1. Supplementary materials

Appendix A: International trade in copper

The 16 regions defined in the TIAM-IFPEN model

TIAM name	Region					
AFR	Africa					
AUS	Australia and New Zealand					
CAN	Canada					
СНІ	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)					

Table 1 : Regions of the TIAM-IFPEN model

The evolution of the raw copper trade between 2005 and 2015 is depicted in Fig. 1. The increasing importance of China as a raw copper importer is clearly pinpointed while imports have decreased in other parts of the world. This illustrates China's strategy of specializing in copper refining, as further supported by the evolution of the trade structure of refined copper discussed below. The exporting region CSA-Central and South America (Chile and Peru) dominates raw copper exports, reflecting its large reserves.



Fig. 1: Distribution of raw copper imports and exports (in % of global monetary value) for the years 2005 and 2015

Source: Resourcetrade.earth

The annual production of refined copper disaggregated by region over the 1990-2015 period is represented in Fig. 2. Consistent with its growing imports of raw copper, China has become the leader in refined copper production. This performance stands out, given that production of refined copper in

other regions has stayed rather stable, suggesting that China has acquired leadership on the refined copper market while facing low competition from countries such as Japan, Russia and the USA.



Fig. 2: Production of refined copper (Mt/yr)

CSA copper production increased until 1999 before stabilizing. Further insights into the Chinese strategy can be deduced from the refined copper trade structure and its evolution, represented in Fig. 3. It seems that China has increased its refined copper production in order to feed its domestic production of copper-containing products. China is the leader in the production of refined copper, and also the secondlargest importer of the material, accounting for around 30% of global copper monetary import value in 2015.

Fig. 3: Distribution of refined copper imports and exports (in % of global monetary value) for the years 2005 and 2015

Source: UN Comtrade

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.

Appendix B: Regionalized mining CAPEX and OPEX

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 strataboun d	Democrati c 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 strataboun d	Democrati c 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	Nevsun	Porphyry	Serbia	5.7	71.4	0.9	1 543.2	480.1

Table 2: CAPEX and OPEX retrieved from companies' reports around the world

(scenario	Company I TD.							
DSO+Main	company Libi							
mine)								
Cukaru Peki								
(scenario	Nevsun	- ·						
DSO+extende	Company LTD.	Porphyry	Serbia	3.7	56.6	1.1	2 226.7	428.9
d mine)								
Xietongmen	Continental							
Copper	Minerals Corp	Porphyry	China	0.5	58.6	0.8	2 035.3	569.5
deposit	of Canada							
Jiama copper								
mine								
expansion								
project (phase								
2; addition of								
a new								
flotation	China gold							
plant,	international	Porphyry	China	0.6	67	2.4	2 566.1	297.9
expansion of	resources							
the								
underground								
mine,								
development								
of two open								
pit mines)								
	Sagittarius							
Tampakan	Mines,	Pornhyry	Philippines	0.6	62.2	1 /	888 0	1 600 0
Mine Project	Indophil and	гогрийту	Funiphines	0.0	02.2	1.4	000.7	1 000.0
	Xstrata							

Appendix C: Overview of the road transport and power sectors

The road transport sector has been disaggregated between passenger light-duty vehicles (PLDV) (small, medium and large size), buses, minibuses, commercial vehicles (CV) (light, heavy and medium trucks) and 2/3-wheelers (Fig. 4). Existing and future vehicles have been accounted for with their techno-economical parameters. For all technologies across the entire study period 2005-2050, we have taken into account efficiency (fuel consumption over short and long distances), average annual vehicle mileage, lifespan cost (purchase cost, O&M fixed and variable costs), etc. All these attributes have been derived from IEA transport data and the BEAVeR¹ model developed by IFP Énergies Nouvelles (IFPEN).



Fig. 4: Overview of road transport technologies in the TIAM-IFPEN model

¹ 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.

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

Fig. 5 : Evolution of the two different shape of mobility (BAU and Sustainable) according to the travel mode (Urban and Extra-Urban)





Source: IEA Mobility model 2019

In the power sector (Fig. 6), a wide range of fossil and renewable sources have been considered, with the characterization of existing and future technologies (additionally categorized as centralized or decentralized related to their size) in detail (cost and technical parameters).

or decentralized related to their size) in detail (cost and technical parameters).



Fig. 6: Overview of the power sector in the TIAM-IFPEN model

The following power generation technologies are covered by the model: renewable energy technologies (RETs) (solar PV and CSP, onshore and offshore wind, hydro, biomass), fossil technologies (coal, natural gas, oil), and nuclear (For more details of their techno-economic assumptions, see (Hache et al., 2019a)). The inventories of existing and future generation technologies were taken from the World Energy Outlook 2018 (International Energy Agency 2018), IRENA (International Renewable Energy Agency 2018) and the European Commission database. Electricity grids are not explicitly modelled and electricity is not traded between regions. This is probably not a major limitation as most electricity trade will be intraregion (between countries). However, it is important to consider this in further development of the model for some regions (e.g., the United States of America and Canada).

Source: (Loulou et Labriet, 2008)