Potential Bottleneck in the Energy Transition: the Case of Cobalt in an Accelerating Electro-Mobility World

Gondia Sokhna Seck, Emmanuel Hache, Charlène Barnet

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Gondia Sokhna SECK[a], Emmanuel HACHE[a,b,c*], Charlène BARNET[a]

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Abstract

Within the context of the energy transition, decarbonization of the transport sector is the cornerstone of many public policies. As a key component in the cathodes of lithium-ion batteries and nickel metal hydride batteries used in electric or hybrid vehicles, cobalt is expected to face a dynamic demand in the coming decades. Numerous questions are arising regarding the criticality risks of this key metal of the energy transition. In order to assess the availability of cobalt until 2050, we rely on our linear programming world energy-transport model, TIAM-IFPEN. Two climate scenarios were considered (2°C and 4°C), each with two different mobility scenarios (Business-as-Usual mobility and Sustainable mobility) and for each mobility scenario, three lithium-ion battery chemistry mix trajectories were considered (high, central and low cobalt content) by 2050. Results show that in the most stringent scenario 83,2% of cobalt resources identified in 2013 would be extracted from the ground by 2050 to satisfy global consumption. Two Thirds of world production is from Africa while China consumes 1/3 of the total demand by 2050. We identify several ways to meet the increasing demand for cobalt resources. Public policies must therefore focus on 3 complementary axes: promoting the development of sustainable mobility; prioritizing low cobalt content batteries in electric vehicles; and concentrating efforts on the implementation and the deployment of a system for recovering, sorting and recycling waste.

Keywords: Energy transition, Transport sector, Critical raw materials, EV battery, Cobalt, Bottom-up modeling

JEL Classification: Q32, Q40, 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, Dr E. Hache, emmanuel.hache@ifpen.fr

Highlights

- Criticality assessment with the first TIAM model with endogenous cobalt supply chain
- Cumulative primary cobalt is 57.9% of current resources in a 2 °C scenario by 2050
- Cumulative cobalt demand is 83% of current resources in a 2 °C scenario by 2050
- Cobalt criticality depends on future cathode evolution in electric vehicle batteries

1. Introduction

To curb climate change and mitigate its environmental consequences, a shift towards more sustainable economies is needed. The renewable energy transition and the rise of electric mobility are put forward as key levers to reduce Greenhouse Gases (GHG) emissions and air pollution, with low-carbon technologies becoming increasingly popular. From 2010 to 2018, the average annual growth rate of the supply of renewables was 2.5%; this figure even reaches 14.4% for new renewables capacity for electricity generation whose growth is driven by solar photovoltaic (PV) (42.8%) and wind power (17.9%) technologies (IEA, 2020a). The same applies to the electric mobility sector. Supported by public policies and technological progress, electric vehicles (EVs) registered an annual average increase of 60% between 2014 and 2019 according to the 2020 Global EV Outlook of the International Energy Agency (IEA, 2020b). There are now 7.2 million electric vehicles around the world, almost half of them in China. This number could reach between 140 million (Stated Policies Scenario) and 245 million (Sustainable Development Scenario) in 2030 according to the IEA scenarios (IEA, 2020b).

The number of countries that have pledged to reach net-zero emissions by mid-century or soon after continues to grow, but so do global greenhouse gas emissions. A considerable number of actions would be needed to turn today's impressive ambitions into reality and tackle the climate crisis, a great challenge of our times. Doing so requires nothing short of a total transformation of the energy systems that underpin our economies (IEA, 2021). These profound transformations and the underlying low-carbon innovations that support them are putting pressure on the consumption of certain raw materials (Bazilian, 2018 ; Deetman et al., 2018) like lithium (Kushnir and Sanden, 2012; Speirs and al., 2014; Hache et al., 2019a), copper (Seck et al. 2020), cement (Hache et al., 2020) or Rare Earth Elements (REEs) (Alonso et al., 2012; Ballinger et al., 2020; Guedes et al., 2020), leading to a more complex future for the geopolitics of energy (Hache, 2018, Hache et al., 2019b). Indeed, while dependence on hydrocarbons could be reduced in the future as low-carbon technologies become more widely deployed, trade relationships and the balance of power might be redefined by the new dependencies generated by mineral-intensive clean technologies (de Ridder, 2013; Nansai et al., 2015; Hache et al., 2018; Månberger and Johansson, 2019).

In this vein, the security of the supply chain of a material such as cobalt is receiving increasing attention because of its use in the production of high-performance alloys and also to make rechargeable batteries. Initially, the main use of cobalt was in the superalloy sector, but this changed in 2006, when batteries became the first end-use sector (USGS, 2008).

Today, the manufacture of rechargeable batteries – mainly of the lithium-ion, nickel-cadmium, and nickel-metal-hydride types – accounts for 55% of cobalt end-use, and this upward trend looks set to continue. As cobalt is a key element in many other fields (aerospace, defense, energy, telecommunications) (Fortier et al., 2018), the question arises as to whether the supply of cobalt can satisfy world demand in all sectors in the medium or long term. The issue of cobalt supply security is not new, however. As early as in the 1980s, the United States, Japan, the United Kingdom, France and the Federal Republic of Germany were acknowledging the strategic character of cobalt for their economies and seeking to minimize their dependence on foreign cobalt by stockpiling or planning to do so (Sibley, 1980; Promisel and Gray, 1982). Gupta and Gupta (1983), using an econometric method, were among the first to quantify the future demand for cobalt based on past data. In the late 2000s, as low-carbon technologies began their breakthrough, criticality assessment studies for strategic materials flourished as a means of anticipation and to enable strategic planning. States then began to release official lists of critical materials to their economies: the European Union (Critical Raw materials, European Raw Materials Alliance), the United States (List of critical minerals issued by the Office of the Secretary, Interior), Australia (Critical Minerals Strategy), Japan, China (Barteková and Kemp, 2016) are a few examples.

The notion of criticality is not universal and the evaluation that is made depends on the methodology used and the risks studied. Graedel and Nuss (2014) define criticality as an approach based on an assessment of the risks associated with the production, use, or end-of-life management of a raw material. From one study to another and depending on the prism adopted, a metal can therefore be qualified as critical or not, as shown by the literature reviews carried out on this theme (Erdmann and Graedel, 2011; Hayes and McCullough, 2018; Watari et al., 2020). These can be economic, geopolitical, technological, environmental, or social in nature. Much of the early literature was then dedicated to the criticality of REEs, but in recent years a growing number of other metals have been covered (Hache et al., 2019a). From the review of the literature on criticality, it appears that cobalt is of great interest. Thus, cobalt is treated in 22 of the 88 publications studied by Watari et al. (2020), making it the 10th most represented element in these criticality studies even though it is not the most critical element according to the Yale University methodology (Graedel et al., 2015). In their effort to organize and evaluate the latest comprehensive criticality studies, Hayes and McCullough (2018) found out that cobalt is among the elements the most commonly identified as critical. Extensive and well-recognized work on the criticality of energy transition metals has been conducted by teams from the U.S. Geological Survey's National Mineral Information Centre and from the Centre for Industrial Ecology, School of Forestry and Environmental Studies of Yale University. Graedel (2011) wrote about the availability of what he called "Energy Metals" and warned of the additional challenges associated with the production of daughter metals whose supply seemed more problematic according to the findings of Nassar et al. (2015). As a by-product of nickel and copper, cobalt has been included in this latest study whose findings suggest that cobalt supply is not among the riskiest by-products. The main obstacles to cobalt supply security have been synthesized by Shedd et al. (2017) and highlight, among other things, the by-product nature of cobalt, the concentration of production in the Democratic Republic of Congo, and the growing Chinese hold on the value chain. On the other hand, Valero et al. (2018) identified cobalt as one of the 13 elements which have a very high risk of being subjects to bottlenecks in the future. Moreau et al. (2019) reached a similar conclusion by demonstrating that reserves of cobalt are likely to be depleted before a renewable energy system can be deployed on a large scale in 2050. Studies focused on the lithium-ion battery industry and taking into account a larger portion of the cobalt value chain, including the refining stage, came to similar conclusions. Supply risk exists for the mining and refining stages mainly due to the by-product nature of cobalt and the political instability of the main supplier country (Olivetti et al., 2017; Helbig et al., 2018; Song et al., 2019; Sun et al., 2019).

It is then both relevant and worthwhile to evaluate the increasing need for cobalt with the development of long-term, net-zero GHG emission, climate change resilient and sustainable development pathways. Therefore, as pointed out by Hache et al. (2019b), long-term energy analyses might not be accurate or might need to be reassessed if the potential future limitations on the supply of materials are not accounted for by both the energy modelers and the policy makers. Limiting global warming to below 1.5°C is undoubtedly challenging (IPCC, 2018) and has inspired numerous alternative pathways for meeting the COP21 objectives. A literature review shows that (Seck et al., 2020), current approaches related to the REE demand analysis could rely on snapshot retrospective analyses of the main drivers of supply disruptions and the environmental sustainability of the cobalt flows/production (Chen et al., 2019, 2020; Piçarra et al., 2021; Wang and Ge, 2020; Brink et al., 2020; Sun et al., 2019; Godoy Léon et al., 2021; Hatayama and Tahara, 2018) or lately on long-term modelling of cobalt production and demand. The latter is either based on historical trends or hypothesis on future growth rates based on expert opinion (Habib et al., 2016), or long-term production modelling via bell-shaped production curves (Rachidi et al., 2021), or ultimately using long-term energy models to explore geopolitical supply risk, to analyse vulnerabilities and environmental impacts of REE mining.

Using long-term energy models is currently dominating the scientific literature and can be subdivided into two streams of studies: Exogenous estimation of future cobalt demand and production by using results of foreseen deployment of clean energy technologies from a foresight energy model or a specific process deployment scenario (Hsieh et al., 2020; Habib et al., 2020; Ou et al., 2021; Abdelbakry et al., 2021; Tang et al., 2021; Nguyen et al., 2021) and recently an endogenous integration of raw materials supply chain as additional constraint in foresight energy system models. Notwithstanding most of the studies using this approach found in the literature were top-down models focusing more on rare earth elements and solely considering environmental aspects (Alonso et al., 2012; Wang et al., 2017b; Ge et al., 2016; Cao et al., 2019), while few on other raw materials (Tisserant and Pauliuk, 2016; Deetman et al., 2018; Fu et al., 2020). It is also important to note the relative scarcity of research articles devoted to the endogenous modelling of future demand for cobalt. The reason for this might be the difficult access to data and their lack of reliability few years ago (Gupta and Gupta, 1983; Godoy León and Dewulf, 2020). Tisserant and Pauliuk (2016) estimated the future cobalt demand in different world regions from 2007 to 2050. They used a multiregional input–output (MRIO) model hybridized by disaggregating cobalt flows from the nonferrous metal sector. Deetman et al. (2018) also presented a solft-link methodology to analyze scenarios toward 2050 for the demand of five metals (cobalt included) in electricity production, cars, and electronic appliances. They used a dynamic stock model to compile the available product and capital stock data from IMAGE, an integrated assessment model (IAM) into data on the annual demand for cars, appliances, and energy generation technologies. On the other hand, Fu et al. (2020) have performed scenario modeling whose focused on short-term analysis of cobalt supply and demand up to 2030 to identify the changes with increasing demand. However, as stated by the authors, the supply and demand scenarios are independent of one another. Moreover, the implications of stringent climate targets on the cobalt demand have not been considered in the study.

In this context, this article contributes by filling the gap identified in the scientific literature on energy system optimization models by implementing the whole cobalt supply and demand end-uses in a bottom-up integrated assessment model. We have developed the first bottom-up long-term energy model TIAM-IFPEN (TIMES Integrated Assessment Model) with an endogenous cobalt supply chain from the resources to the end-use sectors. By taking into account climate constraints and the availability of cobalt resources (i.e. as a by-product of copper and nickel resources), the development of its consuming-sectors and trade balances, the model could be useful to provide unique insights on cobalt.

We present in this paper the main findings related to this endogenous representation of the cobalt supply chain in order to assess its dynamic criticality, along with technological changes through to 2050. Understanding how the limited availability of cobalt can impede the low-carbon technology roll-out throughout the economy is essential. Thus, the model would be valuable to examine the geological, geopolitical, and production risks associated with the evolving energy transition, particularly the penetration of new types of LIBs in transportation sector.

To assess cobalt availability through to 2050, two climate scenarios (2°C and 4°C) have been analyzed with two different mobility scenarios each. For each mobility scenario, we have defined three different mix of lithium-ion battery chemistries in the transport sector. Recycling has also been implemented into all these scenarios. The rest of the article is organized as follows: Section 2 describes the methodology, the overall structure of the TIAM-IFPEN model, and the specific features and assumptions considered for a detailed analysis of cobalt criticality. Section 3 presents our main results and related analyses on the cobalt supply chain at global and regional levels, cobalt resource availability and the implications of different cathode chemistries and more sustainable road transport mobility. Finally, Section 4 summarizes the main conclusions.

2. Model description and sectorial assumptions

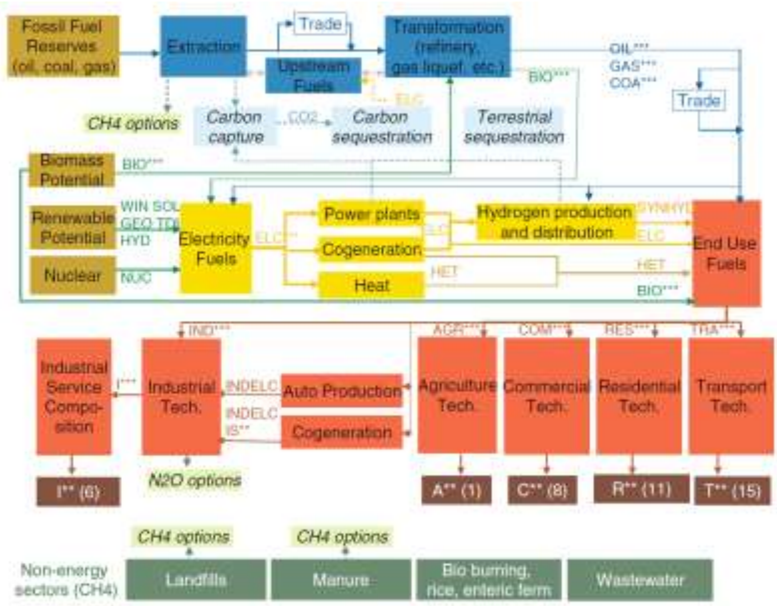
The TIAM-IFPEN model (TIMES Integrated Assessment Model), a bottom-up linear programming model which has been developed at IFP Energies Nouvelles (IFPEN), uses a MARKAL-TIMES framework (Fishbone et al., 1983; Loulou et al., 2004, 2016). It is a global multi-regional model that has a rich technological basis for assessing the dynamics of the global energy system, from resource extraction to energy end-use, over a long-term period of more than 100 years. It was developed for analyzing and assessing the possible consequences of different energy, environmental or legislative orientations with an explicit and detailed representation of technologies and types of energy. The objective function, which is the total discounted cost of the system over the selected time horizon, is the criterion that is minimized by the TIMES model.

A detailed description of the TIAM-IFPEN model is provided in Seck et al. (2020). In a nutshell, the model is disaggregated into 16 regions[1] and includes explicit detailed technological descriptions of the energy system in each region. Building on a database of hundreds of energy-related processes and commodities, TIAM-IFPEN simulates the entire global energy system from resource extraction to end-use. In other words, the processes are

[1] The regions represent either individual countries or aggregates of several countries: China, United States, European Union, Japan, Mexico, Other Developing Asian countries, Central & South America, Other Eastern European countries, Canada, South Korea, Russia, Africa, Middle East, Australia-New Zealand, India, Central Asia & the Caucasus

logically interrelated, the chain of processes with transformation, transport, distribution and conversion of energy into services from primary resources and raw materials to the energy services needed by the end-use sectors (Fig. 1)

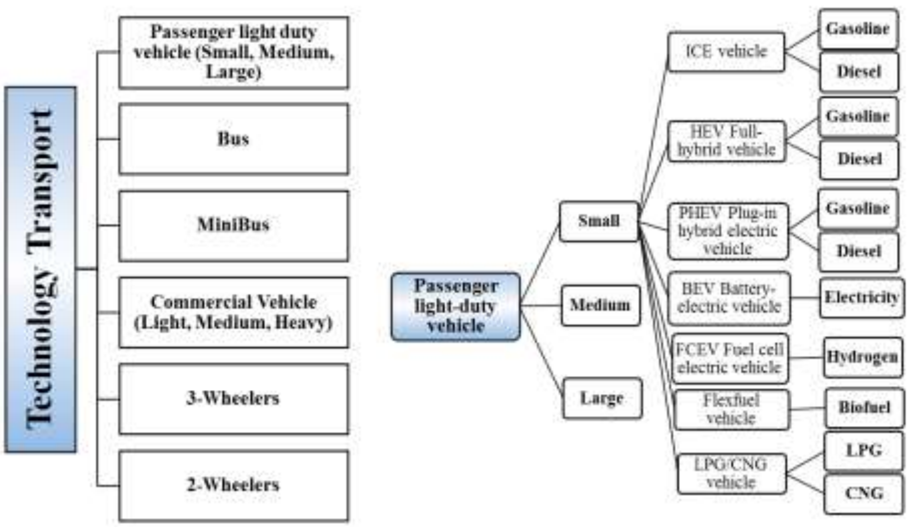
Fig. 1: TIAM model's Reference Energy System



Source: Loulou and Labriet, 2008

TIAM-IFPEN also includes a climate module which per se is directly inspired by the Nordhaus-Boyer model (Nordhaus and Boyer, 1999).

Fig. 2: Overview of road transport technologies in the TIAM-IFPEN model



All power generation technologies have been covered by the model and the road transport sector has been disaggregated into passenger light-duty vehicles (small, medium and large), buses, minibuses, commercial vehicles (light, medium and heavy trucks) and 2/3-wheelers (Fig. 2).

TIAM-IFPEN has been used successfully in analyzing the interactions between low-carbon energy transition and raw material criticality, such as the assessment of future risks related solely to the lithium supply chain (Hache et al., 2018, 2019a), the dynamic criticality of copper through to 2050 based on current known resources, urban mining and resource availability (Seck et al., 2020), and the analyses of the rare earth elements demand and their water stress impacts with the energy transition by 2050 (Guedes et al., 2021). We have enriched the TIAM-IFPEN input database with a more detailed description of battery technologies for EVs. The rationale behind this choice is that it will allow assessing the evolution of cobalt criticality as a function of the battery penetration scenario with an accelerated uptake of EVs in stringent climate scenarios.

2.1. Battery technology choices in cobalt consumption of EVs

Lithium-ion batteries (LIBs) are widely used today. Indeed, lithium has a number of characteristics that make it a material of choice for batteries, including high electro-positivity and a very low mass, resulting in high power and light-weight batteries (Świantowska and Barboux, 2015). Li-ion batteries have three major applications: portable electronic devices, road-transport, and power supply systems. The first LIB was commercialized by Sony Corporation in 1991. For a long time, the largest market has been portable electronic devices, but the fast development of electric vehicles the last years has overcome this sectorial demand. In 2018, the transport segment accounted for 38% of the total Li-ion batteries market[2]. Batteries for road transport are used in battery-electric vehicle (BEV) or in plug-in hybrid vehicle (PHEV) (cars, trucks, buses), electric motorcycles, e-bikes, e-scooters, e-wheels, etc. Large commercialization of Li-ion batteries since the 1990s has helped drive down costs consistently. Consequently, the volume weighted average lithium-ion battery pack price (which includes the cell and the pack) fell 85% from 2010 to 2018, reaching an average of $176/kWh (BloombergNEF EV Outlook 2019)[3]. Although storage applications for the power system are still mainly at the demonstration and pilot stages, low battery pack cost could drive a strong growth of this market in the future.

Other battery technologies have been explored by certain car manufacturers (for example nickel-metal hydride batteries - NiMH – developed by Mitsubishi). But Li-ion presents both higher specific energy and power, which is of great advantage for electric vehicles throughout their life cycle. Consequently, Li-ion is today the only commercial technology used for road transport applications (Opitz et al., 2017). There is a range of different technologies within the

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[2] Global Li-ion Batteries Market, Forecast to 2025

[3] https://about.bnef.com/electric-vehicle-outlook/

Li-ion family of batteries. Li-ion batteries are mainly categorized according to their cathode matrix. The cathode matrix can differ, and the variety of active materials results in significantly different battery characteristics (Zubi et al., 2018; Nitta et al., 2015). The most common lithium metal oxides used as cathode materials are (i) lithium-cobalt-oxide (LCO), (ii) lithium-manganese-oxide (LMO), (iii) lithium-iron-phosphate (LFP), (iv) lithium nickel-cobalt-aluminium oxide (NCA) and (v) lithium nickel-manganese-cobalt oxide (NMC). Table 1 lists the main characteristics of Li-ion batteries. LMO and LCO are not used for transport applications because of low thermal stability at high temperatures.

Table 1: Overview of 5 Li-ion battery technology characteristics*

	NMC	NCA	LFP	LMO	LCO
Cathode main components (+ lithium)	Nickel, Manganese, Cobalt	Nickel, Cobalt, Aluminium	Iron, Phosphor	Manganese	Cobalt
Commercial year	2004	1999	1999	1996	1991
Energy specific range (Wh/kg)	140-200	200-250	90-140	100-140	150-190
Power	High	High	Very high	High	Low
Durability (cycle life)	1000-2000	1000-1500	2000	1000-1500	500-1000
Safety	High stability at moderate temperature and voltage	High stability at moderate temperature and voltage	High stability - Decompose at high temp. Do not explode	Low thermal stability (>250°C)	Low thermal stability (>150°C)
Cost	++	+++	+	+	++
Application	EVs, portable electronics, power tools, medical devices, grid	EVs, grid	e-bikes, EVs, grid, buses, large vehicles	e-bikes, power tool and medical devices	Mobile phones, laptops

Source: Zubi et al., 2018; Harper et al., 2019

*Legend colors according to use in automotive sector (Gray: poor performance, No color: ideal performance)

Most batteries used today are NMC both for BEV and PHEV, except for the American Tesla (NCA), Daimler (both NCA and NMC) and some Chinese OEMs[4] such as BYD (LFP) (McKinsey, 2018). LFP technology is very safe (decomposes at high temperatures and does not explode) with a long-life cycle and relies on abundant resources, with a relatively low

[4] Original Equipment Manufacturers

impact on the environment. Nevertheless, its specific energy remains low in comparison with NCA and NMC batteries. NCA present highest specific energy (and so reduce the weight of the battery) but NMC present longer lifetimes, which make them a preferred choice for PHEV. Indeed, with small range (c.a. 30km) the battery should be charged (cycled) often. The NMC battery can then be used a longer time. In addition, PHEV requires high power (higher P/E ratio than BEV), so NMC is best suited.

Looking to forecasts of different agencies (McKinsey, IEA, etc.), NMC batteries are expected to remain the dominant technology on the market in the coming decades. A global tendency towards Ni-rich cathode, i.e. cathodes containing higher ratios of nickel compared to manganese or cobalt, is expected globally (LiNixMnyCoz, where x + y + z = 1 and x can be as large as 0.6). NCM811 for example has a higher content of nickel and a lower content of cobalt and manganese (stoichiometry 8 Nickel for 1 Cobalt for 1 Manganese) than NMC111 (ratio 1 nickel for 1 cobalt for 1 manganese). The market is growing from NMC 111 -> NMC 532 -> NMC 622 -> NMC 811 to no-cobalt chemistries. Even if NMC ratios up to 911 are under development, it is complicated to remove cobalt and manganese completely from the NMC-structure as they mitigate those issues to a certain point. Cobalt, for example, is essential in maintaining the correct degree of nickel oxidation, while manganese ions play an important role in stabilizing the structure. In addition, decreasing the manganese ratio decreases the specific power. Finally, stoichiometric Ni-rich NMC material is very difficult to obtain and non-stoichiometric layer structure exhibits poor electrochemical performance (Ding et al. ,2017; Croy et al., 2019).

In addition to Ni-rich batteries other chemistries are also regarded as future potential for EVs. Future visions focus on new approaches to meet the challenge of high energy densities (Kurzweil, 2015). The two more explored solutions consist of solid-state batteries (with a solid electrolyte that does not decompose at high voltage) or metal-air batteries (with a cathode composed of pure oxygen and the anode of pure metal). Lithium is still seen as a metal of choice for those two new technology paradigms. But some researchers are also oriented towards sodium-ion batteries instead of lithium-ion batteries because sodium is much more available and affordable than lithium. Nevertheless, metallic sodium still poses safety issues and cannot be applied in aqueous solutions, requiring other materials or sodium-air batteries. A large panel of other technologies are also regarded (Multivalent metals batteries, Halide batteries, Ferrite batteries, organic batteries, Redox-flow batteries, Proton battery, etc.) but most are far from market launches (Kurzweil, 2015; Poizot et al., 2015).

In this article, the raw material content is based on the NMC111, NMC622, NMC811, NCA and LFP battery technologies, disaggregated per vehicle size. Indeed, the cobalt content per unit capacity has been disaggregated by technology type according to the battery size in order to take into account the large disparities in material needs between conventional and low-carbon technologies (Table 2 & Table 3).

Table 2: Battery size assumed for EVs in TIAM-IFPEN model

		Battery size (kwh/veh)			
		PHEV		EV	
		2015	2030	2015	2030
Passenger light duty vehicles	Vehicle small size	8	12	40	60
	Vehicle medium size	12	15	40	80
	Vehicle large size	15	20	60	90
Bus				340	340
Commercial vehicles	Light	12	15	60	90
	Medium	35	35	170	200
	Heavy	50	50	350	350
2-wheelers				3	4
3-wheelers				4	6

Source: Authors

Table 3: Cobalt content by cathode chemistry type considered in TIAM-IFPEN model

	Cobalt content (kg/kWh)
NCA	0.13
NMC 111	0.40
NMC 622	0.19
NMC 811	0.09
LFP	

Source: IEA, 2018

Three scenarios of expected battery technology commercialization timeline have been considered in this article in agreement with the IEA GEVO 2019 world analyses till 2030 and onwards (Table 4).

Table 4: Scenario of cathode Chemistry in EVs assumed in our model

Cobalt content scenarios	Mix of chemistries from 2030
High Cobalt	10% NCA, 90% NMC622
Central Cobalt	10% NCA, 40% NMC622, 50% NMC811
Low Cobalt	10% NCA, 90% NMC 811

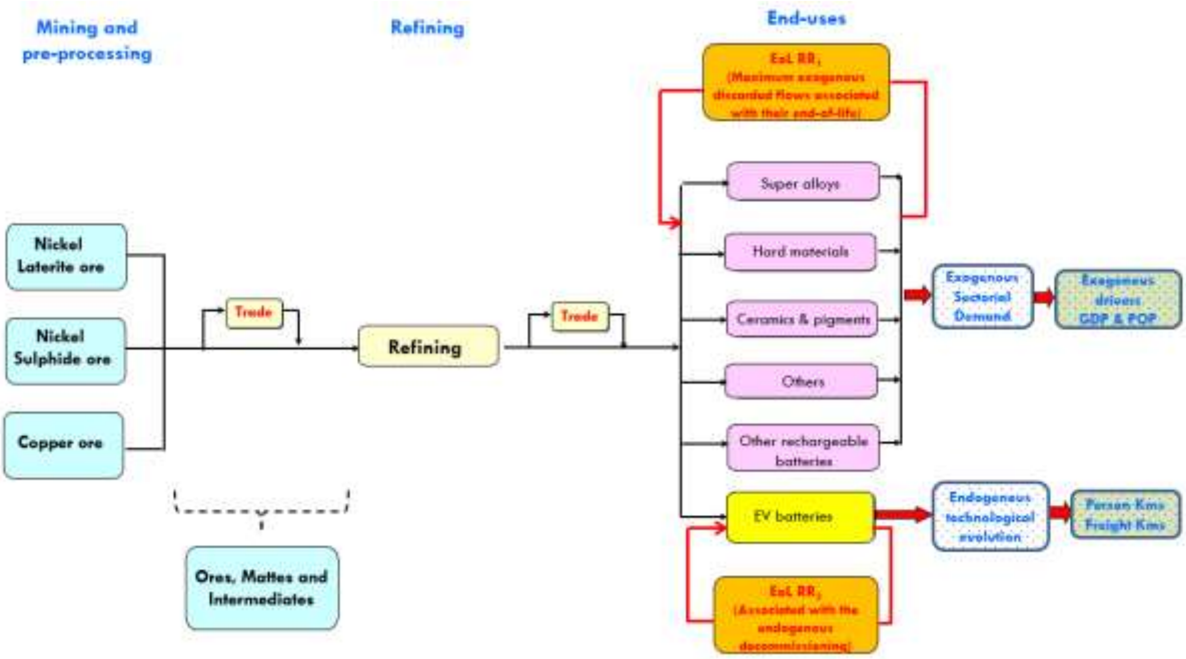
Source: IEA, 2019a

The cathode chemistries of automotive lithium-ion battery packs are transitioning towards higher nickel content to provide higher energy density. There is broad consensus that the main chemistries currently in use are LFP, NCA and NMC, with the latter being subject to a transition from NMC 111 to chemistries with lower cobalt content in order to manage the risks associated with cobalt supply and to increase energy density.

2.2. Description of cobalt chain in TIAM-IFPEN model

The TIAM-IFPEN model allows us to estimate the cumulative demand for cobalt till 2050 and to analyze the possible criticality risks for this metal. The entire value chain of cobalt from ore to different end-uses has been implemented in the model to evaluate its demand under different scenarios. Half of the world's cobalt production comes from nickel mining as a by-product, while the other half comes from copper mining. Overall world production of cobalt can be divided in two groups. Cobalt production depends on the ore type wherein its occurred (Fig. 3). In TIMES model, the inter-regional trading structure of a given commodity basically consists of one or several exchange processes, each of which defines a portion of the trading network for the commodity (Loulou et al., 2016). These trade aspects between the different regions have been considered for the intermediates and refined compounds. Historically, cobalt concentrates produced in the Democratic Republic of the Congo (DRC) were exported to other countries for further processing (Dai et al., 2018). As of 2017, however, cobalt concentrates are processed within DRC and exported as crude cobalt hydroxide, in response to the DRC's pending ban on the export of cobalt concentrates (Bloomberg, 2017). Most of the cobalt hydroxide produced in the DRC is exported to China (USGS 2017), where it is processed into refined components.

Fig. 3: Simplified description of the cobalt chain in TIAM-IFPEN model



2.2.1. Refining and primary cobalt supply

The earth's cobalt resources amount to 25 million tons (Shedd, 2000-2020). Most of them are found in the Copper Belt, a mining area that stretches between the Copperbelt Province in Zambia, the Haut-Katanga, and Lualaba Provinces in the Democratic Republic of Congo (DRC). The remaining resources are mainly distributed between Australia, Cuba, Canada, Russia and the United States. An additional 120,000 million tons[5] of cobalt are found at the bottom of the Atlantic, Indian and Pacific Oceans. However, their exploitation has not yet been undertaken at this time due to significant technological, economic, and legal barriers (Slack et al., 2017). The environmental impact of deep-sea cobalt mining could also be disastrous for marine life and could be irreversible (Heffernan, 2019).

Cobalt production mirrors the unequal distribution of the earth's resources. The DRC accounted for only 28% of world production in 2000 (Shedd et al., 2017). World output reached 143,000 tons in 2019, of which 100,000 tons, or nearly 70%, originated from the DRC. Currently, among the most important producers, Russia comes next with 6,100 tons, i.e. 4.3% of world production, followed by Australia with 5,100 tons, accounting for 3.6%. The share of the other players - the Philippines, Cuba, Madagascar, Canada, Morocco, China, and New Caledonia - does not exceed 3.2%. Extractive activities are therefore highly geographically concentrated.

The finding is the same for refining: China dominated refining activities with a 50% market share in 2018 (Gulley, 2019), with the remaining part being carried out mainly in Finland, Belgium, and Canada. This percentage was only 3% in 2000 (Alves Dias, 2018).

2.2.2. Cobalt end-uses

Cobalt is used in a wide range of applications, making it a key metal for modern industries like aerospace industry, chemistry, energy and defence sectors, etc.[6] In recent years, it has become an essential element of lithium-ion electric batteries which represent 55% in world end-uses in 2019 (**Erreur ! Référence non valide pour un signet.**).

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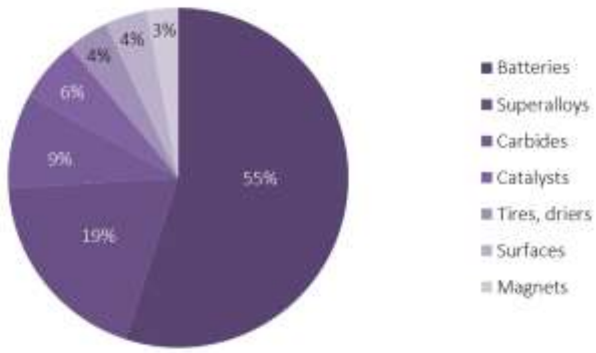
[5] Data in metric tons of cobalt content.

[6] The use of cobalt dates to Antiquity when it was employed as a pigment for Chinese porcelain for example. Because of its high mechanic and temperature resistance, cobalt is widely found in chemistry and metal working as a component of super alloys used in aerospace industry and in nuclear reactors. Other major usages comprise magnets for the renewable energy and defence sectors (marine propulsion systems, missile guidance systems, sensors and radars), in inks and pigments, employed as a catalyst in processes for the production of clean fuels and integrated in numerous electronic components (integrated circuits, processors, etc.).

Fig. 4: Cobalt end-uses in the world



Source: Jébrak, 2019

They can be found in small electronic equipment, energy storage devices and electric vehicles. All these diverse applications and the difficult substitution of cobalt without losing performance make it a strategic metal for both military and manufacturing industries (Cobalt Institute[7]; Jébrak, 2019; Slack et al., 2017). In this article, the end-uses have been aggregated into 6 groups:

- Super-alloys (Aerospace, Land based turbines, Medical (prosthetics), others),
- Hard metals (Cutting tools, mining, oil & gas drilling, etc.),
- Ceramics/Pigments (Ceramics, glass, and coloring applications)
- Others (Catalysts, Magnets, Hard facing, Electroplating, etc.)
- Other battery chemicals (mobile phones, laptops, etc.)
- Battery chemicals for road transport vehicles

2.2.3. Secondary cobalt supply via recycling in end-uses

Global cobalt supply will be affected by the degree of recycling as it creates an alternative supply source. Thus, recycling could contribute to reducing of the level of cobalt criticality.

The End-of-Life Recycling Rate (EoL-RR) indicator has been implemented by end-use sectors in our model for cobalt to consider the efficiency of each sectorial old scrap recycling. This indicator is determined as the fraction of metal contained in EoL products that is collected, pre-treated, and finally recycled back in the anthropogenic cycle. Table 5 and

Table 6 below provide the assumed lifetime and the evolution of EoL-RR for each end-use products calculated from latest literature. In the case of EV batteries, a collection rate of about 70% in 2020 and at least 85% from 2030 onwards has been assumed (Drabik and Rizos,

[7] https://www.cobaltinstitute.org/cobalt-uses.html

2018). The average lifetime of cobalt-bearing products considered in the model is around 1 year for hard materials and 5-8 years for the others.

Table 5: Lifetime of end-uses considered in the model

	Average lifetime (in years)
EV batteries	8
Other batteries	5
Super-alloys	5
Hard metals	1
Ceramics/Pigments	5
Others	5

Source: Alves Dias et al., 2018

Table 6: End-of-Life Recycling rate (EoL-RR) considered in the model

		EoL-RR	
		2020	**2030**
EV batteries		66.5%	80.8%
Other end-uses	OCDE	35%	
	Non-OCDE	30%	

Source: Alves Dias et al., 2018; Drabik and Rizos, 2018

Trades have been also considered in the model to analyze future international mined and refined cobalt exchanges and strategies according to each region's needs and endowments.

2.3. Scenario specifications

We have carried out several scenarios to define different pathways for cobalt demand and assess its criticality under different stringent environmental, mobility or technological constraints. **The evolution of the GDP and population have been extracted, respectively, from the IEA** (Fulton et al., 2009) **and the UN population division (UN, 2019).** We then run 6 different scenarios, two climate scenarios with two mobility shapes and three types of cathode chemistry for electric vehicle.

The two climate scenarios represent two environmental pathways which are consistent with limiting the expected global average temperature increase by 2100 to 4°C above pre-industrial levels for the Scen 4D scenario and at 2°C for the Scen 2D scenario.

Two future shapes of transport mobility have been assumed and derived from the IEA Mobility Model (MoMo Model) (Fulton et al., 2009) (See Appendix A):

- a Business-as-Usual scenario (BAU Mob) where a continuing increase of car-dependencies is assumed,
- a Sustainable Mobility (Sustainable Mob) where priority is given to sustainable modes of mobility such as public and non-motorized transport.

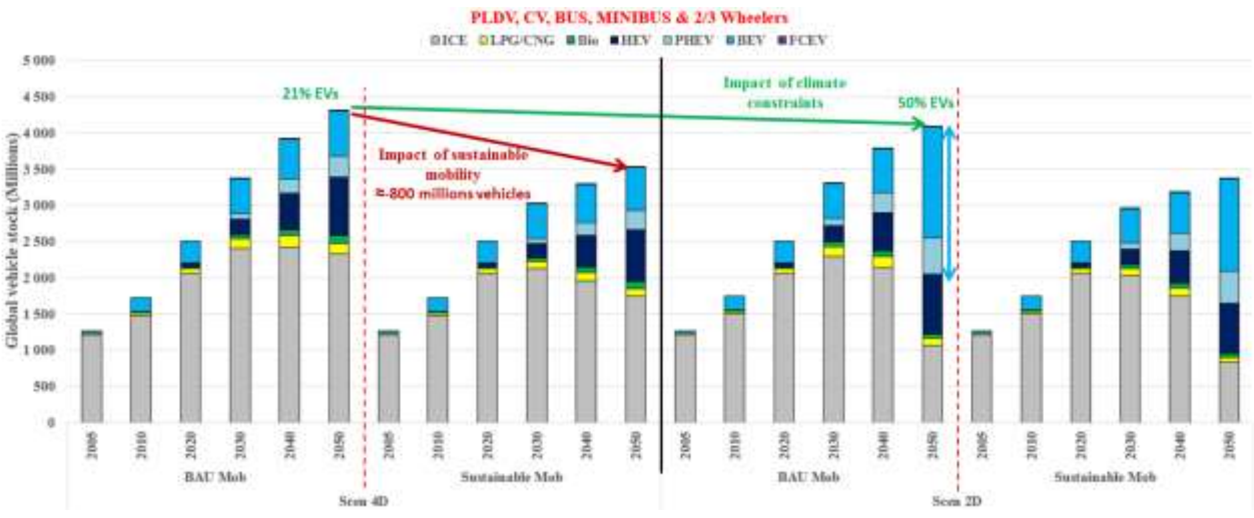
3. Results and discussion

3.1. Evolution of the transport sector by 2050

By comparing the two climate scenarios Scen 4D and Scen 2D in a Business-as-Usual mobility (BAU Mob) configuration, our results show that the level of ambition in climate policies has a significant impact on the structure of the global vehicle fleet by 2050 (Fig. 5). Limiting global warming to 2°C compared to the pre-industrial levels would indeed require a substantial electrification of the global fleet with the share of EVs rising from 21% in a Scen 4D scenario to 50% in a Scen 2D. More than half of the EVs are 2/3-wheelers, mainly located in China and India. The shift from an ICE dominated mix to an EVs dominated mix is only observed from 2040 onward in the most stringent climate scenario (2°C target).

Fig. 5 also pinpoints the impact of the mobility shift on the evolution of the global vehicle stock from 2005 to 2050 between scenarios Scen 4D and Scen 2D. Whatever the climate scenario considered, the total number of vehicles on the road is lower with the development of sustainable modes of mobility such as public and non-motorized transport. The global fleet is reduced from 4.3 and 4.1 billion vehicles in the 4°C and the 2°C scenarios by 2050, respectively, to around 3.5 and 3.4 billion by transitioning from BAU mobility to more sustainable mobility.

Fig. 5: Impact of climate constraints and mobility shape on the evolution of the global vehicle stock in 2D et 4D scenarios



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

TIAM-IFPEN results showed that the global EV fleet (2/3-wheelers excluded) would be between 110 and 140 million vehicles in 2030. In a nutshell, Table 7 compares our results with IEA's forecasts in the IEA Global EV Outlook (GEVO) 2019 in the New Policies Scenario and EV30@30 scenario.

Table 7: Comparison between our future global EV stock in 2030 with recent literature

	Our results		IEA GEVO 2019	
	4°C Scenario	2°C Scenario	Stated Policies scenario[8]	EV30@30 scenario[9]
2030	110 million	180 million	130 million	250 million

3.2. Cobalt demand

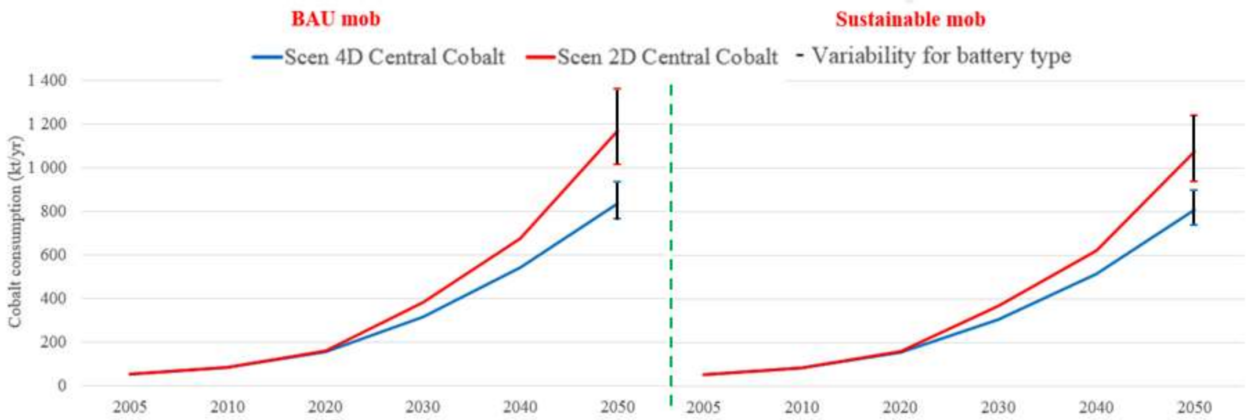
3.2.1. Global demand evolution by 2050

Our results show that annual cobalt consumption is expected to grow continuously until 2050 (Fig. 6). Fig. 6 displays the evolution of the yearly cobalt consumption in the two climate scenarios (Scen 4D and 2D) according to the mobility scenarios (BAU and Sustainable mob) and cobalt content scenarios (High, Central and Low cobalt). The red and blue lines represent the Central cobalt scenarios. In the graph, intervals (shown as vertical black lines) are included to give the variability of the cobalt consumption due to a High cobalt content scenario (maximum point of the "variability for battery type") and Low cobalt scenario (minimum point). The highest consumption of cobalt by 2050 is observed in the Scen 2D with a continuing increase of the car-dependencies (BAU mobility) with a hypothesis of battery technologies with a high cobalt content (High cobalt scenario). In this case, from 2020 to 2050, the annual cobalt consumption is expected to grow nine-fold to around 1360 kt. Nevertheless, this yearly demand for cobalt would be reduced to 1010 kt in a sustainable mobility framework. It should also be pointed out that between 22-32% less is observed in the less ambitious climate scenario (Scen 4D).

[8] 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) (IEA, 2019b).

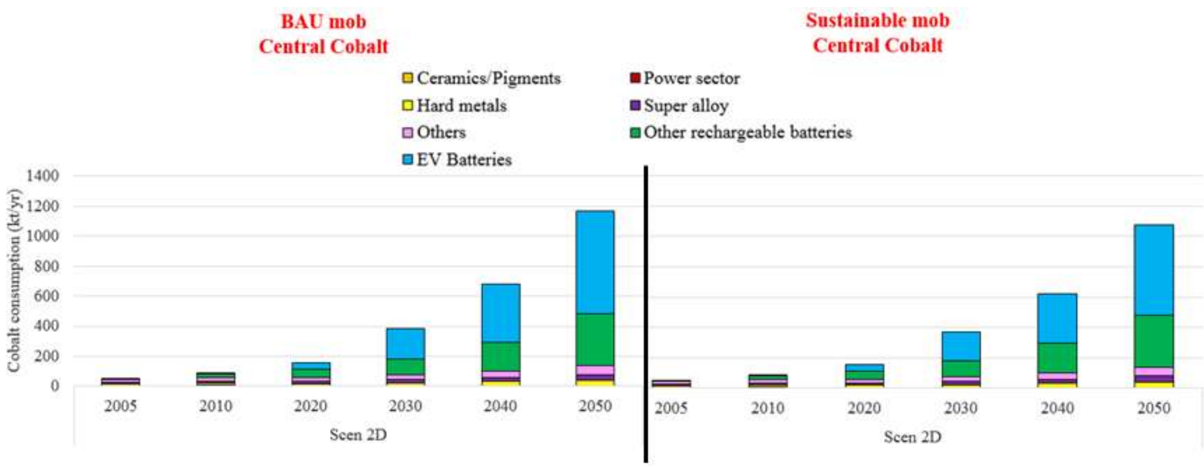
[9] The EV30@30 Scenario takes into account the pledges of the Electric Vehicle Initiative's EV30@30 Campaign to reach a 30% market share for EVs in all modes except two-wheelers by 2030 (IEA, 2019a).

Fig. 6: Evolution of annual global cobalt consumption depending on different climate, mobility and cobalt content scenarios



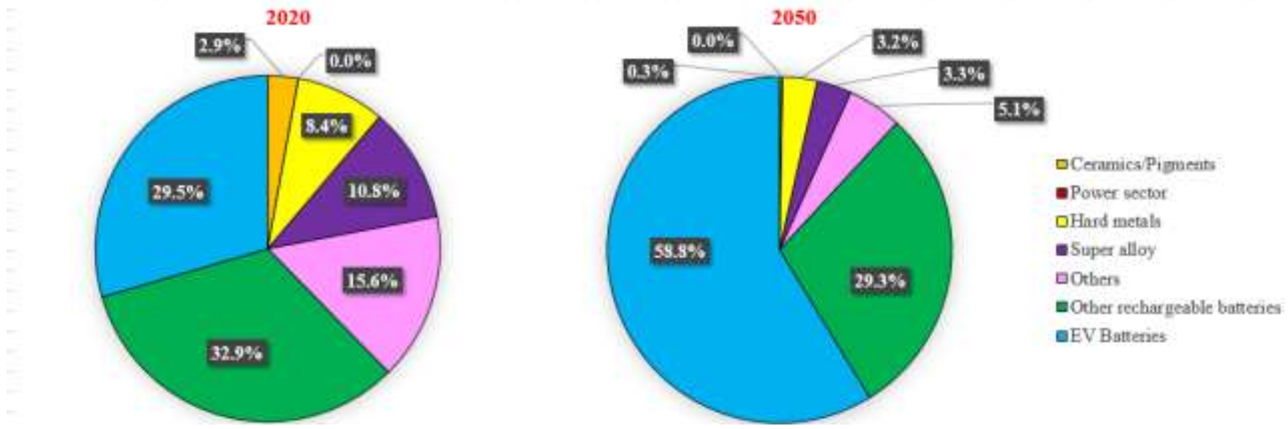
The model results allow following the disaggregation of the yearly cobalt consumption by end-uses at the global level and even by region. In Fig. 7, the example of the Scen 2D with a hypothesis of a central cobalt scenario has been displayed according to the two mobility scenarios (BAU and Sustainable mob).

Fig. 7: Disaggregation by end-uses of the yearly cobalt consumption in the 2°C scenario with central cobalt content according to the mobility scenarios



The increase in demand for cobalt by 2050 is mainly due to the shift to electric mobility, as suggested by the evolution of the whole road transport sector presented in the previous section.

Fig. 8: Breakdown of cobalt consumption by end uses in 2020 vs 2050 (Scen 2D - BAU mob - Central Cobalt)



In a Scen 2D with BAU mob and Central Cobalt scenario (Fig. 8), EV batteries account for 29.5% of the cobalt consumption in 2020 while it is expected to be around 58.8% in 2050. Their share will increase slightly to 64.5% in the case of a High Cobalt scenario. The results presented in this section highlight the impact of choices in the technology of batteries on global cobalt trends.

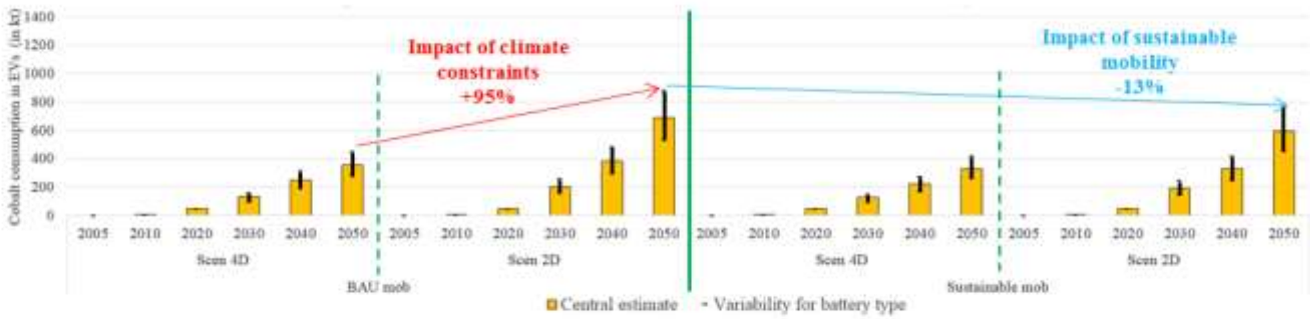
3.2.2. Global demand evolution in the EVs sector

Fig. 9 shows the evolution of demand of cobalt in the electric vehicles. As explained in previous section, the results are presented in a bar chart with consumption intervals (shown as vertical black lines) with the different penetration scenarios of battery type. The central estimate corresponds to the central cobalt scenario.

Assuming a central cobalt scenario and BAU mobility, the annual demand for cobalt in the EVs sector will increase from 46.4 kt in 2020 to reach in 2050, 354 kt/year in Scen 4D and 687 kt/ in Scen 2D (Fig. 9). An increase of 95% is observed in the cobalt demand due to the impact of ~~a~~ more stringent climate constraints, while the mobility shift to a more sustainable pathway would reduce this demand by 13%.

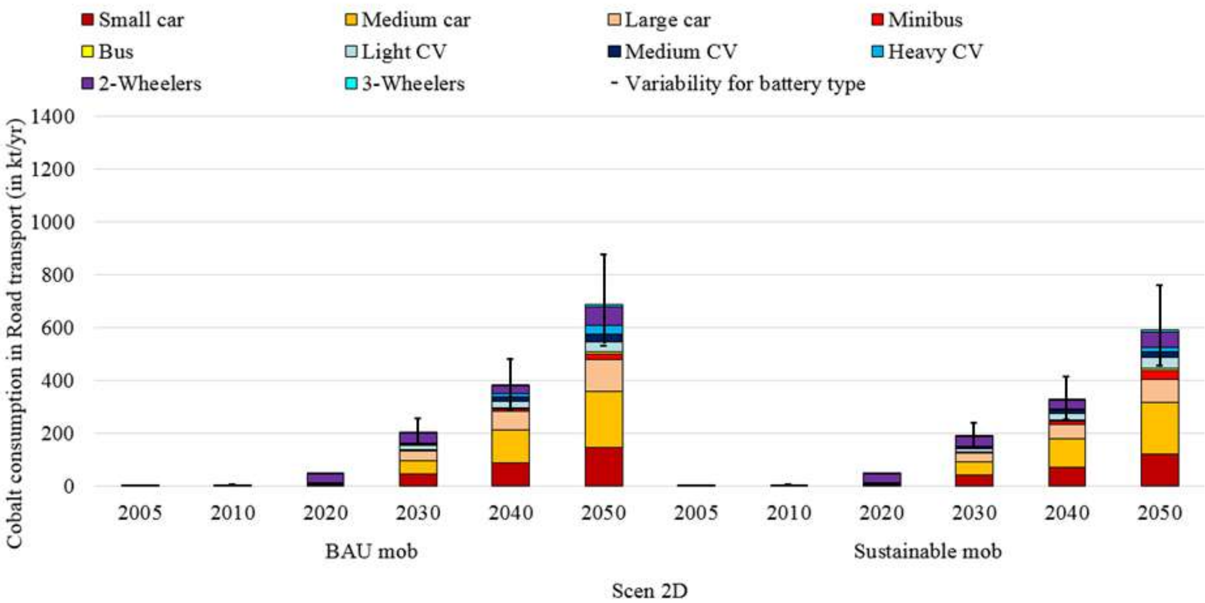
Higher cobalt demand is expected when assuming a mix of chemistries for batteries with high cobalt content. In 2050, with the BAU mobility, about 450 kt are consumed by the EVs in the Scen 4D while they almost double to 876 kt in the Scen 2D. This considerable increase is in fact in line with the high degree of electrification of the vehicle fleet between now and 2050.

Fig. 9: Annual cobalt consumption in EV's from 2005 to 2050 depending on climate scenarios, mobility choices and battery technology mix



One of the levers for reducing cobalt consumption in the electric vehicle sector is to opt for batteries that consume less of it. As shown in Fig. 9, the cobalt consumption avoided through the shift from a mix of high cobalt-intensive battery technologies toward less cobalt-intensive batteries would be between 300-350 kt per year in 2050 in the Scen 2D. Regardless of the mobility scenario, climate policies have a major impact on the annual global cobalt consumption due to the decarbonization of the road transport with the adoption of EVs to meet the GHG emission reduction target.

Fig. 10: Evolution of the cobalt demand in EVs per vehicle segments according to the cobalt content scenario in the 2°C scenario



The importance of the different vehicle segments in the consumption of cobalt is represented in Fig. 10 by a disaggregation of the road transport vehicles. The histogram represents the evolution of the Central cobalt scenario, while the consumption intervals (shown as vertical black lines) give insights into the total consumption in the high and low cobalt scenarios (max and min points). Indeed, Fig. 10 reflects vehicle segments in which the sustainable mobility policies may have major impact. In such a configuration, public transport would indeed be given more prominence than individual solutions. Therefore, the absolute consumption of passenger cars (small, medium, and large cars) is decreasing from 478 kt/year to 406 kt/year in 2050 in the Scen 2D, reflecting the decrease of car-dependency. This trend can also be observed for commercial vehicles and 2/3-wheelers while the demand for cobalt for buses and minibuses increases by almost 45%.

The transport policy choices made in the future will impact cobalt consumption. Even if this influence is smaller compared to the climate target one, it should not be neglected, especially if the objective of limiting global warming by 2°C is to be achieved. Indeed, the implementation of sustainable mobility policies favoring public and non-motorized transport would avoid the consumption of around 100 kt of cobalt per year, thus reducing the pressure on the primary cobalt supply. It therefore appears that a stringent climate constraint coupled with the absence of a sustainable mobility policy appears to be the riskiest configuration to the security of cobalt supply.

3.3. Cobalt criticality

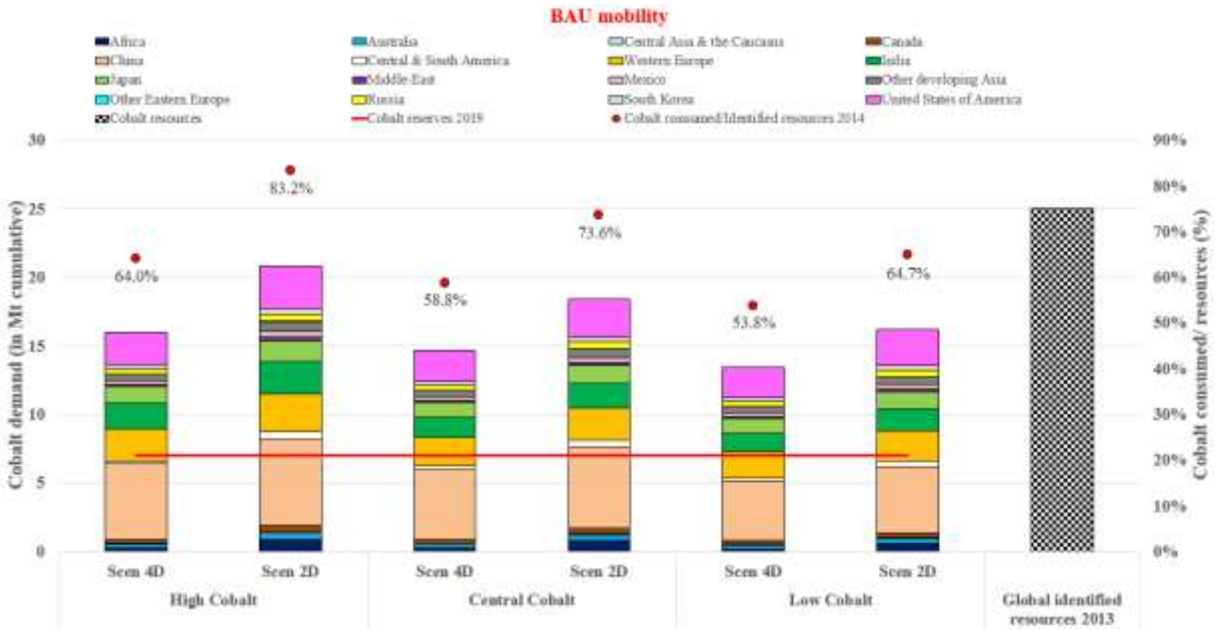
3.3.1. Geological risks

To assess cobalt criticality, we considered the cumulative demand of cobalt between 2013-2050 and compared it with global known resources to obtain a ratio of the cumulative consumption of cobalt on identified resources. As the results with respect to the evolution of the yearly demand for cobalt suggested, climate constraints have a strong impact on cobalt criticality. Looking at the BAU mobility with a high cobalt scenario (predominance of NMC622 batteries) (Fig. 11(a)), the cumulative cobalt demand between 2013-2050 reaches 64% of the known cobalt resources in the Scen 4D while it is 83.2 % in the Scen 2D. Opting for less cobalt-intensive NMC811 batteries in EVs reduces the ratio of the cumulative cobalt consumption and the known resources to 53.8% and 64.7%, respectively, in the Scen 4D and 2D.

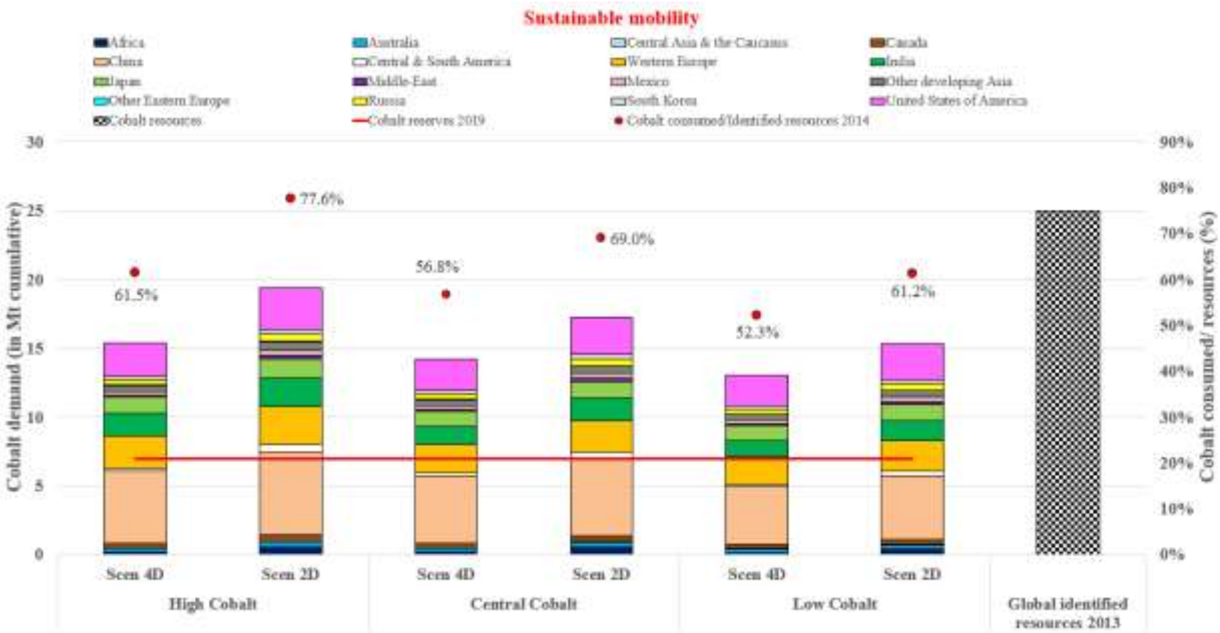
In Fig. 11(b), the consequences of more sustainable mobility on cobalt consumption is be assessed. It varies significantly across the scenarios. These reduced cumulative cobalt consumptions over the period 2013-2050 are between 1.5%-5.6% from the less constrained scenario (Scen 4D with Low cobalt content scenario) to the most constrained one (Scen 2D with High Cobalt content scenario).

Fig. 11: Comparison between cumulative cobalt consumption between 2013-2050 under two climate scenarios, different battery and global cobalt resources in 2013 (a) BAU mobility (b) Sustainable mobility

(a)



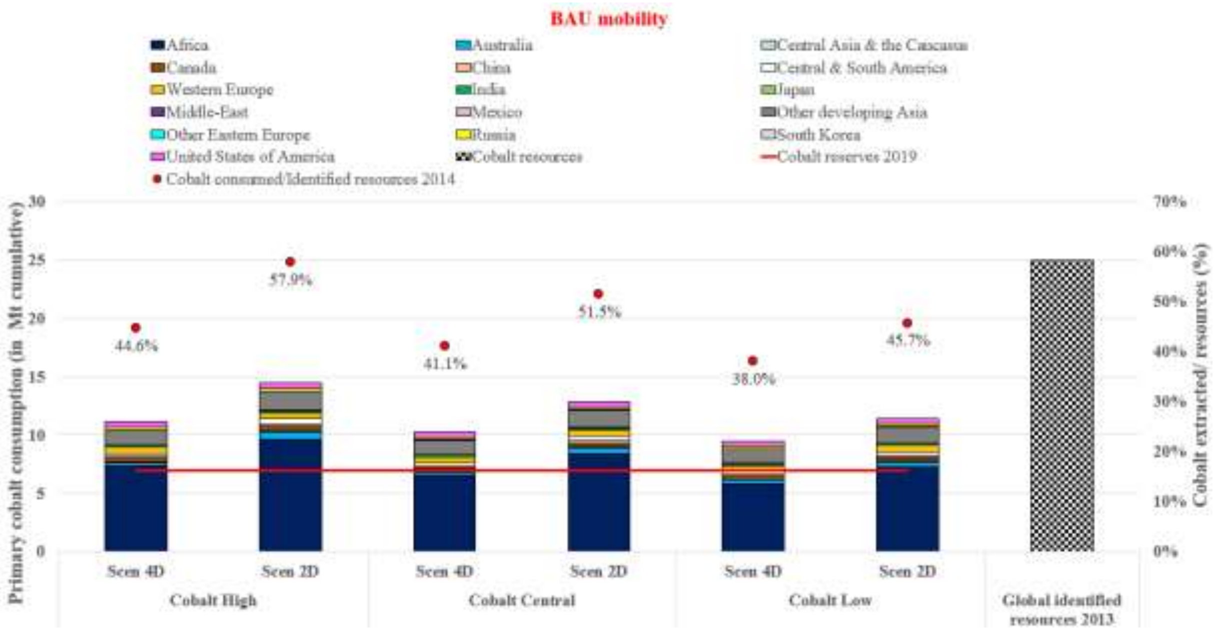
(b)



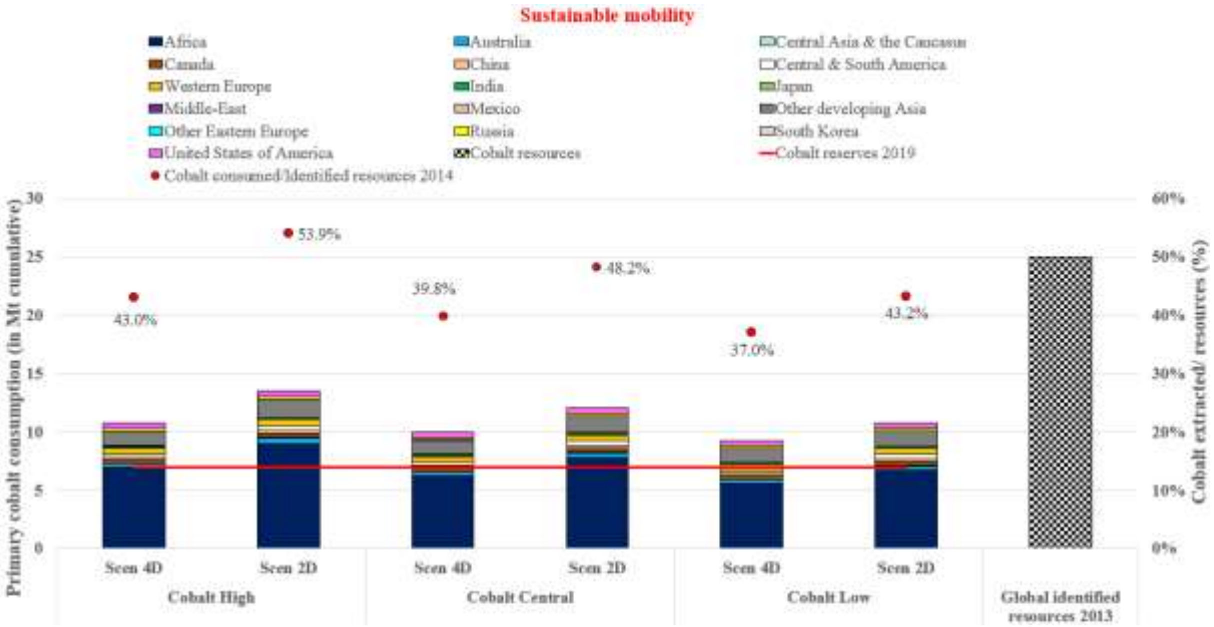
Considering the cumulative primary cobalt production in BAU mobility scenario (Fig. 12(a)), 57.9% and 44.6% of the cobalt resources will be extracted between 2013-2050 in the Scen 4D and Scen 2D, respectively. Comparing Fig. 11 and Fig. 12 underlines the importance of the secondary production in the cobalt value chain during the period 2013-2050. The secondary cobalt production allows avoiding the extraction of 15-25% of the known resources between 2013-2050 according to the scenarios. These two graphs also highlight the highest producing regions, the highest consuming regions (or both). China is still the leading consumer of cobalt with one-third of the global cumulative cobalt consumption, followed by the United States of America (15%), Western Europe (14%), India (11.5%) and Japan (7.6%). These 5 regions represent more than three-quarters of the global cobalt demand. 60-65% of primary production is originating from the African continent, while cumulative Chinese-mined production represents only 1.5 to 2.3% of the total primary cobalt production depending on the scenarios. This reflects both a very high level of dependence on imports and a strong need for collection and recycling systems to reduce dependence on cobalt-rich foreign countries. This finding is also observed for Western Europe, India, Japan, Middle East, Mexico, Russia South Korea, and the United States of America. Conversely, Africa and the other developing Asian countries registered a strong production growth of cobalt ores which are exported for refining processes. This group of countries recorded a low level of refined cobalt consumption. Australia, Canada and Central and South America seem more or less able to cover their needs according to the scenarios considered.

Fig. 12: Comparison between cumulative primary cobalt production between 2013-2050 under two climate scenarios, different battery, and global cobalt resources in 2013 (a) BAU mobility (b) Sustainable mobility

(a)



(b)



3.3.2. Cobalt criticality as regards to economic, environmental, and strategic risks

Economic, strategic, and environmental risks must be considered in addition to the geological dimension. From an economic perspective, the difficulty lies in the fact that cobalt supply cannot adjust quickly to demand due to its by-product nature (Olivetti et al., 2017; van den Brink et al., 2020). Cobalt production – and more generally all metals processes – may be subject to environmental criticality. It has been shown that extractive activities have multiple negative outcomes, and cobalt is no exception. The biggest impacts of cobalt extractions are the GHG emissions induced by the consumption of fossil fuels for extraction and refining processes and the consequences on human health of the emissions of diverse particles (arsenic, cadmium, cobalt, and manganese) (Farjana et al., 2019). These ecological externalities raise questions as cobalt is a key element in so-called carbon neutral technologies. Lastly, but most importantly, the strategic risks weighing on the cobalt value chain are the greatest threats to supply security.

Among all the risks registered on the supply chain of cobalt (Table 8), two of them deserve to be explained in the following sections: the first one is linked to the continued concentration of extractive activities in the DRC; and the second one to China's growing influence on the cobalt value chain.

Table 8: Main current risks on cobalt market

Risk Factors	Criteria	Indicators	Articles
Supply risks	**Risk of supply reduction or constraint:** ▪ Lead time for new capacity (up to ten years).	▪ EoL recycling rate	Helbig et al., 2018 Olivetti et al., 2017 Zhang et al., 2017

	▪ By-product nature: cobalt level of supply is dependent on main product supply (nickel and copper). ▪ Recycling, WEEE management: inefficiency in the collection of cobalt consuming devices. ▪ "Conflict metal" risk due to its features (i.e. high value per weight and possibility for artisanal mining)		Månberger and Johansson, 2019 Song et al., 2019 Godoy León et al., 2020 Wang and Ge, 2020
	Risk of demand increase: ▪ Future technology demand: expected surge in electric mobility.	▪ By-product dependence	Helbig et al., 2018 Sun et al., 2019 Van Den Brink et al., 2020 Zhang et al., 2017
	Concentration risk: ▪ Country concentration: lack of diversification of both mining (DRC) and refining (China) production. ▪ Company concentration.	▪ Country concentration (HHI[10]) ▪ Company concentration (HHI)	Helbig et al., 2018 Van Den Brink et al., 2020
	Political and geopolitical risks: ▪ Political stability and strategy in the main mining and refining countries ○ New regulation risk: the amendments to the DRC's mining code were greeted coldly by multinationals ○ China's "new normal" economic model ▪ Competition between countries and multinational corporations to gain control over the mining production.	▪ WGI-PV[11] ▪ PPI[12] ▪ HDI[13]	Abadie, 2011 Buhmann, 2018 Geenen and Cuvelier, 2019 Helbig et al., 2018 Månberger and Johansson, 2019 Sovacool, 2019 Van Den Brink et al., 2020 Verweijen, 2017 Zeuner, 2018
Environmental risks	▪ Significant for local ecosystems: soil and water pollution if poor waste management, use of acid in processing. ▪ Might also come from the exploitation of new kinds of resources: seabed mining.	▪ EPI[14]	Amnesty International, 2017 Cheyns et al., 2014 Miller et al., 2018 Scheele et al., 2016
Social risks	▪ 20% of mining in DRC is artisanal, which is associated with health and safety concerns for miners, plus child labor. Cases of corruption in both artisanal and large-scale mining.		Banza Lubaba Nkulu et al., 2018 Cheyns et al., 2014 Scheele et al., 2016 Sovacool, 2019

3.3.2.1. The risk linked to the continued concentration of extractive activities in the DRC

[10] Herfindahl-Hirschman Index

[11] World Governance Index – indicators for political stability and absence of violence

[12] Policy Perception Index

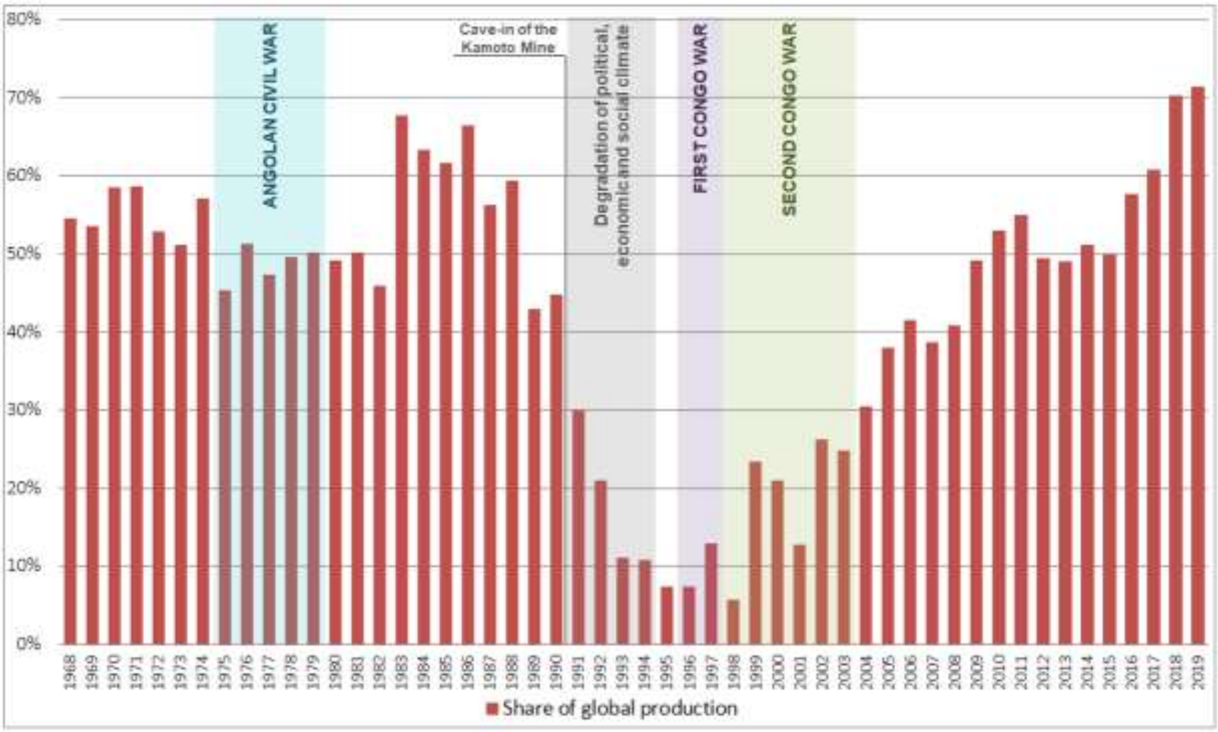
[13] Human Development Index

[14] Environmental Performance Index

Our modeling work enabled us to identify some future trends for mining production. It appears that the DRC, should maintain its leadership in cobalt mining by 2050 with a share of primary production ranging between 60% and 67% depending on the scenarios (Fig. 12). Only "Other Asian developing group of countries" would constitute a serious alternative of supply with about 11% of global primary production (Fig. 12). This persistence of the concentration of mining activities in DRC must be analyzed in relation to the additional risk that the region's instability poses to the supply security. Since its independence in 1960, the DRC has indeed been the theatre of episodes of political and social turmoil. This turmoil has repeatedly affected the mined or refined production of cobalt and the use of trade routes, causing interruptions or severe decrease in production (See Appendix B).

As a consequence, the DRC fell from first to sixth place in world cobalt production in 1993 and accounted for only 5.7% of global production in 1998, its lowest level ever (Fig. 13). Since the beginning of 2000, no perturbation of cobalt production caused by conflicts or an unstable political and social situation has been recorded. However, the four mining provinces of former Katanga have been subject to separatist attacks attempt. Dissatisfaction with the government and hostility between the different communities have persisted for decades, and these tensions are rekindled at regular intervals, as after the 2011 elections for example. The Katanga region is therefore not immune to a rapid and unpredictable deterioration of the political and social climate (International Crisis Group, 2016).

Fig. 13: Zaire/Democratic Republic of Congo' share in global cobalt mine production from 1968 to 2019



Source: (USGS, 1932-1993); (USGS, 1994-2016); (Shedd, 2000-2020)

It is also important to mention the uncertainty related to the country's legislative and regulatory frameworks, which can generate an uncertain business climate for companies and can lead to disruptions in production or exports. More recently, a new mining code was promulgated in 2018 to replace the 2002 mining code, which was deemed to be very favorable to the mining industry held by private foreign investors[15]. Its main objective was to obtain more revenues from its natural resources by increasing state sovereignty in the mining sector. The DRC has one of the lowest per capita GDPs in the world even though it is richly endowed with natural resources. The DRC accounted for nearly 70% of mining extraction but for only 3% of refined cobalt production in 2015. It benefits little from the economic spin-offs of its mining activities because of its upstream positioning in the value chain and the strong presence of foreign companies in the country's mining sector. However, this new mining code has raised concerns and oppositions from foreign investors and companies.

According to our results, no major shifts are expected by 2050: whatever the climate scenario and mobility policy considered, Africa would still provide for more than 60% of primary cobalt and would not account for more than 4,5% of the global cobalt consumption. This continued concentration of cobalt mining production in Africa could become very problematic if events causing disruptions to cobalt supplies were to occur again.

Another difficulty linked to the exploitation of the DRC's cobalt reserves lies in the recent debate on whether to qualify cobalt as a "conflict mineral". “Conflict minerals” refers to a group of minerals defined by U.S. Security and Exchange Commission (SEC) as “*cassiterite, columbite-tantalite, gold, wolframite, or their derivatives, or any other minerals or their derivatives determined by the Secretary of State to be financing conflict in the Covered Countries*”. Although cobalt is mined in DRC, the Lualaba and Haut-Katanga provinces are not presently the theatre of armed group conflicts. Cobalt is then not a conflict mineral under

[15] The new mining code, supplemented by application texts, provides in particular for:

- the abolition of the stability clause of 10 years, now limited to 5 years;
- an increase in the Congolese State's participation in operating companies from 5 to 10%.
- a new calculation of royalties by raising the rates on ores from 2.5 to 3.5%, and up to 10% for strategic minerals such as cobalt.
- the introduction of a 50% tax on super profits when raw material prices increase by more than 25% compared to the forecasts projected in the feasibility study;
- less advantageous taxation increased foreign exchange repatriation obligations, and limited subcontracting possibilities to legal entities under Congolese law and with Congolese capital.

http://congomines.org/system/attachments/assets/000/001/467/original/J.O._n%C2%B0_spe%C3%ACcial_du_28_mars_2018_CODE_MINIER.PDF.pdf?1523182711 (Accessed on June 2019)

https://www.tresor.economie.gouv.fr/PagesInternationales/Pages/c4657524-6a6d-4cf3-8391-9d70556e302b/files/fe8753b8-2add-480a-afaa-94399bc6f0b0 (Accessed on October 1st, 2020) this definition and the Section 1502 of the Dodd-Frank Wall Street Reform & Consumer Protection Act[16] does not apply to it. Calling cobalt a "conflict metal" is therefore incorrect. Nevertheless, in recent years, cobalt has been awarded the dark title of "Blood Diamond of the batteries" (Airhart, 2018; Conca, 2018; Safehaven.com, 2017) with the hazardous working conditions, exposure to potentially carcinogenic dust, child labor, etc. due to a proliferation of clandestine mines linked to the high market value of cobalt and increased foreign demand. Borrowing a narrative similar to that of the "conflict minerals" campaigns of the early 2000s, NGOs are putting pressure on EV manufacturers to clean their supply chains and to advocate for the establishment of a due diligence regulatory framework (Prause, 2020). Then, although cobalt is still out of the scope of "conflicts minerals", this issue is regularly raised, and cobalt's supply chain is an object of increasing scrutiny

3.3.2.2. The risk related to China's growing influence on the cobalt value chain

China is the main consumer of cobalt worldwide but is only responsible for 1.4% of mined production, resulting in a 80 % reliance on foreign cobalt for the year 2015 (Chen et al., 2020). As for other metals (copper for example) that are key to the decarbonization of the energy and transport system, China has been seeking to secure its cobalt supply. Until the end of the 1990s, China relied mainly on its national resources to supply its industries. In the early 2000s, securing the foreign supply of raw materials became a major concern, resulting in the production of an international economic and commercial development strategy known as the "*Go out strategy*" (Konijn, 2014; Küblböck et al., 2019). Since 2013, this dynamic has been reinforced by the implementation of the new Silk Roads: the Belt and Road Initiative (BRI). In 2015, the central place of energy in the cooperation priorities envisaged by the Chinese authorities within the framework of the BRI is reasserted. These lines of collaboration relate to the joint development of renewable energy projects, infrastructure connectivity and collaboration in the field of exploitation and processing of resources including metals (NDRC, 2015). According to the China Investment Tracker of the American Enterprise Institute[17], more than $182 billion (nearly 9% of the total) were invested in the metals sector by China between 2005 and 2018, making it the country's fourth largest investment destination. In the case of cobalt, the agreements between China and the DRC, known as the

[16] The Section 1502 of the Dodd-Frank Wall Street Reform & Consumer Protection Act requires companies listed to the stock market to investigate their supply chain and do their best to ensure there are not supporting armed groups financing or human rights abuse.

[17] The American Enterprise Institute, « China Global Investment Tracker », 2018, https://www.aei.org/china-global-investment-tracker/.

"Resources versus Infrastructure" agreements or Barter deals, are a good illustration of this approach (Konijn, 2014; Gulley et al., 2019). At the beginning of 2019, around 90% of the copper and cobalt produced by the DRC is exported to China. Chinese companies are in the country's mining industry as well as in the public works and civil engineering sectors[18]. In 2018, 8 of the 14 largest cobalt mines were in the hands of Chinese entities (Farchy and Warren, 2018). Thus, by adding the share of foreign cobalt production held by Chinese enterprises and Chinese domestic production, China’s influence in the market increases from 2% to 14% for cobalt extractions and from 11% to 33% for the production of intermediate cobalt products. China's influence on the value chain does not stop in the upstream part of the value chain. In 2015, China produced nearly 54% of the world's refined cobalt, compared with just over 1% at the start of the new millennium. According to our modeling results, China is expected to remain the largest consumer of cobalt in 2050, accounting for a third of global demand and its share of mine production is expected to be around 2%. Consequently, China’s strategy for securing cobalt supply may generate increased competition for access to cobalt sources and make the blue metal less available on the global market (Gulley et al., 2019). Even though China is increasing its effective control on the cobalt supply chain, it is not immune to production disruptions that could be caused by production shocks in the DRC as seen above. Therefore, several research articles are pleading for active policies promoting secondary production of cobalt to mitigate China’s dependence on cobalt imports (Zeng and Li., 2015; Chen et al., 2019; Wang and Ge, 2020).

4. Conclusion

We assessed the criticality level of cobalt, a key metal for decarbonization of the road transport sector. We used an energy system optimization model which integrates a detailed representation of the cobalt value chain and the cobalt content of the relevant technologies in the energy and transport sectors. Our findings suggest that cobalt can be critical in several ways.

First, according to our results, 83,2% of cobalt resources identified in 2013 would be consumed between 2013-2050 in a 2°C scenario (Scen 2D), and the primary cobalt consumption would represent around 57.9% of the cobalt resources during the same period. The results highlight the importance of secondary cobalt production (recycling) which is around 15-25% of the cumulative global cobalt resources between 2013-2050. The results

[18] Direction Générale du Trésor, Service Economique Kinshasa, La Chine en RD Congo : présence économique, financements et les créance : https://www.tresor.economie.gouv.fr/Articles/2019/03/20/la-chine-en-rd-congo-presence-economique-financements-et-les-creances (consulté le 20 avril 2020)

also support that several countries or regions are likely to have a strong level of import dependency by 2050. This is the case of China, Western Europe, India, Japan, Middle East, Mexico, Russia South Korea, and the United States of America. On the other hand, about two-thirds of world production will be realized by the African continent while China will consume more than one-third of the total cobalt demand. The definition of our scenarios and hypotheses allows us to identify several levers to reduce the pressure on cobalt resources. On the demand side, public policies dedicated to sustainable mobility should be encouraged and priority should be given to less cobalt-intensive batteries. Promoting these types of battery technologies can save up to nearly 350 kt of cobalt. The role of mobility is also clearly emphasized, and these two public policies must be carried out jointly. The choice of battery technology and its influence on the demand for raw materials is only valid with regard to the study of a given metal, since the change of technology implies the need for an alternative, a substitute, for which criticality issues may exist too. It is also interesting to note that the waste-management hierarchy considers prevention (not using an object) to be preferable to substitution or recycling. On the supply side, efforts must be concentrated on the implementation and the deployment of waste recovery, sorting and recycling systems. This is more important for regions such as China, Western Europe, United States of America, India, and Japan, which will swallow up most of the cobalt produced in the world without having sufficient domestic production. In such a context, recycling appears to be an essential tool for securing cobalt supply. The risks related to the continued concentration of extractive activities in the DRC because of the chronic political instability or to China's growing influence on the entire cobalt value chain could reinforce the uncertainty of the global cobalt supply chain in the future.

Other perspectives of our global model for further research on cobalt would be to analyze the impact of an increasing collection rate which could be specified by region. The implementation of other raw materials such as nickel or rare-earth metals either in the transport sector for a complete representation of main electric vehicle battery raw materials or in the power sector with the increasing penetration rate of renewable energy technologies (RETs) would be very valuable. TIAM-IFPEN could be very useful as a decision-making tool to better understand investments in low-carbon technologies based on future raw material resource constraints for better sectorial assessment.

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5. References

- Abadie, D., (2011), "Canada and the geopolitics of mining interests: a case study of the Democratic Republic of Congo", Review of African Political Economy, Vol. 38, No. 128, 289–302.
- Airhart, E., (2018), "Alternatives to Cobalt, the Blood Diamond of Batteries", WIRED: https://www.wired.com/story/alternatives-to-cobalt-the-blood-diamond-of-batteries/
- Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., Kirchain, (2012), "Evaluating rare earth element availability: a case with revolutionary demand from clean technologies", Environmental Science & Technology, 46, 3406–3414.
- Alves Dias, P., Blagoeva, D., Pavel, C., Arvanitidis, N., (2018), "Cobalt: demand-supply balances in the transition to electric mobility", Technical report by the Joint Research Centre (JRC), European Commission, Publications Office of the European Union, JRC112285.
- Amnesty International, (2017), "Time to recharge - Corporate action and inaction to tackle abuses in the cobalt supply chain", Amnesty International Ltd, AFR 62/7395/2017.
- Ballinger, B., Schmeda-Lopez, D., Kefford, B., Parkinson, B., Stringer, M., Greig, C., Smart, S., (2020), "The vulnerability of electric-vehicle and wind-turbine supply chains to the supply of rare-earth elements in a 2-degree scenario", Sustainable Production and Consumption, 22, 68-76.
- Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.-M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., (2018), "Sustainability of artisanal

mining of cobalt in DR Congo", Nature Sustainability, Vol 1, 495-504, 10.1038/s41893-018-0139-4

- Barteková, E., Kemp, R., (2016), "Critical raw material strategies in different world regions", United Nations University, Maastricht Economic and social Research institute on Innovation and Technology, Working paper Series, #2016-005.
- Bazilian, M.D., (2018), "The mineral foundation of the energy transition", The Extractive Industries and Society, 5, 93–97.
- Bloomberg, 2017. Congo Halts Sicomines Copper Exports, Orders Local Refining. https://www.bloomberg.com/news/articles/2017-10-08/congo-halts-sicomines-copper-exports-orderslocal-processing
- Buhmann, K., (2018), "Chinese Mineral Sourcing Interests & Greenland's Potential as a Source of 'Conflict-Free Conflict Minerals'", Arctic Yearbook 2018: China & the Arctic, 84-101.
- Cao Z., Liu G., Zhong S., Dai H., Pauliuk S., (2019), Integrating Dynamic Material Flow Analysis and Computable General Equilibrium Models for Both Mass and Monetary Balances in Prospective Modeling: A Case for the Chinese Building Sector, Environ. Sci. Technol. 53, p224−233.
- Chen, Z., Zhang, L., Xu, Z., (2019), "Tracking and quantifying the cobalt flows in mainland China during 1994–2016: Insights into use, trade and prospective demand", Science of the Total Environment, 672, 752–762.
- Chen, Z., Zhang, L., Xu, Z., (2020), "Analysis of cobalt flows in mainland China: Exploring the potential opportunities for improving resource efficiency and supply security", Journal of Cleaner Production, Volume 275, 122841.
- Cheyns, K., Banza Lubaba Nkulu, C., Ngombe, L.K., Asosa, J.A., Haufroid, V., De Putter, T., Nawrot, T., Kimpanga, C.M., Numbi, O.L., Ilunga, B.K., Nemery, B., Smolders, E., (2014), "Pathways of human exposure to cobalt in Katanga, a mining area of the D. R. Congo", Science of The Total Environment, volume 490, 313-321.
- Conca, J., (2018), "Blood Batteries – Cobalt and the Congo », Forbes: https://www.forbes.com/sites/jamesconca/2018/09/26/blood-batteries-cobalt-and-the-congo/#5eb8e787cc6e

- Croy J.R., Gutierrez A., He M., Yonemoto B.T., Lee E., Thackeray M.M., (2019), “Development of manganese-rich cathodes as alternatives to nickel-rich chemistries”, Journal of Power Sources, 434, 226706
- Dai Q., Kelly J.C., Elgowainy A., (2018), Cobalt Life Cycle Analysis Update for the GREET Model, Energy Systems Division, Argonne National Laboratory.
- Deetman, S., Pauliuk, S., van Vuuren, D.P., van der Voet, E., Tukker, A., (2018), “Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances”, Environmental Science & Technology, 52, 4950-4959.
- De Ridder, M., (2013), “The Geopolitics of Mineral Resources for Renewable Energy Technologies”, The Hague Centre for Strategic Studies.
- Ding Y., Mu D., Wu B., Wang R., Zhao Z., Wu F., (2017), “Recent progresses on nickel-rich layered oxide positive electrode materials used in lithium-ion batteries for electric vehicles”, Applied Energy, 195, p 586-599.
- Drabik E., Rizos V., (2018), “Prospects for electric vehicle batteries in a circular economy”, CEPS Research Reports No 2018/05, https://www.ceps.eu/wp-content/uploads/2018/07/RR%202018_05_Circular%20Impacts_batteries.pdf
- Erdmann, L., Graedel, T.E., (2011), “Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses”, Environ. Sci. Technol. 2011, 45, 7620–7630.
- Farchy, J., et Warren, H., (2018), “China Has a Secret Weapon in the Race to Dominate Electric Cars”, Bloomberg, https://www.bloomberg.com/graphics/2018-china-cobalt/
- Farjana, S.H., Huda, N., Parvez Mahmud, M.A., (2019), “Life cycle assessment of cobalt extraction process”, Journal of Sustainable Mining, 18, 150–161.
- Fishbone, L.G., Giesen, G., Goldstein, G., Hymmen, H.A., Stocks, K.J., Vos, H., (1983), In User's Guide for MARKAL (BNL-51701). Upton, New York. Brookhaven National Laboratory.
- Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, J., Gambogi, J., McCullough, E.A., (2018), “U.S. Draft Critical Mineral List—Summary of Methodology and Background Information—U.S. Geological Survey Technical Input Document in Response to Secretarial Order No. 3359”, U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 2018–1021.

- Fu, X., Beatty, D.N., Gaustad, G.G., Ceder, G., Roth, R., Kirchain, R.E., Bustamante, M., Babbitt, C., A. Olivetti, E.A., (2020), “Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand”, Environmental Science and Technology, 54(5), 2985–2993.
- Fulton L., Cazzola P., Cuenot F., (2009), IEA Mobility Model (MoMo) and its use in the ETP 2008, Energy Policy 37, p3758-3768
- Ge J., Lei Y., Zhao L., (2016), China’s Rare Earths Supply Forecast in 2025: A Dynamic Computable General Equilibrium Analysis, Minerals 6, 95.
- Geenen, S., Cuvelier, J., (2019), “Local elites’ extraversion and repositioning continuities and changes in Congo’s mineral production networks”, The Extractive Industries and Society, 6 390–398.
- Godoy León, M.F., Dewulf, J., (2020), “Data quality assessment framework for critical raw materials. The case of cobalt”, Resources, Conservation & Recycling, 157, 104564.
- Godoy León, M.F., Blenginib, G.A., Dewulf, J., (2020), “Cobalt in end-of-life products in the EU, where does it end up? – The MaTrace approach”, Resources, Conservation & Recycling, 158, 104842.
- Godoy León, M.F., Blengini, G.A., Dewulf, J., (2021), “Analysis of long-term statistical data of cobalt flows in the EU”, Resources, Conservation & Recycling, 173, 105690.
- Graedel T., 2011, On the Future Availability of the Energy Metals, Annual Review of Materials Research Vol. 41, pp323-335
- Graedel, T.E, Nuss, P., (2014). Employing considerations of criticality in product design. JOM 66, pp.1-7.
- Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., Reck, B.K., (2015). “Criticality of metals and metalloids”, Proc. Natl. Acad. Sci (PNAS), 112, 4257–4262. https://doi.org/10.1073/pnas.1500415112.
- Guedes, F., Seck., G.S., Hache, E., Lewandowski, E., (2021), "Rare earth elements demand and energy transition in 2050: exploring water stress and environmental impacts", Renewable and Sustainable Energy Transition, Under Review.
- Gulley, A.L., McCullough, E., Shedd, K., (2019), “China's domestic and foreign influence in the global cobalt supply chain”, Resources Policy, 62, 317-323.
- Gupta, P., Gupta, S., (1983), “World demand for Cobalt: An econometric study”, Resources Policy, December 1983.

- Habib K., Hamelin L., Wenzel H., (2016), “A dynamic perspective of the geopolitical supply risk of metals”, Journal of Cleaner Production 133, p850-858
- Habib K., Hansdottir S.T., Habib H., (2020), “Critical metals for electromobility: Global demand scenarios for passenger vehicles, 2015–2050”, Resources, Conservation & Recycling 154, 104603
- Hache, E., (2018), "Do renewable energies improve energy security in the long run?", International Economics. Volume 156, Décembre, pp.127-135. https://doi.org/10.1016/j.inteco.2018.01.005
- Hache E., Seck G.S., Simoen M., (2018), Electrification of the world's automobile fleet and the criticality of lithium by 2050, ADEME Technical report, ADEME (French Environment & Energy Management Agency), in Press https://www.ademe.fr/sites/default/files/assets/documents/electrification-parc-automobile-criticite-lithium-horizon-2050_2018.pdf
- Hache, E., Seck, G.S., Simoen, M., Bonnet, C., Carcanague, (2019a), "Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport", Applied Energy 40, pp.6-25.
- Hache, E., Carcanague, S., Seck, G.S., Bonnet, C., Simoën, M., (2019b), « Vers une géopolitique de l’énergie plus complexe ? Une analyse prospective tridimensionnelle de la transition énergétique », IFPEN – IRIS, Policy Research Working Paper, January 2019.
- Hache, E., Seck, G.S., Simoën, M., Bonnet, C., Jabberi, A., Carcanague S., (2020), "The impact of future power generation on cement demand: an international and regional assessment based on climate scenarios", International Economics, 163,114-133 https://doi.org/10.1016/j.inteco.2020.05.002
- Harper, G., Sommerville, R., Kendrick, E. et al., (2019), “Recycling lithium-ion batteries from electric vehicles”, Nature 575, 75–86. https://doi.org/10.1038/s41586-019-1682-5
- Hatayama, H., Tahara, K., (2018), “Adopting an objective approach to criticality assessment: Learning from the past”, Resources Policy, 55 (2018), 96–102.
- Hayes, S.M., McCullough, E.A., (2018), “Critical minerals: A review of elemental trends in comprehensive criticality studies”, Resources Policy, 59 (2018) 192–199.
- Heffernan, O., (2019), “Deep-sea Dilemma. Mining the Ocean floor could solve mineral shortages – and lead to epic extinctions in some of the most remote ecosystems on Earth”, Nature, Vol 571, 465-468.

- Helbig, C., Bradshaw, A.M., Wietschel, L., Thorenz, A., Tuma, A., (2018), "Supply risks associated with lithium-ion battery materials", Journal of Cleaner Production, 172, 274-286.
- Hsieh I-Y.L., Pan M.S., Green W.H. (2020), "Transition to electric vehicles in China: Implications for private motorization rate and battery market", Energy Policy 144, 111654.
- Intergovernmental Panel on Climate Change (IPCC), 2018, Global Warming of 1.5 ºC
- International Crisis Group, (2016), "Katanga: Tensions in DRC's Mineral Heartland", International Crisis Group, Africa Report N°239.
- International Energy Agency (IEA), (2018), "Global EV Outlook 2018 Towards cross-modal electrification", IEA Publications.
- International Energy Agency (IEA), (2019a), "Global EV Outlook (GEVO) 2019 – Scaling-up the transition to electric mobility", IEA Publications.
- International Energy Agency (IEA), (2019b), World Energy Outlook (WEO)
- International Energy Agency (IEA), (2020a), "Renewables Information - Overview", IEA Statistics report.
- International Energy Agency (IEA), (2020b), "Global EV Outlook 2020 – Entering the decade of electric drive?", IEA Publications.
- International Energy Agency (IEA), (2021), "Net Zero by 2050 A Roadmap for the Global Energy Sector", IEA Publications.
- Jébrak, M., (2019), "Le cobalt en 2020 : économie, géologie et nouveaux développements", Géologues, 204, 55-57.
- Konijn, P., (2014), "Chinese Resources-For-Infrastructure (R4I) Swaps: An Escape from the Resource Curse?", South African Institute of International Affairs (SAIIA), SAIIA Occasional Paper 201.
- Küblböck, K., Tröster, B., Ambach, C., (2019), "Going global: Chinese natural resource policies and their impacts on Latin America", Austrian Foundation for Development Research (ÖFSE) Briefing Paper, No. 24.
- Kurzweil P., (2015), "Advances in Battery Technologies for Electric Vehicles, Chapter 7: Post-lithium-ion battery chemistries for hybrid electric vehicles and battery electric vehicles".

- Kushnir, D., Sanden, B.A., (2012), « The time dimension and lithium resource constraints for electric vehicles », Resources Policy, 37, 93–103.
- Loulou, R., Goldstein, G., Noble, K., (2004). Documentation For the MARKAL Family Models. ETSAP. http://www.etsap.org.
- Loulou, R., Labriet, M., (2008), "ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure", Computational Management Science, February, Volume 5, Issue 1–2, pp. 7–40.
- Loulou, R., Remme, U., Kanudia, A., Lehtila, A., Goldstein, G., (2016). Documentation Forthe TIMES Model. ETSAP. http://www.etsap.org.
- Månberger, A., Johansson, B., (2019), "The geopolitics of metals and metalloids used for the renewable energy transition", Energy Strategy Reviews, 26, 100394.
- McKinsey, (2018), "Lithium and cobalt – A tale of two commodities".
- Miller, K.A.,Thompson, K.F., Johnston, P., Santillo, D., (2018), "An Overview of Seabed Mining Including the Current State of Development, Environmental Impacts, and Knowledge Gaps", Frontiers in Marine Science, Volume n°4.
- Moreau, V., Dos Reis, P.C., Vuille, F., (2019), "Enough Metals? Resource Constraints to Supply a Fully Renewable Energy System", Resources, 2019, 8, 29; doi:10.3390/resources8010029.
- Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Shigetomi, Y., Suh, S., (2015), "Global Mining Risk Footprint of Critical Metals Necessary for Low- Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum in Japan", Environmental Sciences & Technology, 49, 2022−2031.
- Nassar, N.T., Graedel, T.E., Harper, E. M., (2015), "By-product metals are technologically essential but have problematic supply", Sci. Adv., 2015;1:e1400180.
- National Development and Reform Commission (NDRC), (2015), "Vision and Actions on Jointly Building Silk Road Economic Belt and 21st Century Maritime Silk Road", Ministry of Foreign Affairs, and Ministry of Commerce of the People's Republic of China, with State Council authorization, March 2015.
- Nguyen R.T., Eggert R.G., Severson M.H., Anderson C.G., (2021), "Global Electrification of Vehicles and Intertwined Material Supply Chains of Cobalt, Copper and Nickel", Resources, Conservation & Recycling 167, 105198.

- Nitta N., Wu F., Lee J. T., Yushin G., (2015), “Li-ion battery materials: present and future”, Materials Today 18, Issue 5.
- Nordhaus, W. D., Boyer J., (1999), “Roll the DICE Again: Economic Models of Global Warming”. Yale University, manuscript edition.
- Olivetti, E.A., Ceder, G., Gaustad, G.G., Fu, X., (2017), “Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals”, Joule, 1, 229–243.
- Opitz A., Badami P., Shen L., Vignarooban K., Kannan A.M., (2017), “Can Li-Ion batteries be the panacea for automotive applications?”, Renewable and Sustainable Energy Reviews, Volume 68, Part 1, p685-692.
- Ou S., Hsieh I-Y.L., Lin Z., Yu R., Zhou Y., Bouchard J. (2021), “China’s vehicle electrification impacts on sales, fuel use, and battery material demand through 2050: Optimizing consumer and industry decisions”, iScience 24, Issue 11, 103375
- Piçarra A., Annesley I. R., Otsuki A., de Waard R., (2021), “Market assessment of cobalt: Identification and evaluation of supply risk patterns”, Resources Policy 73, 102206
- Poizot P., Dolhem F., Gaubicher J., Renault S., (2015). “Perspectives in Lithium Batteries, Lithium Process Chemistry – chapter 6”. ISBN 978-0-12-801417-2.
- Prause, L., (2020), " Chapter 10 - Conflicts related to resources: The case of cobalt mining in the Democratic Republic of Congo”, The Material Basis of Energy Transitions, 153 – 167.
- Promisel, N.E., Gray, A.G., (1982), “USA tackels critical materials”, Resources Policy, 8(2), 143-146.
- Rachidi N.R., Nwaila G.T., Zhang S.E., Bourdeau J.E., Ghorbani Y., (2021), “Assessing cobalt supply sustainability through production forecasting and implications for green energy policies”, Resources Policy 74, 102423.
- Safehaven.com, (2017), “Cobalt prices to rocket as tech giants scramble for supplies. PR Newswire”, Retrieved from https://www.prnewswire.com/news-releases/cobalt-prices-to-rocket-as-tech-giants-scramble-for-supplies-657690933.html
- Scheele, F., Umpula Nkumba, E., Ben-Bellah, D., Bwenda, C., (2016), “Cobalt blues: Environmental pollution and human rights violations in Katanga’s copper and cobalt mines”, Stichting Onderzoek Multinationale Ondernemingen (SOMO) (Centre for Research on Multinational Corporations), ISBN: 978-94-6207-094-3.

- Seck, G.S., Hache, E., Simoën, M., Bonnet, C., Carcanague S., (2020), "Copper at the crossroads: Assessment of the interactions between low-carbon energy transition and supply limitations", Resources, Conservation & Recycling, 163, December. https://doi.org/10.1016/j.resconrec.2020.105072
- Shedd, K.B., McCullough, E.A., Bleiwas, D.I., (2017), "Global trends affecting the supply security of cobalt", Mining Engineering, December 2017, 37-42.
- Shedd, K.B., (2000-2020), "Mineral Commodity Summaries: Cobalt", U.S. Geological Survey.
- Sibley, S.F., (1980), "Cobalt: a strategic and critical resource of industrialized nations, supplied by developing nations", Natural Resource Forum, 4, 403-413.
- Slack, J.F., Kimball, B.E., Shedd, K.B., (2017), "Cobalt, chap. F of Schulz, K.J., DeYoung, J.H., Jr., Seal, R.R., II, and Bradley, D.C., eds., Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply", U.S. Geological Survey Professional Paper, 1802, F1– F4.
- Song, J., Yan, W., Cao, H., Song, Q., Ding, H., Lv, Z., Zhang, Y., Sun, Z., (2019), "Material flow analysis on critical raw materials of lithium-ion batteries in China", Journal of Cleaner Production, 215, 570-581.
- Sovacool, B.K., (2019), "The precarious political economy of cobalt: Balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo", The Extractive Industries and Society, 6, 915–939.
- Speirs, J., Contestabile, M., Houari, Y., Gross, R., (2014), "The future of lithium availability for electric vehicle batteries", Renewable and Sustainable Energy Reviews, 35, 183–193.
- Sun, X., Hao, H., Liua, Z., Zhao, F., Song, J., (2019), "Tracing global cobalt flow: 1995–2015", Resources, Conservation & Recycling, 149, 45–55.
- Światowska J., Barboux P., 2015. Lithium process chemistry. Resources, extraction, batteries and recycling. Chapter 4 – lithium battery technologies: from the electrodes to the batteries. Elsevier, p.125–66
- Tang C., Sprecher B., Tukker A., Mogollon J.M., (2021), "The impact of climate policy implementation on lithium, cobalt and nickel demand: The case of the Dutch automotive sector up to 2040", Resources Policy 74, 102351

- The American Enterprise Institute, (2018), « China Global Investment Tracker », https://www.aei.org/china-global-investment-tracker/.
- Tisserant, A., Pauliuk, S., (2016), "Matching global cobalt demand under different scenarios for co-production and mining attractiveness", Economic Structures, 5:4.
- United Nations (UN), Department of Economic and Social Affairs, Population Division, (2019), Probabilistic Population Projections Rev. 1 based on the World Population Prospects 2019 Rev. 1: http://population.un.org/wpp/
- U.S. Geological Survey (USGS), (1932-1993), "Mines Minerals Yearbook archive", National Minerals Information Center, Courtesy of the University of Wisconsin Ecology and Natural Resources Collection, https://www.usgs.gov/centers/nmic/bureau-mines-minerals-yearbook-1932-1993.
- U.S. Geological Survey (USGS), (1994- 2016), "Minerals Yearbook: Cobalt", USGS annual publications, https://www.usgs.gov/centers/nmic/cobalt-statistics-and-information.
- USGS, (2008), "2006 Minerals Yearbook -Cobalt", United States Geological Survey: Washington, DC, April 2008.
- Valero, A., Valero, A., Calvo, G., Ortego, A., (2018), "Material bottlenecks in the future development of green technologies", Renewable and Sustainable Energy Reviews 93 (2018) 178–200.
- Van Den Brink, S., Kleijn, R., Sprecher, B., Tukker, A., (2020), "Identifying supply risks by mapping the cobalt supply chain", Resources, Conservation & Recycling, 156, 104743.
- Verweijen, J., (2017), "Luddites in the Congo? Analyzing violent responses to the expansion of industrial mining amidst militarization", City, 21(3-4): 466–482.
- Wang, Y., Ge, J., (2020), "Potential of urban cobalt mines in China: An estimation of dynamic material flow from 2007 to 2016", Resources, Conservation & Recycling, 161, 104955.
- Wang X., Ge J., Li J., Han A., (2017), Market impacts of environmental regulations on the production of rare earths: a computable general equilibrium analysis for China, Journal of Cleaner Production 154, p614-620
- Watari, T., Nansai, K., Nakajima, K., (2020), "Review of critical metal dynamics to 2050 for 48 elements", Resources, Conservation & Recycling, 155, 104669.
- Zeng, X., Li, J., (2015), "On the sustainability of cobalt utilization in China", Resources, Conservation and Recycling,

- Zeuner, B., (2018), “An obsolescing bargain in a rentier state: multinationals, artisanal miners, and cobalt in the Democratic Republic of Congo”, Frontiers in Energy Research, 6:123.
- Zhang, S., Ding, Y., Liu, B., Chang, C., (2017), “Supply and demand of some critical metals and present status of their recycling in WEEE”, Waste Management, 65, 113-127.
- Zubi G., Dufo-López R., Carvalho M., Pasaoglu G., (2018), “The lithium-ion battery State of the art and future perspectives”, Renewable and Sustainable Energy Reviews 89, p292-308.

6. Supplementary materials

Appendix A: TIAM-IFPEN

TIAM-IFPEN is a well-established version of the global TIAM model developed under the Energy Technology Systems Analysis Program of the International Energy Agency (IEA-ETSAP). It is a bottom-up integrated assessment model based on the TIMES generator.

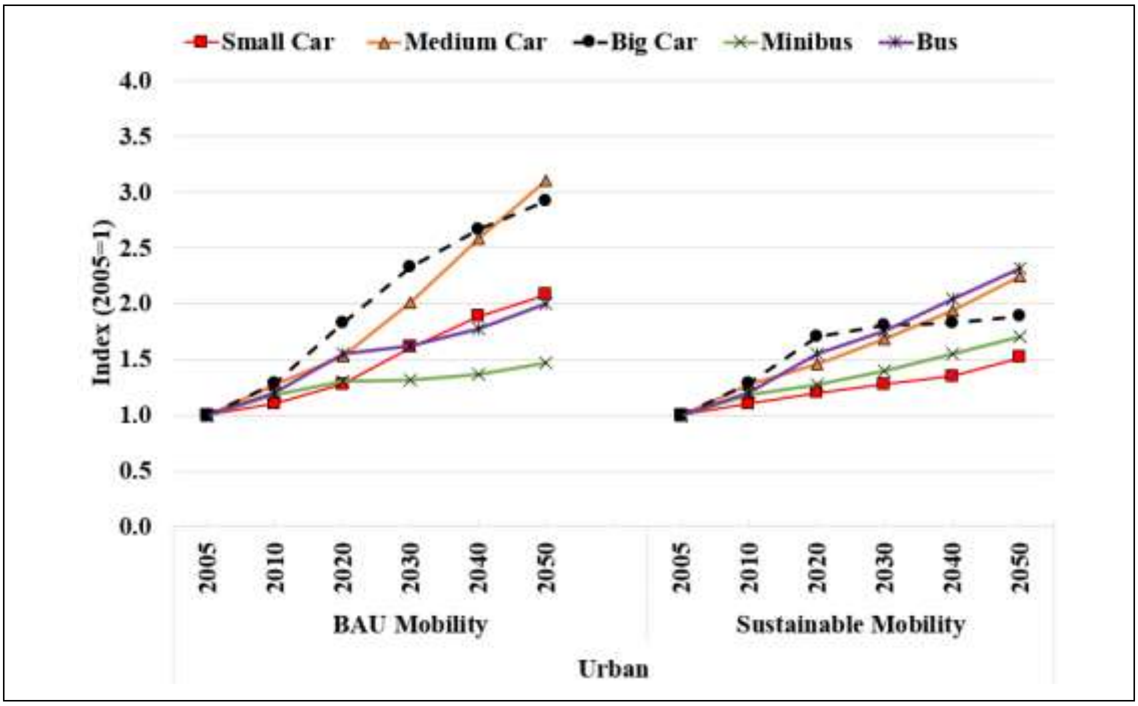
- ❖ GDP and population scenarios

The evolution of the GDP and population have been extracted, respectively, from the IEA and the UN population division (UN, 2019). World population rises to about 9.7 billion in 2050 in the median scenario, while world GDP (ppp)[19] grows to US$283,500 billion in 2050.

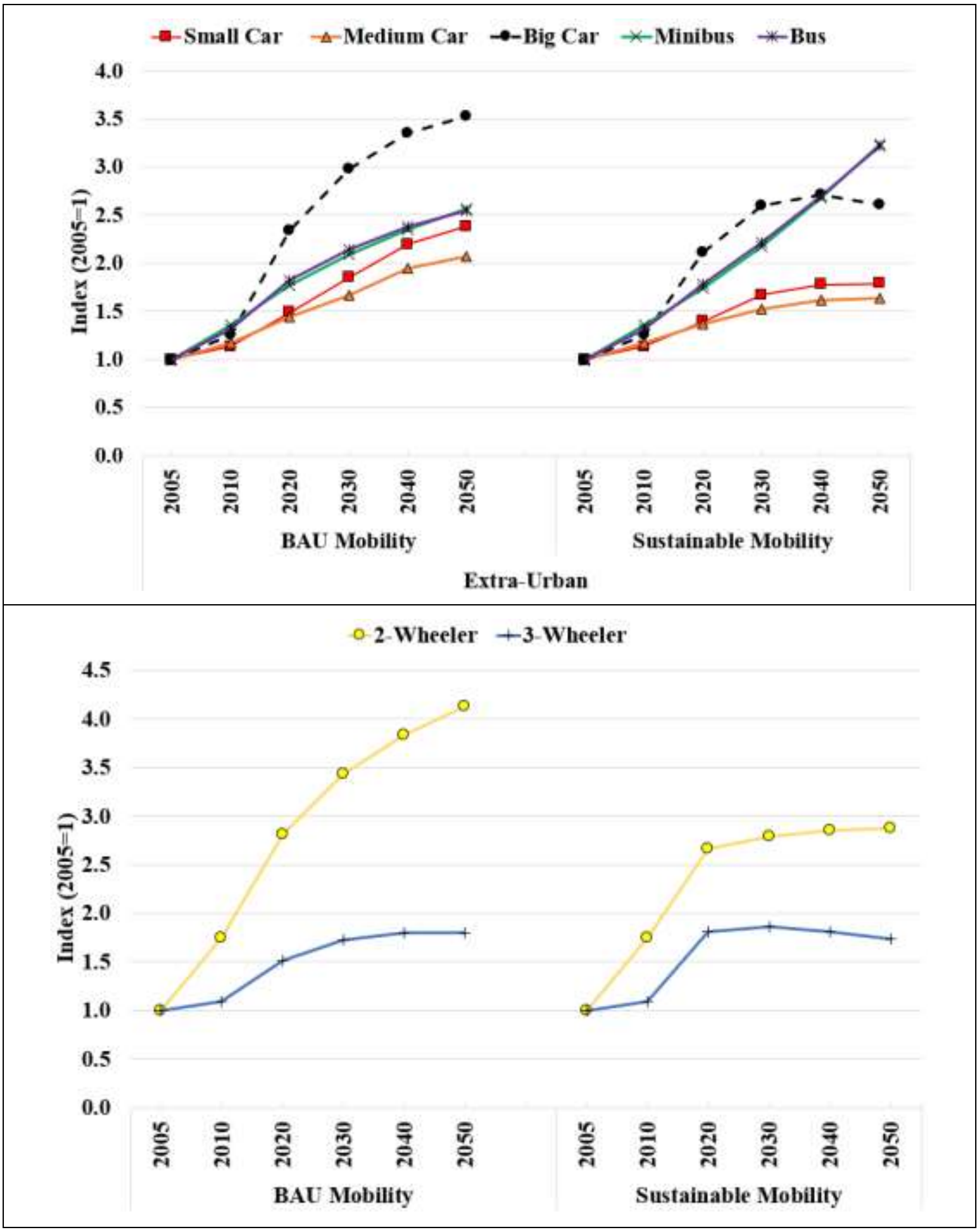
- ❖ Mobility scenarios

The different mobility (BAU and Sustainable) demands have been derived from the IEA MoMo model (Fulton et al., 2009) with a disaggregation by vehicle size and by short and long distance (urban and extra-urban mobility) (Fig. 14). These two mobility scenarios are used to analyze the impact of a public policy on the development of the transport sector, and therefore the consumption of raw materials, in a context of climate constraints.

Fig. 14 : Evolution of the two different shape of mobility (BAU and Sustainable) according to the travel mode (Urban and Extra-Urban)



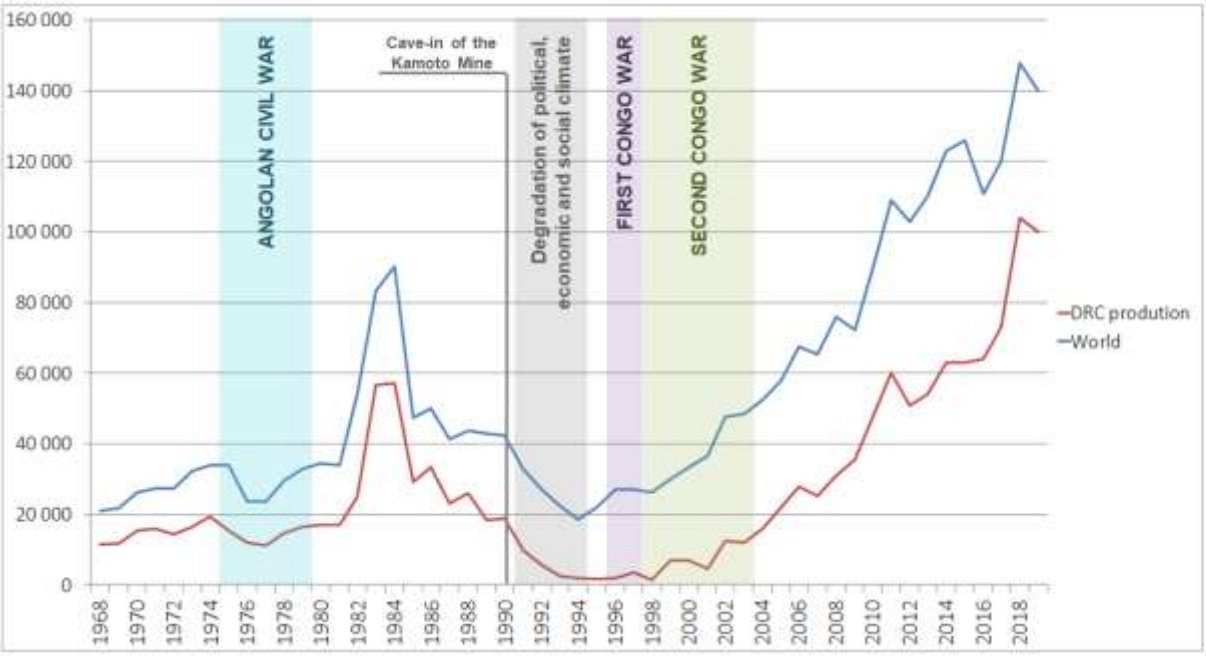
[19] GDP at purchasing power parity



Source: IEA Mobility model 2019

Appendix B

Fig. 15: Zaire/Democratic Republic of the Congo cobalt mine production (metal content) from 1968 to 2019



Source: (USGS, 1932-1993), (USGS, 1994-2016), (Shedd, 2000-2020)

Table 9: Cobalt supply disruptions since the 1970s

Year	Event nature	Event	Impact
1975	Business and political climate uncertainty	Suspension of the *Société Minière de Tenke Fungurume* (SMTF) copper-cobalt project because of the uncertain climate generated by the civil war taking place in Angola.	Delay or suspension of copper-cobalt projects
1976	Political and social unrest	Supply shortage from Zaire after bridges along commercial roads (Benguela Railroad) used by Zaire were damaged in the Angolan civil war.	Supply shortage
1977	Conflict Political and social unrest	Invasion of the Shaba Province was invaded by troops coming from Angola: • Disturbance of the commercial roads because the Benguela Railroad remained closed. • Delay of transmission line and expansion projects or downscaling of projects.	Production decline
1978	Conflict Political and social unrest	Invasion of the mining city of Kolwesi in Shaba province by the FLNC (*Front National pour la Libération du Congo*): • Takeover of copper and cobalt mines • Repatriation of foreign employees	Disruption of refining and extractions activities
1986		Obsolescence of the Mining facilities and equipment.	Production decline
1990	Industrial accident	Collapse of Gécamines'main underground copper-cobalt mine (Kamoto).	Production decline
1991	Political and social unrest	Difficulties in completing the democratization process generating political, social and economic unrest: • Riots and looting spread from Kinshasa to the mining regions. • Destruction of Gécamines'office in Kolwesi. • Withdrawal of international financial support.	Production decline Interruption of production Lack of maintenance of facilities
1992	Political and social unrest	Persistent political and social unrest.	Production decline Lack of maintenance of

			facilities
1993	Political and social unrest	Persistent political and social unrest.	Production decline (Zaire fell from being 1st world producer to 6th) Lack of maintenance of facilities
1997	Political and social unrest Conflict	Takeover of the country by military forces opposed to the government of Zaire. The country is renamed Democratic Republic of Congo.	Production decline Lack of maintenance of facilities
1998	Political and social unrest Conflict	Rebellion led by soldiers opposed to the new government.	Delay or suspension of copper-cobalt projects Decline of industrial production and rise of artisanal mining
1999	Political and social unrest Conflict	Rebellion led by soldiers opposed to the new government.	Delay or suspension of copper-cobalt projects Decline of industrial production and rise of artisanal mining
2000	Political and social unrest Conflict Corporate failure	Rebellion led by soldiers opposed to the new government. Revocation of a joint venture contract between Gécamines, the Government of Congo (Kinshasa), and Ridgepointe Overseas Developments Ltd by the Ministry of Mines.	Delay or suspension of copper-cobalt projects
2007	Change in legislation	Official forbiddance of unprocessed cobalt ores exports declared by the Government of Katanga province.	Decrease of total cobalt exports

Source: (USGS, 1932-1993), (USGS, 1994-2016), (Shedd, 2000-2020)