources_minerales_et_energie_0.pdf)
871 [content/uploads/2017/06/Ancre_Rapport_2015-Ressources_minerales_et_energie_0.pdf](https://www.allianceenergie.fr/wp-content/uploads/2017/06/Ancre_Rapport_2015-Ressources_minerales_et_energie_0.pdf)
- 872 [2] World Bank, 2017, The Growing Role of Minerals and Metals for a Low Carbon Future,
873 Washington,
874 [http://documents.worldbank.org/curated/en/207371500386458722/pdf/117581-WP-](http://documents.worldbank.org/curated/en/207371500386458722/pdf/117581-WP-P159838-PUBLIC-ClimateSmartMiningJuly.pdf)
875 [P159838-PUBLIC-ClimateSmartMiningJuly.pdf](http://documents.worldbank.org/curated/en/207371500386458722/pdf/117581-WP-P159838-PUBLIC-ClimateSmartMiningJuly.pdf).
- 876 [3] OECD, 2018, Global Material Resources Outlook to 2060. Economic drivers and
877 environmental consequences, Paris.
- 878 [4] Kolotzek C., Helbig C., Thorenz A., Reller A., Tuma A., 2018, A company-oriented model
879 for the assessment of raw material supply risks, environmental impact and social
880 implications, Journal of Cleaner Production 176, p566-580.
- 881 [5] Baldi L., Peri M., Vandone D., 2014, Clean Energy Industries and Rare Earth Materials:
882 Economic and financial issues, Energy Policy 66, p53-61.
- 883 [6] Glöser, S., Tercero Espinoza, L., Gandenberger, C., Faulstich, M., 2015, Raw material
884 criticality in the context of classical risk assessment. Resour. Pol. 44, p35-46.

- 885 [7] Harper E.M., Diao, Z., Panousi, S., Nuss, P., Eckelman, M.J., Graedel, T.E., 2015a. The
886 criticality of four nuclear energy metals. *Resources, Conservation and Recycling* 95, p193-
887 201
- 888 [8] Harper E.M., Kavlak, G., Burmeister, L., Eckelman, M.J., Erbis, S., Sebastian Espinoza,
889 V., Nuss, P., Graedel, T.E., 2015b, Criticality of the geological zinc, tin, and lead family.
890 *Journal of Industrial Ecology* 19, p628-644
- 891 [9] Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander,
892 E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M., Zhu, C., 2012,
893 Methodology of metal criticality determination. *Environ. Sci. Technol.* 46, p1063-1070.
- 894 [10] Nassar N.T., Du, X., Graedel, T.E., 2015, Criticality of the rare earth elements. *Journal of*
895 *Industrial Ecology* 19, p1044-1054
- 896 [11] Bach, V., Berger, M., Henßler, M., Kirchner, M., Leiser, S., Mohr, L., Rother, E., Ruhland,
897 K., Schneider, L., Tikana, L., Volkhausen, W., Walachowicz, F., Finkbeiner, M., 2016,
898 Integrated method to assess resource efficiency – ESSENZ, *J. Clean. Prod.* 137, p118-130
- 899 [12] Bach V., Finogenova N., Berger M., Winter L., Finkbeiner M., 2017, Enhancing the
900 assessment of critical resource use at the country level with the SCARCE method – Case
901 study of Germany, *Resources Policy* 53, p283–299
- 902 [13] Bonnet, C., Carcanague, Hache, E., S., Seck, G., Simoen, M., 2019, Some geopolitical
903 issues of the energy transition, Working Paper GENERATE n°4, 19p.
- 904 [14] Kushnir D., Sanden B.A., 2012, The time dimension and lithium resource constraints for
905 electric vehicles, *Resources Policy* 37, pp93–103.
- 906 [15] Speirs J., Contestabile M., Houari Y., Gross R., 2014, The future of lithium availability for
907 electric vehicle batteries, *Renewable and Sustainable Energy Reviews* 35, pp183-193.
- 908 [16] Hache, E., Seck, G., Simoen, M., 2018, Electrification du parc automobile mondial et
909 criticité du lithium à l'horizon 2050", ADEME-IFPEN Report, 75p.
910 [https://www.ademe.fr/electrification-parc-automobile-mondial-criticite-lithium-a-lhorizon-](https://www.ademe.fr/electrification-parc-automobile-mondial-criticite-lithium-a-lhorizon-2050)
911 2050
- 912 [17] Hache E., Seck, G.S., Simoën, M., Bonnet, C., Carcanague, S., 2019a, Critical raw
913 materials and transportation sector electrification: A detailed bottom-up analysis in word
914 transport, *Applied Energy* 240, pp.6-25.
- 915 [18] Helbig, C., Bradshaw A. M., Wietschel L., Thorenz A., Tuma A., 2018, Supply risks
916 associated with lithium-ion battery materials, *Journal of Cleaner Production* 172, pp274-
917 286.

- 918 [19] Alonso E., Sherman A., Wallington T., Everson M., Field F., Roth R., Kirchain R., 2012,
919 Evaluating rare earth element availability: a case with revolutionary demand from clean
920 technologies. *Environ. Sci. Technol* 46, pp3406–3414.
- 921 [20] Baldi L., Peri M., Vandone D., 2014, Clean Energy Industries and Rare Earth Materials:
922 Economic and financial issues, *Energy Policy* 66, pp.53–61.
- 923 [21] Nassar, N.T., Du, X., Graedel, T.E., 2015, Criticality of the rare earth elements. *Journal of*
924 *Industrial Ecology* Volume 19, p1044-1054.
- 925 [22] Hache, E., Carcanague, S., Bonnet, C., Seck, G., Simoën, M., 2019b, Vers une géopolitique
926 de l'énergie plus complexe ?, *Revue Internationale et Stratégique* n°113, Printemps 2019,
927 pp.73-81.
- 928 [23] Tilton, J.E., 2003a, *On Borrowed Time? Assessing the Threat of Mineral Depletion*
929 (Resources for the Future, Washington, DC).
- 930 [24] Tilton, J. E., 2003b, Assessing the threat of mineral depletion. *Minerals and Energy-Raw*
931 *Materials Report*, 18(1), 33-42.
- 932 [25] Gordon, R.B., Bertram, M., Graedel, T.E., 2006, Metal stocks and sustainability. *Proc.*
933 *Natl. Acad. Sci. États-Unis* 103, 1209–1214.
- 934 [26] Tilton, J.E., Lagos, G., 2007, Assessing the long-run availability of copper, *Resources*
935 *Policy*, Volume 32, Issues 1–2, pp.19-23, ISSN 0301-4207,
936 <https://doi.org/10.1016/j.resourpol.2007.04.001>.
- 937 [27] Gordon, R.B., Bertram, M., Graedel, T.E., 2007, On the sustainability of metal supplies: A
938 response to Tilton and Lagos, *Resources Policy* 32, pp. 24-28.
- 939 [28] Vidal O., 2018, *Matières premières et énergie: les enjeux de demain*. Collection Energie,
940 ISTE Editions.
- 941 [29] International Wrought Copper Council/ International Copper Association, 2019, dataset,
942 <https://copperalliance.org/trends-and-innovations/data-set/>
- 943 [30] Ballinger B., Schmeda-Lopez D., Kefford B., Parkinson B., Stringer M., Greig C., Smart
944 S., 2020, The vulnerability of electric-vehicle and wind-turbine supply chains to the supply
945 of rare-earth elements in a 2-degree scenario, *Sustainable Production and Consumption* doi:
946 <https://doi.org/10.1016/j.spc.2020.02.005>
- 947 [31] Wübbecke, J., 2013, Rare earth elements in China: Policies and narratives of reinventing an
948 industry. *Resources Policy* 38, pp. 384–394.

- 949 [32] European Commission, 2008, The Raw Materials Initiative—Meeting our Critical Needs
950 for Growth and Jobs in Europe, COM(2008)699 final. European Commission (EC),
951 Brussels, Belgium.
- 952 [33] European Commission, 2011, Tackling the Challenges in Commodity Markets and on Raw
953 Materials, COM (2011) 25 final. European Commission, Brussels, Belgium.
- 954 [34] European Commission, 2014, Report on Critical Raw Materials for the EU, Report of the
955 Ad-hoc Working Group on Defining Critical Raw Materials. European Commission (EC),
956 Brussels, Belgium.
- 957 [35] European Commission, 2017, Report on the 2017 list of Critical Raw Materials for the EU.
958 European Commission (EC), Brussels, Belgium.
- 959 [36] U.S. Congress, 1939, Strategic and Critical Materials Stock Piling Act, Act of June 7, 1939,
960 ch. 190, 53 stat. 811 enacted by the 76th United States Congress
- 961 [37] Sörme, L., Bergbäck, B. & Lohm, U., 2001, Century Perspective of Heavy Metal Use in
962 Urban Areas. A Case Study in Stockholm. *Water, Air, & Soil Pollution: Focus* 1, 197–211.
963 <https://doi.org/10.1023/A:1017564407076>
- 964 [38] Zhang L., Yuan Z., Bi J., 2011, Estimation of Copper In-use Stocks in Nanjing, China,
965 *Journal of Industrial Ecology*, <https://doi.org/10.1111/j.1530-9290.2011.00406.x>
- 966 [39] van Beers D., Graedel T.E., 2007, Spatial characterisation of multi-level in-use copper and
967 zinc stocks in Australia, *Journal of Cleaner Production* 15, Issues 8–9, pp. 849-861
- 968 [40] Hao M., Wang P., Song L., Dai M., Ren Y., Chen W-Q., 2020, Spatial distribution of
969 copper in-use stocks and flows in China: 1978–2016, *Journal of Cleaner Production* 261,
970 121260
- 971 [41] Soulier M., Pfaff M., Goldmann D., Walz R., Geng Y., Zhang L., Tercero Espinoza L. A.,
972 2018a, The Chinese copper cycle: Tracing copper through the economy with dynamic
973 substance flow and input-output analysis, *Journal of Cleaner Production* 195 (2018)
974 435e447
- 975 [42] Zhang L., Yang J., Cai Z., Yuan Z., 2014, Analysis of copper flows in China from 1975 to
976 2010, *Science of The Total Environment* 478, 15 April 2014, Pages 80-89
- 977 [43] Gorman M., Dzombak D., 2020, Stocks and flows of copper in the U.S.: Analysis of
978 circularity 1970–2015 and potential for increased recovery, *Resources, Conservation and*
979 *Recycling* 153, February 2020, 104542

- 980 [44] Wang M., Liang Y., Yuan M., Cui X., Yang Y., Li X., 2018, Dynamic analysis of copper
981 consumption, in-use stocks and scrap generation in different sectors in the U.S. 1900–2016,
982 *Resources, Conservation and Recycling* 139, December 2018, Pages 140-149
- 983 [45] Chen W., Wang M., Li X., 2016, Analysis of copper flows in the United States: 1975–
984 2012, *Resources, Conservation and Recycling* 111, August 2016, Pages 67-76
- 985 [46] Spatari S., Bertram M., Gordon R.B., Henderson K., Graedel T.E., 2005, Twentieth century
986 copper stocks and flows in North America: A dynamic analysis, *Ecological Economics* 54,
987 Issue 1, pp. 37-51
- 988 [47] Soulier M., Glöser-Chahoud S., Goldmann D., Tercero Espinoza L.A., 2018b, Dynamic
989 analysis of European copper flows, *Resources, Conservation & Recycling* 129 (2018) 143–
990 152
- 991 [48] Bonnin M., Azzaro-Pantel C., Pibouleau L., Domenech S., Villeneuve J., 2013,
992 Development and validation of a dynamic material flow analysis model for French copper
993 cycle, *chemical engineering research and design* 91, pp. 1390–1402
- 994 [49] Glöser, S., Soulier, M., Tercero Espinoza, L.A., 2013, Dynamics analysis of global copper
995 flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty
996 evaluation, *Environmental Science & Technology* 47, pp. 6564-6572.
- 997 [50] Mearns R., Giurco D., Mudd G., Mason L., 2012, Life cycle assessment: a time-series
998 analysis of copper, *Journal of Cleaner Production* 33, pp. 97-108
- 999 [51] Song X., Pettersen J.B., Pedersen K.B., Røberg S., 2017, Comparative life cycle assessment
1000 of tailings management and energy scenarios for a copper ore mine: A case study in
1001 Northern Norway, *Journal of Cleaner Production* 164, pp. 892-904
- 1002 [52] Jingjing C., Zhaohui W., Yufeng W., Liquan L., Bin L., De'an P., Tiejong Z., 2019,
1003 Environmental benefits of secondary copper from primary copper based on life cycle
1004 assessment in China, *Resources, Conservation and Recycling* 146, pp. 35-44
- 1005 [53] Fisher F.M., Cootner P.H., Baily M.N., 1972, An econometric model of the world copper
1006 industry, Massachusetts Institute of Technology and Stanford University, 50 memorial
1007 drive Cambridge, mass. 02139
- 1008 [54] Rohatgi P.K., Weiss C., 1977, Technology Forecasting for Commodity Projections: A Case
1009 Study on the Effect of Substitution by Aluminum on the Future Demand for Copper,
1010 *Technological Forecasting and Social Change* 11, 2546
- 1011 [55] Schipper B.W., Lin H-C., Meloni M.A., Wansleeben K., Heijungs R., van der Voet E.,
1012 2018, Estimating global copper demand until 2100 with regression and stock dynamics,
1013 *Resources, Conservation and Recycling* 132, pp. 28-36

- 1014 [56] Halada K., Shimada M., Ijima K., 2008, Forecasting of the Consumption of Metals up to
1015 2050, *Materials Transactions* 49, pp. 402-410
- 1016 [57] Elshkaki A., Graedel T.E., Ciacci L., Reck B.K., 2016, Copper demand, supply, and
1017 associated energy use to 2050, *Global Environmental Change* 39, pp. 305-315
- 1018 [58] Vidal O., Rostom F.Z., François C., Giraud G., 2019, Prey–Predator Long-Term Modeling
1019 of Copper Reserves, Production, Recycling, Price, and Cost of Production, *Environ. Sci.*
1020 *Technol.* 53, pp. 11323–11336
- 1021 [59] Zhang L., Yang J., Cai Z., Yuan Z., 2015a, Understanding the Spatial and Temporal
1022 Patterns of Copper In-Use Stocks in China, *Environ. Sci. Technol.* 49, pp. 6430–6437
- 1023 [60] Zhang L., Cai Z., Yang J., Yuan Z., Chen Y., 2015b, The future of copper in China—A
1024 perspective based on analysis of copper flows and stocks, *Science of the Total Environment*
1025 536, pp. 142–149
- 1026 [61] Habib K., Hamelin L., Wenzel H., 2016, A dynamic perspective of the geopolitical supply
1027 risk of metals, *Journal of Cleaner Production* 133, pp. 850-858
- 1028 [62] Dutta T, Kim K-H., Uchimiya M., Kwon E. E., Jeon B-H., Deep A., Yun S-T., 2016,
1029 Global demand for rare earth resources and strategies for green mining, *Environmental*
1030 *Research* 150, pp. 182-190.
- 1031 [63] Rollat A., Guyonnet D., Planchon M., Tuduri J., 2016, Prospective analysis of the flows of
1032 certain rare earths in Europe at the 2020 horizon, *Waste Management* 49, pp. 427-436
- 1033 [64] Wang X., Yao M., Li J., Zhang K., Zhu H., Zheng M., 2017a, China’s Rare Earths
1034 Production Forecasting and Sustainable Development Policy Implications, *Sustainability* 9,
1035 1003
- 1036 [65] Wang X., Lei Y., Ge J., Wu S., 2015, Production forecast of China's rare earths based on
1037 the Generalized Weng model and policy recommendations, *Resources Policy* 43, pp. 11-18
- 1038 [66] Roper L.D., 2009, World Mineral Reserves. Website With Hubbert’s Type Variant of
1039 Resource Assessment
- 1040 [67] Laherrere J., 2010, Copper Peak. Posted by de Sousa, L., 2010 The oil drum Europe April 1,
1041 2010. 6307:1-27
- 1042 [68] Wang J., Guo M., Liu M., Wei X., 2020, Long-term outlook for global rare earth
1043 production, *Resources Policy* 65, 101569
- 1044 [69] Pauliuk, S., Arvesen, A., Stadler, K, Hertwich, E. G., 2017, Industrial Ecology in Integrated
1045 Assessment Models. *Nature Clim. Change* 7, 13-20. <https://doi.org/10.1038/nclimate3148>

- 1046 [70] Kuipers K.J.J., van Oers L.F.C.M., Verboon M., van der Voet E., 2018, Assessing
 1047 environmental implications associated with global copper demand and supply scenarios
 1048 from 2010 to 2050, *Global Environmental Change* 49, pp. 106–115
- 1049 [71] Hertwich, E., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D.,
 1050 Ramirez, A., Vega, M.I. Shi, L., 2015. Integrated life-cycle assessment of electricity-supply
 1051 scenarios confirms global environmental benefit of low-carbon technologies, *PNAS*,
 1052 Volume 112, Issue 12, pp. 6277-6282.
- 1053 [72] McLellan, B.C., Yamasue, E., Tezuka, T., Corder, G., Golev, A., Giurco, D., 2016, *Critical
 1054 Minerals and Energy—Impacts and Limitations of Moving to Unconventional Resources.
 1055 Resources* 5, 19.
- 1056 [73] Kalvig, P., Machaceg, E., 2018. Examining the rare-earth elements (REE) supply– demand
 1057 balance for future global wind power scenarios. *GEUS - Geological Survey of Denmark
 1058 and Greenland Bulletin* 41, pp. 87–90.
- 1059 [74] Imholte D.D., Nguyen R.T., Vedantam A., Brown M., Iyer A., Smith B.J., Collins J.W.,
 1060 Anderson C.G., O’Kelley B., 2018, An assessment of U.S. rare earth availability for
 1061 supporting U.S. wind energy growth targets, *Energy Policy* 113, pp. 294-305
- 1062 [75] Habib K., Hansdóttir S. T., Habib H., 2020, Critical metals for electromobility: Global
 1063 demand scenarios for passenger vehicles, 2015–2050, *Resources, Conservation and
 1064 Recycling* 154, 104603
- 1065 [76] Deetman S., Marinova S., van der Voet E., van Vuuren D., Edelenbosch O., Heijungs R.,
 1066 2020, Modelling Global Material Stocks and Flows for Residential and Commercial
 1067 Buildings towards 2050, *Journal of Cleaner Production* 245, 118658
- 1068 [77] Marinova S., Deetman S., Van der Voet E., 2020, Global construction materials database
 1069 and stock analysis of residential buildings between 1970-2050, *Journal of Cleaner
 1070 Production* 247, 119146
- 1071 [78] Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D.,
 1072 Baynes, T., Lenzen, M., Owen, A., 2016, Decoupling Global Environmental Pressure and
 1073 Economic Growth: Scenarios for Energy Use, Materials Use and Carbon Emissions.
 1074 *Journal of Cleaner Production* 132, 45-56. <https://doi.org/10.1016/j.jclepro.2015.06.100>
- 1075 [79] Gunasekara, D, Ford, M, Heyhoe, E, Ahammad, H, Phipps, S, Harman, I, Finnigan, J and
 1076 Brede, Markus, 2008, Global Integrated Assessment Model: A New Analytical Tool for
 1077 Assessing Climate Change Risks and Policies. *Australian Commodities* 15, pp. 195-216.
- 1078 [80] Baynes, T., West, J., Schandl, H., McFallan, S., 2014, MEFISTO: material and energy flows
 1079 integrated with stocks. In: *Gordon Research Conference Industrial Ecology*. Lucca, Italy.

- 1080 [81] Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013, Building Eora: a global multi-
 1081 region input-output database at high country and sector resolution. *Econ. Syst. Res.* 25, pp.
 1082 20-49.
- 1083 [82] Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R.,
 1084 Kirchain, R.E., 2012, Evaluating rare earth element availability: a case with revolutionary
 1085 demand from clean technologies. *Environ. Sci. Technol.* 46, pp. 3406-3414
- 1086 [83] Wang X., Ge J., Li J., Han A., 2017b, Market impacts of environmental regulations on the
 1087 production of rare earths: a computable general equilibrium analysis for China, *Journal of*
 1088 *Cleaner Production* 154, pp. 614-620
- 1089 [84] Ge J., Lei Y., Zhao L., 2016, China's Rare Earths Supply Forecast in 2025: A Dynamic
 1090 Computable General Equilibrium Analysis, *Minerals* 6, 95
- 1091 [85] Cao, Z.; Liu, G.; Zhong, S.; Dai, H.; Pauliuk, S., 2019, Integrating Dynamic Material Flow
 1092 Analysis and Computable General Equilibrium Models for Both Mass and Monetary
 1093 Balances in Prospective Modeling: A Case for the Chinese Building Sector. *Environmental*
 1094 *Science & Technology* 53 (1), pp. 224-233. <https://doi.org/10.1021/acs.est.8b03633>
- 1095 [86] Northey S., Mohr S., Mudd G.M., Weng Z., Giurco D., 2014, Modelling future copper ore
 1096 grade decline based on a detailed assessment of copper resources and mining, *Resources,*
 1097 *Conservation and Recycling* 83, pp. 190-201
- 1098 [87] Mohr, S H, 2010, Projection of World Fossil Fuel Production With Supply and Demand
 1099 Interactions. PhD Thesis, Department of Chemical Engineering, University of Newcastle,
 1100 Newcastle, NSW, 783 p.
- 1101 [88] Mudd, G.M., Weng, Z., Memary, R., Northey, S. A., Giurco, D., Mohr, S., and Mason, L.,
 1102 2012, Future greenhouse gas emissions from copper mining: assessing clean energy
 1103 scenarios. Prepared for CSIRO Minerals Down Under Flagship by Monash University and
 1104 Institute for Sustainable Futures, UTS. ISBN 978-1-922173-48-5
- 1105 [89] Fishbone, L. G., Giesen, G., Goldstein, G., Hymmen, H. A., Stocks, K.J., Vos, H., 1983,
 1106 User's Guide for MARKAL (BNL-51701), Brookhaven National Laboratory, Upton, New
 1107 York.
- 1108 [90] Loulou, R., Goldstein, G., Noble, K., 2004, Documentation for the MARKAL family
 1109 models. ETSAP, <http://www.etsap.org>
- 1110 [91] Loulou, R., Remme, U., Kanudia, A., Lehtila, A., Goldstein, G., 2016, Documentation for
 1111 the TIMES model. ETSAP, <http://www.etsap.org>

- 1112 [92] Loulou, R., Labriet, M., 2008, ETSAP-TIAM: the TIMES integrated assessment model Part
 1113 I: Model structure, Computational Management Science, February, Volume 5, Issue 1–2,
 1114 pp. 7–40.
- 1115 [93] Fulton L., Cazzola P., Cuenot F., 2009, IEA Mobility Model (MoMo) and its use in the
 1116 ETP 2008, Energy Policy 37, p3758-3768.
- 1117 [94] KanORS-EMR, 2018, TIAM-World description, [https://www.kanors-emr.org/models/tiam-](https://www.kanors-emr.org/models/tiam-world)
 1118 world
- 1119 [95] Nordhaus, W. D., Boyer J., 1999, Roll the DICE Again: Economic Models of Global
 1120 Warming. Yale University, manuscript edition
- 1121 [96] Kang S., Selosse S., Maizi N., 2018, Contribution of global GHG reduction pledges to
 1122 bioenergy expansion, Biomass and Bioenergy 111, p142-153.
- 1123 [97] Selosse S, Ricci O., 2014, Achieving negative emissions with BECCS in the power sector:
 1124 new insights from the TIAM-FR model. Energy 7, pp.967–75.
- 1125 [98] Van der Zwaan B., Kober T., Longa F. D., van der Laan A., Kramer G. J., 2018, An
 1126 integrated assessment of pathways for low-carbon development in Africa, Energy Policy
 1127 117, p387-395.
- 1128 [99] Anandarajah G, McDowall W, Ekins P., 2013, Decarbonizing road transport with hydrogen
 1129 and electricity: long term global technology learning scenarios. International Journal
 1130 Hydrogen Energy 38, pp.3419–32.
- 1131 [100] Mudd, G. M., Weng, Z., Jowitt, S. M., 2013, A detailed assessment of global Cu resource
 1132 trends and endowments. Economic geology 108, pp. 1163-1183.
- 1133 [101] Davenport W.G., King M., Schlesinger M. Biswas A.K., 2002, Extractive Metallurgy of
 1134 Copper, Ed. Pergamon
- 1135 [102] Boulamanti, A., Moya, J. A., 2016, Production costs of the non-ferrous metals in the EU
 1136 and other countries : Copper and zinc. Resources policy 49, pp. 112-118.
- 1137 [103] Batker, D., Schmidt, R., 2015, Environmental and social benchmarking analysis of Nautilus
 1138 Mineras Inc. Solwara 1 project. Earth economics.
- 1139 [104] Vidal O., 2018, Mineral Resources and Energy, ISBN 978-1-78548-267-0, 170p.
- 1140 [105] Vidal O., Goffé B., Arndt N., 2013, Metals for a low-carbon society, Nature Geoscience 6,
 1141 pp. 894–896
- 1142 [106] Burnham, A., 2012, Updated Vehicle Specifications in the GREET Vehicle-Cycle Model,
 1143 Technical publication. Argonne National Laboratory

1144 [107] Glöser, S., Soulier, M., Tercero Espinoza, L.A., 2013, Dynamics analysis of global copper
1145 flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty
1146 evaluation, *Environmental Science & Technology* 47, pp. 6564-6572.

1147 [108] Tercero Espinoza, L.A., Soulier, M., 2018, Defining regional recycling indicators for
1148 metals. *Resources, conservation & recycling* 129, pp. 120-128.

1149 [109] United Nations (UN), Department of Economic and Social Affairs, Population Division,
1150 2019, Probabilistic Population Projections Rev. 1 based on the World Population Prospects
1151 2019 Rev. 1: <http://population.un.org/wpp/>

1152 [110] International Energy Agency (IEA), 2019, World Energy Outlook (WEO)

1153 [111] Seck G. S., Krakowski V., Assoumou E., Maizi N., Mazauric V., 2020, Embedding power
1154 system's reliability within a long-term Energy System Optimization Model: Linking high
1155 renewable energy integration and future grid stability for France by 2050, *Applied Energy*
1156 257, 114037

1157 [112] International Energy Agency (IEA), 2019, Global EV Outlook (GEVO) 2019: Scaling-up
1158 the transition to electric mobility.

1159 [113] USGS, 2014, Estimate of Undiscovered Copper Resources of the World in 2013.

1160 [114] International Energy Agency, 2018, World Energy Outlook 2018.

1161 [115] International Renewable Energy Agency, 2018, Renewable Power Generation Costs in
1162 2017.

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1172 6. Supplementary materials

1173 **Appendix A: International trade in copper**

1174 The 16 regions defined in the TIAM-IFPEN model

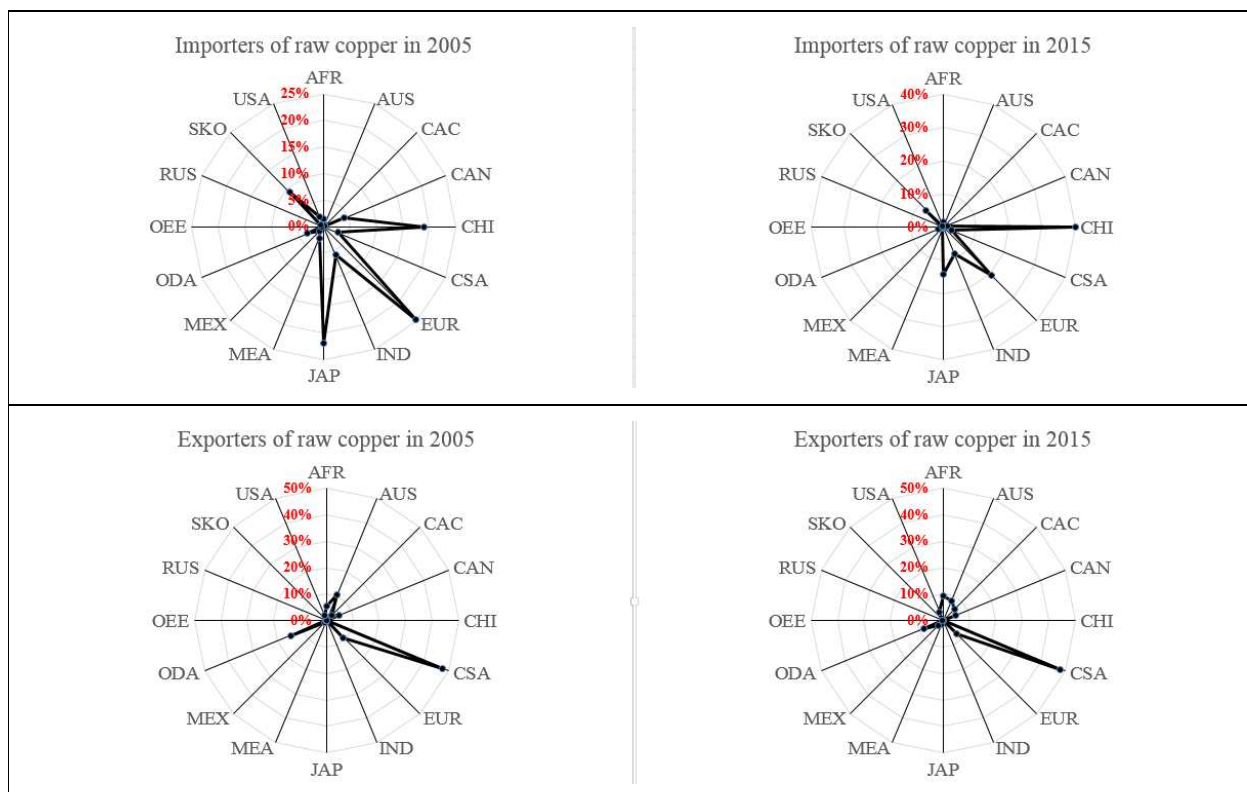
1175 **Table 10 : Regions of the TIAM-IFPEN model**

TIAM name	Region
AFR	Africa
AUS	Australia and New Zealand
CAN	Canada
CHI	China
CSA	Central & South America (Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Other Latin America, Panama, Paraguay, Peru, Trinidad-Tobago, Uruguay, Venezuela)
IND	India
JAP	Japan
MEA	Middle-East (Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, Yemen)
MEX	Mexico
ODA	Other Developing Asia (Bangladesh, Brunei, Chinese Taipei, Indonesia, North Korea, Malaysia, Myanmar, Nepal, Oceania, Other Asia, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam)
SKO	South Korea
USA	United States of America
EUR	Western Europe (Austria, Belgium, Denmark, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, UK)
RUS	Russia
CAC	Central Asia and The Caucasus (Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan)
OEE	Other Eastern Europe (Albania, Belarus, Bosnia-Herzegovina, Macedonia, Montenegro, Serbia, Ukraine, Moldova)

1176
1177 The evolution of the raw copper trade between 2005 and 2015 is depicted in Fig. 21. The
1178 increasing importance of China as a raw copper importer is clearly pinpointed while imports have
1179 decreased in other parts of the world. This illustrates China's strategy of specializing in copper

1180 refining, as further supported by the evolution of the trade structure of refined copper discussed
 1181 below. The exporting region CSA-Central and South America (Chile and Peru) dominates raw
 1182 copper exports, reflecting its large reserves.

1183 **Fig. 21: Distribution of raw copper imports and exports (in % of global monetary value) for the**
 1184 **years 2005 and 2015**

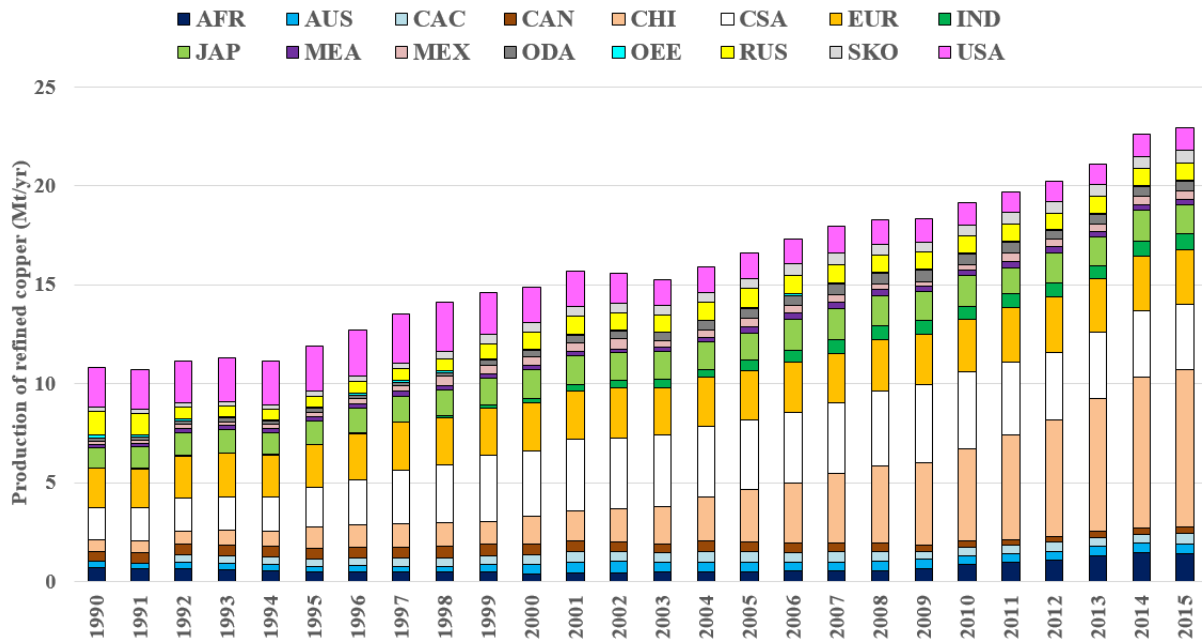


1185 Source: Resourcetrade.earth

1186 The annual production of refined copper disaggregated by region over the 1990-2015 period is
 1187 represented in Fig. 22. Consistent with its growing imports of raw copper, China has become the
 1188 leader in refined copper production. This performance stands out, given that production of refined
 1189 copper in other regions has stayed rather stable, suggesting that China has acquired leadership on
 1190 the refined copper market while facing low competition from countries such as Japan, Russia and
 1191 the USA.

1192

Fig. 22: Production of refined copper (Mt/yr)



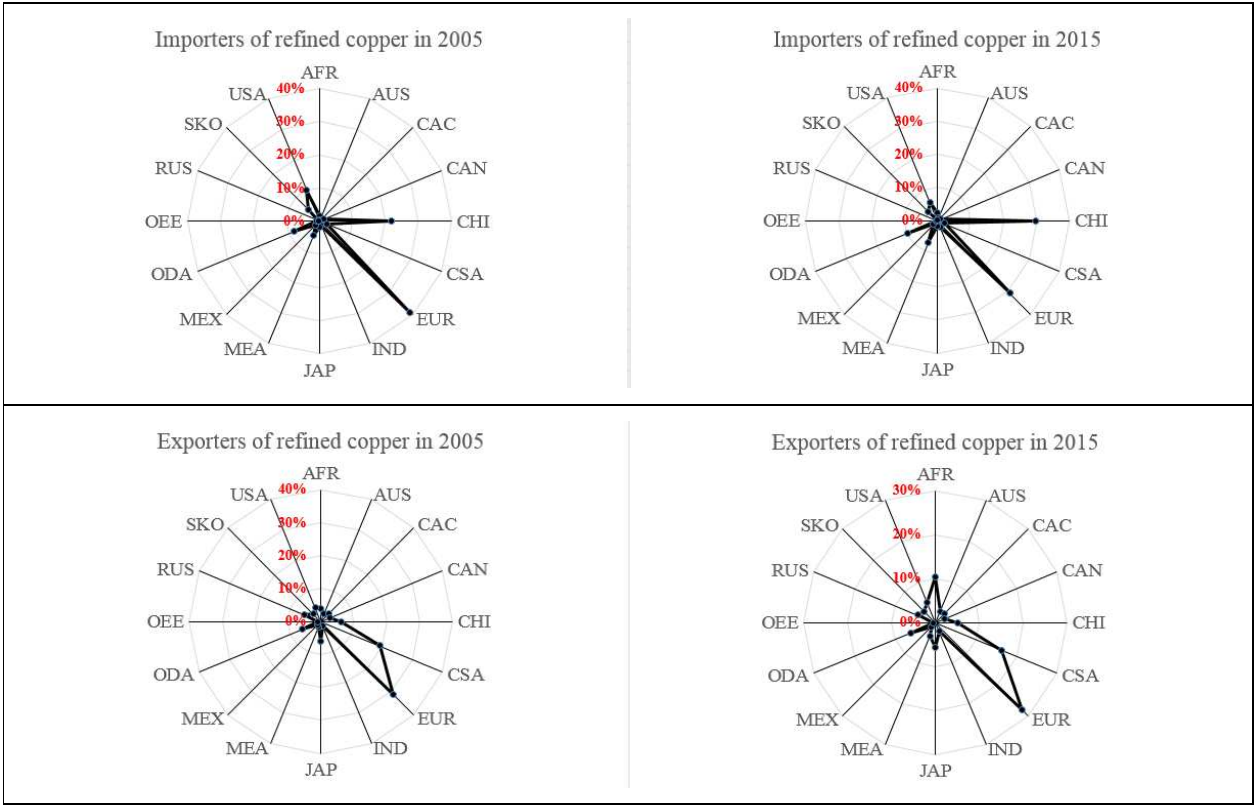
1193

Source: USGS

1194 CSA copper production increased until 1999 before stabilizing. Further insights into the Chinese
1195 strategy can be deduced from the refined copper trade structure and its evolution, represented in
1196 Fig. 23. It seems that China has increased its refined copper production in order to feed its
1197 domestic production of copper-containing products. China is the leader in the production of
1198 refined copper, and also the second-largest importer of the material, accounting for around 30%
1199 of global copper monetary import value in 2015.

1200
1201

Fig. 23: Distribution of refined copper imports and exports (in % of global monetary value) for the years 2005 and 2015



1202

Source: UN Comtrade

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Comparing countries' shares in refined copper exports, we conclude that they are not dominated by the countries with the higher copper reserves. As such, the implementation of the copper trade module would give new geopolitical insight into the regions' future strategies in response to environmental and economic constraints.

1208 **Appendix B: Regionalized mining CAPEX and OPEX**

1209 **Table 11: CAPEX and OPEX retrieved from companies' reports around the world**

Project	Firm(s)	Deposit type	Country	Ore copper grade (%)	Average annual output (kt Cu)	Total capacity (Mt Cu)	Operating costs (US\$/ton Cu)	CAPEX (US\$/ton Cu)
Chuquimata underground mine	Codelco	Porphyry	Chile	0.7	363.8	12.5	2 905.7	343.1
El Teniente New mine project level	Codelco	Porphyry	Chile	0.9	434	17.4	2 905.7	195.7
Cerro Verde mine expansion	Freeport	Porphyry	Peru		272.2	8.2	2 777.8	563.4
Development of Oyu Tolgoi underground mine	Rio Tinto	Porphyry	Mongolia	1.7	560	8.3	2 093.6	639.8
El Arco mine expansion	Southern Copper Corp	Porphyry	Mexico	0.4	190	6.2	2 094.4	471.5
Galore Creek Project	Novagold & Teck	Porphyry	Canada	0.6	146.1	3.1	3 306.9	1 669.2
Wafi-Golpu mines	Harmony Gold & Newcrest	Porphyry	Papua New Guinea	1.3	161	4.5	1 785.7	1 190.7
Kakula	Ivanhoe Mines & Zijin mining group co & Government of Democratic Republic of Congo	Sediment hosted stratabound	Democratic Republic of Congo	5.5	215	5.2	2 711.7	299.6
Kamoa	Ivanhoe Mines & Zijin mining group co & Government of Democratic Republic of Congo	Sediment hosted stratabound	Democratic Republic of Congo	3.8	178	4.8	3 329.0	563.1
Carta Atalaya (project to reopen the old mine)	Rio Tinto	Porphyry	Spain	0.5	32.8	0.6	2 689.6	453.8
Neves Corvo Copper	Somincor (subsidiary of Lunding Mining)	Porphyry	Portugal	1.4	49.5	0.9	3 417.2	335.1
Cukaru Peki (scenario)	Nevsun Company	Porphyry	Serbia	5.7	71.4	0.9	1 543.2	480.1

DSO+Main mine)	LTD.							
Cukaru Peki (scenario DSO+extended mine)	Nevsun Company LTD.	Porphyry	Serbia	3.7	56.6	1.1	2 226.7	428.9
Xietongmen Copper deposit	Continental Minerals Corp of Canada	Porphyry	China	0.5	58.6	0.8	2 035.3	569.5
Jiama copper mine expansion project (phase 2; addition of a new flotation plant, expansion of the underground mine, development of two open pit mines)	China gold international resources	Porphyry	China	0.6	67	2.4	2 566.1	297.9
Tampakan Mine Project	Sagittarius Mines, Indophil and Xstrata	Porphyry	Philippines	0.6	62.2	1.4	888.9	1 600.0

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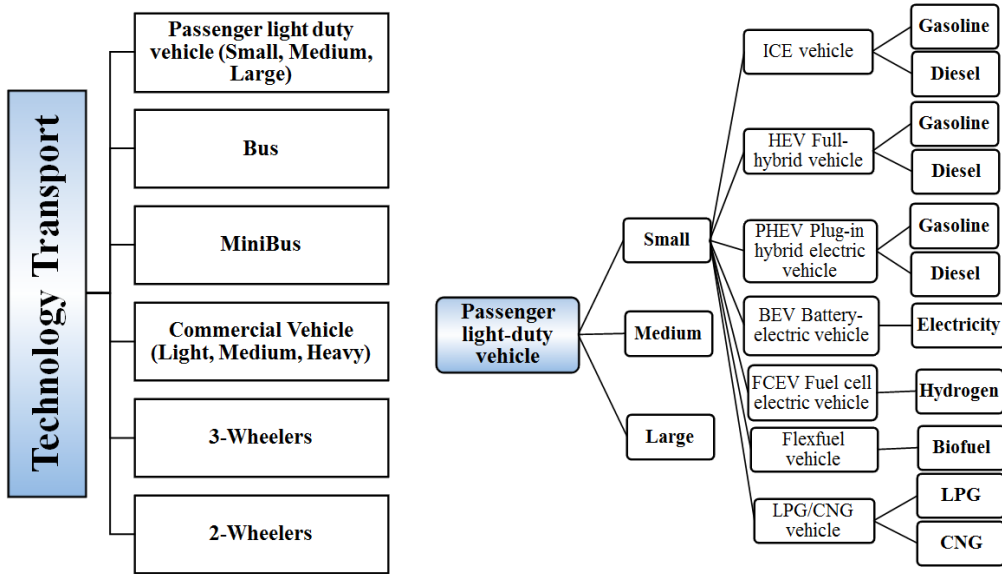
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1224 **Appendix C: Overview of the road transport and power sectors**

1225 The road transport sector has been disaggregated between passenger light-duty vehicles (PLDV)
 1226 (small, medium and large size), buses, minibuses, commercial vehicles (CV) (light, heavy and
 1227 medium trucks) and 2/3-wheelers (Fig. 24). Existing and future vehicles have been accounted for
 1228 with their techno-economical parameters. For all technologies across the entire study period
 1229 2005-2050, we have taken into account efficiency (fuel consumption over short and long
 1230 distances), average annual vehicle mileage, lifespan cost (purchase cost, O&M fixed and variable
 1231 costs), etc. All these attributes have been derived from IEA transport data and the BEAVeR²⁴
 1232 model developed by IFP Énergies Nouvelles (IFPEN).

1233 **Fig. 24: Overview of road transport technologies in the TIAM-IFPEN model**

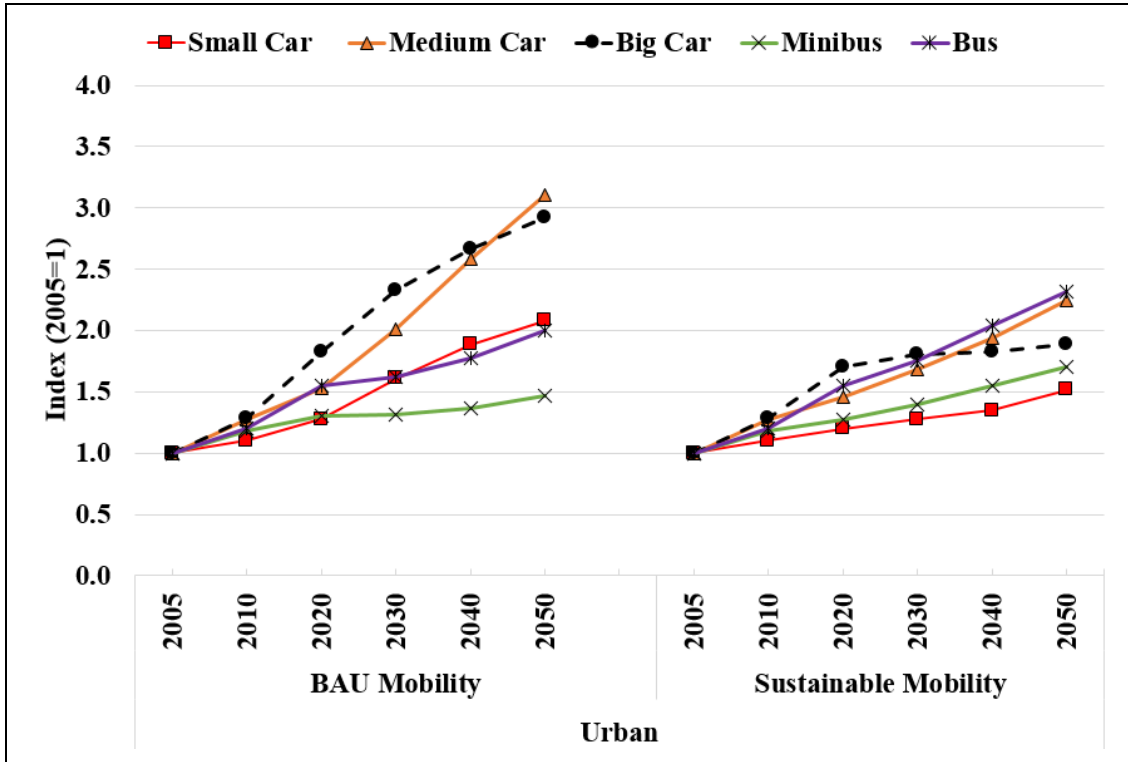


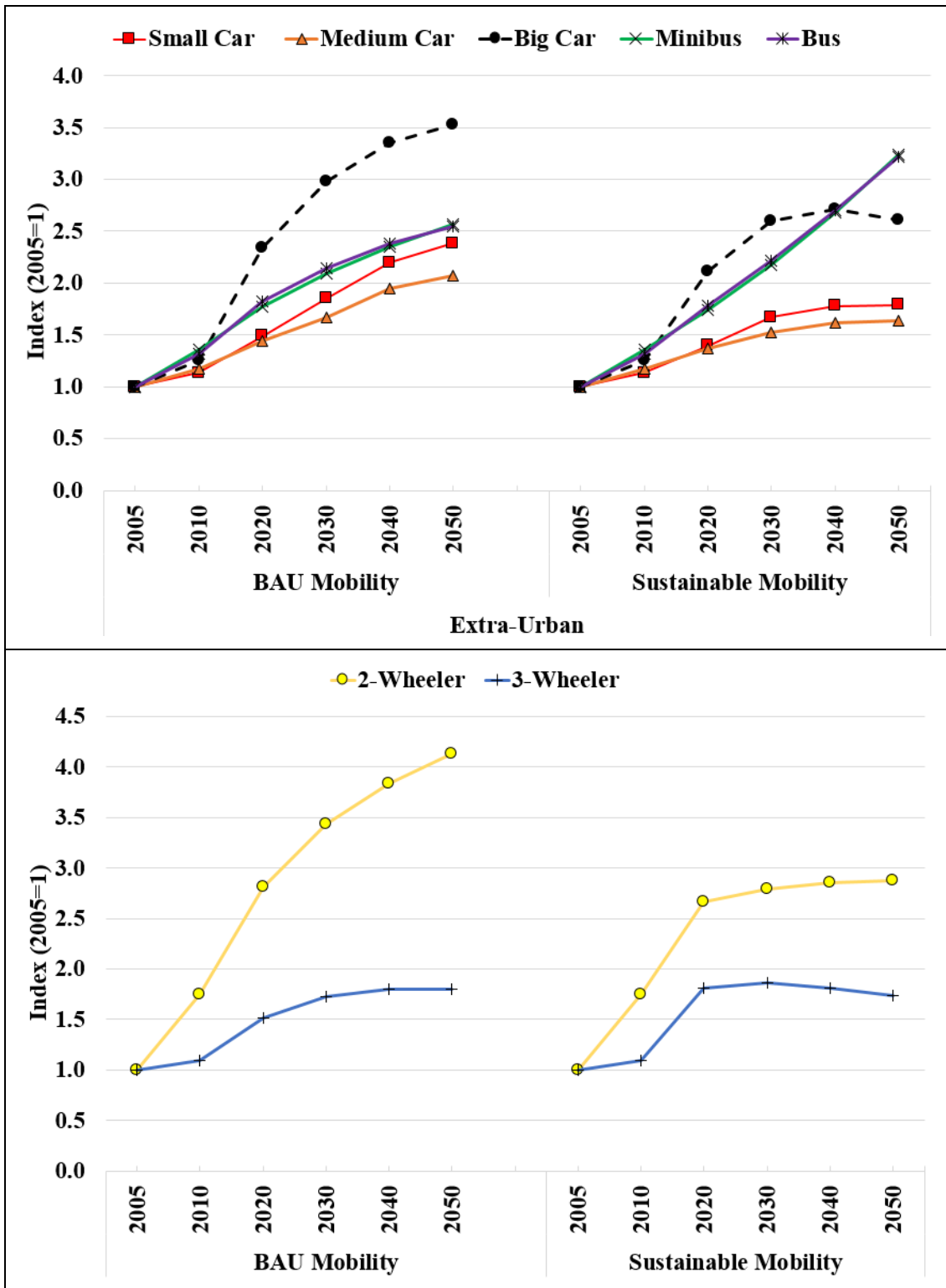
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²⁴ The BEAVeR (Economic and Life-Cycle Assessment of road vehicles) model is a TCO model for calculation and comparison of ownership and usage costs for various road vehicles, including private vehicles, utility vehicles, buses and heavy trucks.

1235 The different mobility demands have been derived from the IEA MoMo model with a
 1236 disaggregation by size and in short and long distance to take into account short distance (urban
 1237 mobility) and long distance (extra-urban mobility) with the roll-out of the electric vehicles.

1238 **Fig. 25 : Evolution of the two different shape of mobility (BAU and Sustainable) according to the**
 1239 **travel mode (Urban and Extra-Urban)**





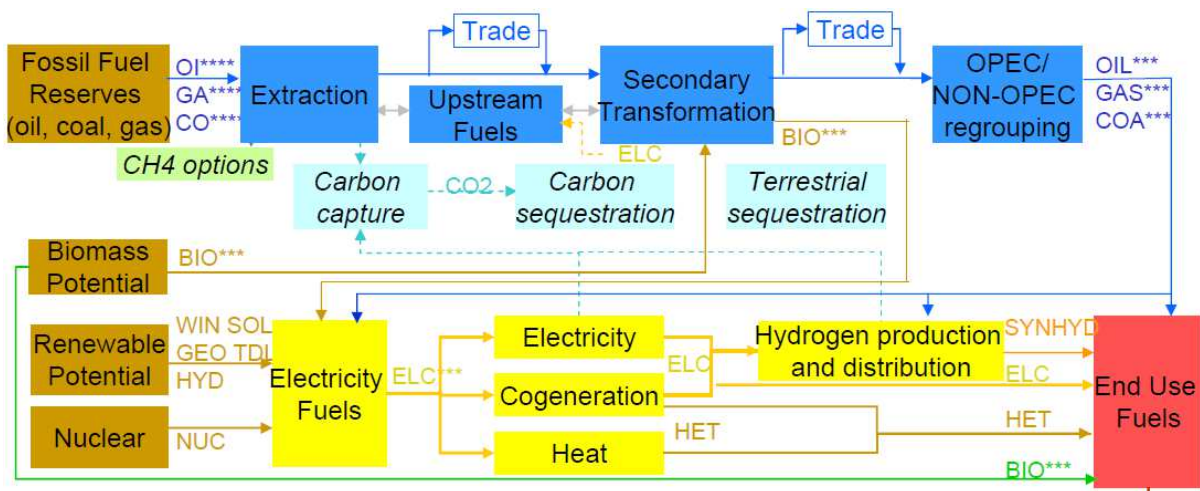
Source: IEA Mobility model 2019

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1242 In the power sector (Fig. 26) , a wide range of fossil and renewable sources have been considered,
 1243 with the characterization of existing and future technologies (additionally categorized as
 1244 centralized or decentralized related to their size) in detail (cost and technical parameters).
 1245 or decentralized related to their size) in detail (cost and technical parameters).

1246 **Fig. 26: Overview of the power sector in the TIAM-IFPEN model**



1247 Source: [92]

1248 The following power generation technologies are covered by the model: renewable energy
 1249 technologies (RETs) (solar PV and CSP, onshore and offshore wind, hydro, biomass), fossil
 1250 technologies (coal, natural gas, oil), and nuclear (For more details of their techno-economic
 1251 assumptions, see [17]). The inventories of existing and future generation technologies were taken
 1252 from the World Energy Outlook 2018 [114], IRENA [115] and the European Commission
 1253 database. Electricity grids are not explicitly modelled and electricity is not traded between
 1254 regions. This is probably not a major limitation as most electricity trade will be intra-region
 1255 (between countries). However, it is important to consider this in further development of the
 1256 model for some regions (e.g., the United States of America and Canada).