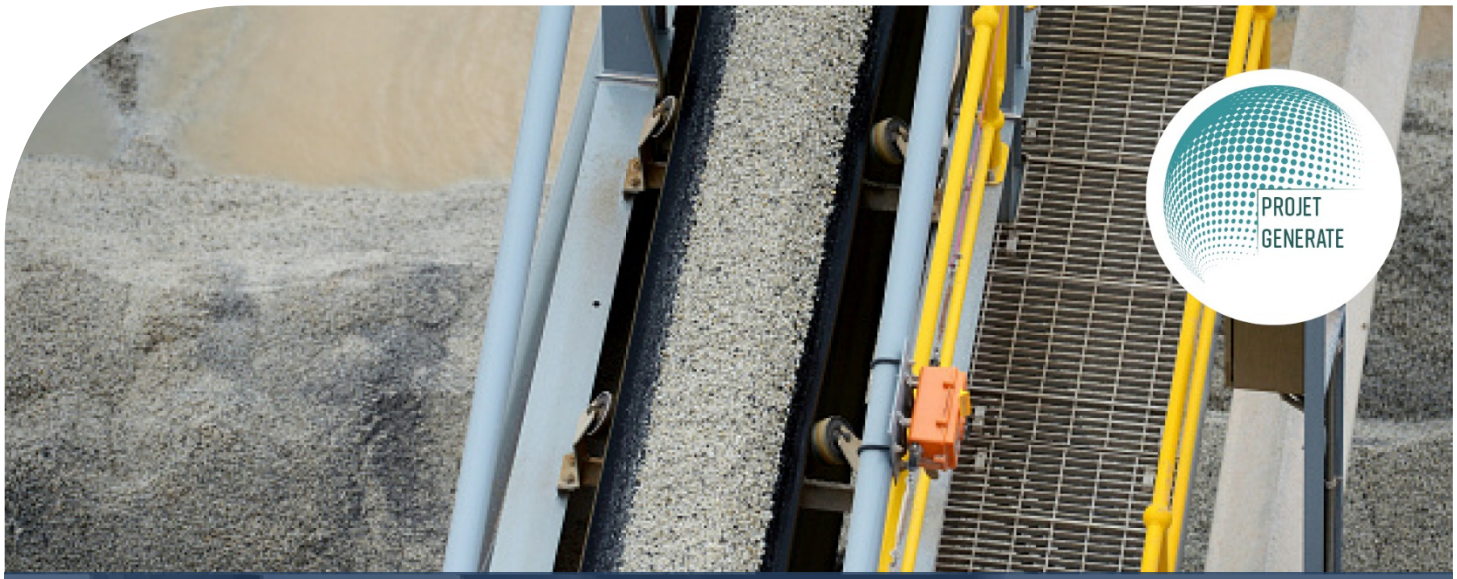

Working Paper 2019-3

CRITICAL RAW MATERIALS AND TRANSPORTATION SECTOR ELECTRIFICATION:

A detailed bottom-up analysis in world transport

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ABSTRACT

The aim of this article is to study the impact of a massive diffusion of electric vehicles in the world transportation sector on the lithium market. Lithium, like other strategic materials, has found new markets in the context of the energy transition. Hence, the capacity of those strategic materials to supply these new markets can be questioned. To achieve this goal, we have developed the first detailed global bottom-up energy model, TIAM-IFPEN (Times Integrated Assessment Model-IFPEN) with an endogenous disaggregated life-cycle inventories. It would clearly assess the dynamic criticality of strategic materials according to the optimal technology paths with environmental and/or energy solicitations through different approaches: geological, geopolitical, and economic towards a sustainable development. Four scenarios have been run taking into account two climate scenarios (4°C and 2°C) with two shapes of mobility each: a high mobility where we assume the impact of urban dispersal with a huge car dependence/usage, and a low mobility where the idea of a sustainability in mobility is assumed. The penetration of electric vehicle (EV) at the global level would push the demand of cumulated lithium but the results show us an absence of geological criticality. Nevertheless, they have clearly highlighted other different forms of vulnerabilities, whether economic, industrial, geopolitical or environmental. A discussion about the future risk factors applied to the lithium market has been also done at a regional scale to analyse more in-depth the impact of the future global fleet development on lithium market. Our study of this particular strategic material shows that the model could be a useful decision-making tool for assessing future raw material market stresses along with energy transition and could be extended to other critical raw materials for more efficient regional and sectorial screening.

Keywords: World transportation; Electrification; Critical raw materials; Lithium; Bottom-up modelling

JEL Classification: Q42, R40, C61

I. INTRODUCTION

Technology is often highlighted in energy transition dynamics at the international level, but large uncertainties remain about the widespread diffusion of low-carbon innovations [1-4]. The cost, the speed of adoption and the acceptance of technologies by different stakeholders are thus fundamental parameters for drawing decarbonisation trajectories. What is given as a certainty with all decarbonisation innovations is the growing need for ores and refined metals [5-6]. A massive diffusion of renewables into the world's energy mix could lead to new and unexpected interdependencies including dependencies on critical materials, a new geopolitics of patents and the implementation of a renewable diplomacy [7-8]. Despite the continuing policy focus on energy system development and the many reports and books written on the topic, the extension of the scope beyond purely energy-oriented issues to the dynamic impact of raw materials related to the energy transition has been seldom targeted in energy modelling analyses.

1.1 Critical assessment methods for raw materials

As an heterogeneous field of research, raw materials supply risk and criticality have been widely discussed since the past decade [9-16]. An extensive part of the first literature was devoted to rare-earth elements criticality [17-25] although for few years increasingly number of metals are in the spotlight, even including non-ferrous-metals [6]. Resource criticality is difficult to define as it depends on the scale of the analysis: micro-level (industrial sector or company), macro-level (country) or global level. Regarding transition technologies, Moss et al. [13] have showed for example the potential limiting role of metals in the specific deployment of the European Union's Strategic Energy Technology Plan (SET-Plan, 2013) when Roelich et al. [26] have tried to assess the material criticality of infrastructure in a global low-carbon electricity scenario focusing on neodymium. At the country level, Viebahn et al. [27] assessed the need of critical minerals to shift the German energy system towards a high share of renewable sources. Logically, according to the scope and purpose of the work, conclusions may differ.

One of the major challenges is then the development of criticality assessment methods. The dimensions of interest considered in criticality assessments [28] are usually vulnerability and supply risk relying on economic, geological or technical concerns [10-11,29] sometimes extended to cope with environmental impacts [30] or social implications [31-32]. The European Commission (EC) criticality assessment methodology [33], based on the economic value of the resource and its supply risk for the EU, is an illustration of such type of assessment methodology. These assessment methods, which have been applied to a wide range of raw materials, are mostly snapshot analysis in time with determined and relevant indicators [34-38]. A time evolution of these indicators should be one of the main future research focus [30]. Other methods relied on past supply disruption events [39] and possible future growth with constant past trends [40] or without including detailed studies of the development of emerging technologies, GDP forecasts, evolution and interactions between all sectors of the economy globally with stringent environmental scenarios [41-42]. Few methods have been also developed in order to assess the dynamic material criticality over time with Life Cycle Assessment (LCA) approaches combined with other models such as a hybrid LCA-IO (Life Cycle Assessment combined with the results from a global Input-Output model) [43], or a hybrid LCI-TIAM ((Life Cycle Inventories combined with the results from the bottom-up model TIAM[1]) [44] or a mathematical algorithm [26]. Various studies have been already conducted with the TIAM model to analyse different climate change mitigation policies by the international modelling community – such as in power supply with the role of nuclear energy in long-term climate scenarios [45-46] or the evolution of energy supply investment in a specific region [47-50], effort sharing among countries for global climate change mitigation [51-55], transportation [56-58].

In this paper, unlike the abovementioned articles, an endogenous integration of raw materials content into our detailed bottom-up model, TIAM-IFPEN, has been implemented in order to allow them to interact endogenously with the different scenarios which could be considered. So, we have developed the first detailed global

[1] TIMES Integrated Assessment Model, a technology rich bottom-up cost optimization belonging to the MARKAL family model

bottom-up energy model with an endogenous disaggregated life-cycle inventories. This model should be able to evaluate the dynamic criticality of strategic materials according to the optimal technology paths while accounting for environmental and/or energy solicitations through different approaches: geological, geopolitical, economic, all being developed for ensuring a sustainable development. There is, therefore, a dual advantage:

- The capacity to endogenously account for the impact of raw material resource constraints (resource availability, extraction cost), technical constraints (physical balances, availability factors, etc.) and non-technical constraints (market penetration limits, policy scenarios, environmental specifications, etc.) on the demand satisfaction or the roll-out of emerging low carbon technologies
- Dynamic assessment of raw materials criticality

This bottom-up energy model, TIAM-IFPEN, would be useful as a good decision-making tool for analysing the dynamics of the raw materials demand taking into account the future developments of the transport and power sectors through stringent environmental scenarios.

1.2 Future structural change of the transport sector: Study case of the lithium criticality

With more than 3 million electric vehicles (EV)[2] in circulation in the world in 2017 according to the Global EV 2018 [59] survey, 2017 continued the trend towards electrification that has existed since 2010. The market of electric passenger light-duty vehicles has increased 10-fold between 2011 and 2016 [59], resulting in a significant increase of the lithium demand for the battery sector (+20% between 2012 and 2017 considering USGS database). In addition, more and more significant policies have been implemented at national scale, especially in China, the European Union and India to accelerate the deployment of electric cars on a global scale. Thus, the structure of the

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

transportation sector is evolving and changing rapidly since few years. This structural evolution will have a strong impact on the lithium market.

Previous works have already been conducted on lithium criticality, mainly focused on estimating the future lithium demand [60-63] with a large variety of time horizons from short-term [64] to mid-long term, until 2100 in Yaksic and Tilton (2009) [61]. Future lithium volumes are mainly depending on the EV scale deployment. The evolution of the EV stock is mostly based on author's assumptions or scenarios borrowed from the literature. For example, Speirs et al. [60] based their estimation on the IEA Blue Map scenarios and used different material intensity to estimate the lithium demand. Most of these works underlined the potential absence of deep lithium depletion in the future in regards to its current resources or reserves. Yaksic and Tilton [61] had for example previously addressed the threat of lithium depletion and concluded that there was possibly no issue on lithium supply till the end of the century, even in a 100% electric scenarios by using the cumulative availability curve[3]. Other research papers have laid emphasis on lithium criticality with larger discussions than resources or reserves constraints [65-67] insisting for example on the impact of recycling [68-69] or batteries technologies [70], including more and more economic concerns such as economies of scale [71]. Market organization and lithium pricing was studied by Maxwell P. [72] which linked the past lithium pricing transparency and competitiveness in regard to the industry status and the number of major players. Geopolitical dimension was also discussed through global material flow analysis (MFA) [73-74] focused exclusively on China [75-76]. South America, and in particular Bolivia, which are the largest resources owner, were also widely spotlighted by literature as lithium critical important factors [77-78], just as China, the first lithium consumer [79]. Nonetheless lithium is also strategic regarding regions with potential future large demand and no important resources, such as Europe, where recycling and substitution impacts were also analysed by Miedema and Moll [80].

[3] The cumulative availability curve shows the quantities of a mineral commodity that can be recovered under current conditions from existing resources at various prices.

Finally, none of these works have considered a global three-dimensional approach taking into account geological (availability and affordability of the resources), geopolitical (supply risks) and economic (different regionalized growth) criteria with the transport evolution and global environmental constraints. The methodology developed in this paper and applied to the case of lithium will allow filling the gap in the scientific research in raw material criticality. Moreover, when comparing the lithium market to the definition of strategic metals given by Graedel et al. [30] and completed by Helbig et al. [11]: (i) The metal is used in many industrial sectors; (ii) It is difficult to find in the short term a suitable substitute for this metal for one or more industrial applications; (iii) The number of industrial applications using this metal is broad and increases over time; (iv) The metal is used in dispersing applications with limited recycling potential; (v) The metal has a great economic value; (vi) The metal production and reserves are geographically concentrated; (vii) The metal production could damage human health and/or ecosystem; Lithium meets 5 out of the 7 above-mentioned criteria. As a strategic metal for battery production, it is quite representative of the new challenges related to the energy transition due to the potential for electrification of vehicles worldwide, the concentration of reserves in a limited number of countries, the limited recycling potential and the oligopolistic industrial structure of its market [81]. It explains why this paper is focusing on the impact of a future increasing electrification of the transport sector on a regionalized lithium demand.

With a high regional breakdown of the world, our TIAM-IFPEN model is particularly well suited to develop foresight exercises by 2050 using an integrated approach. Such an approach allows to understand and discuss the economic, technological, environmental and geopolitical factors that can influence developments in the global transport sector, on which the lithium market may depend heavily. The rest of the paper is organized as follows : Section 2 describes the methodology, the overall structure of the TIAM-IFPEN bottom-up model, and the specific features and assumptions engaged for a detailed raw lithium criticality analysis; Finally, Section 3 presents our main results and related comments on the lithium market in response to climate constraints at global and regional level, to lithium resource availabilities and the implications of future mainstream in road passenger transport mobility, while Section 4 summarizes our

findings and provides policy recommendations regarding risks assessment of the lithium market.

II. METHODOLOGY

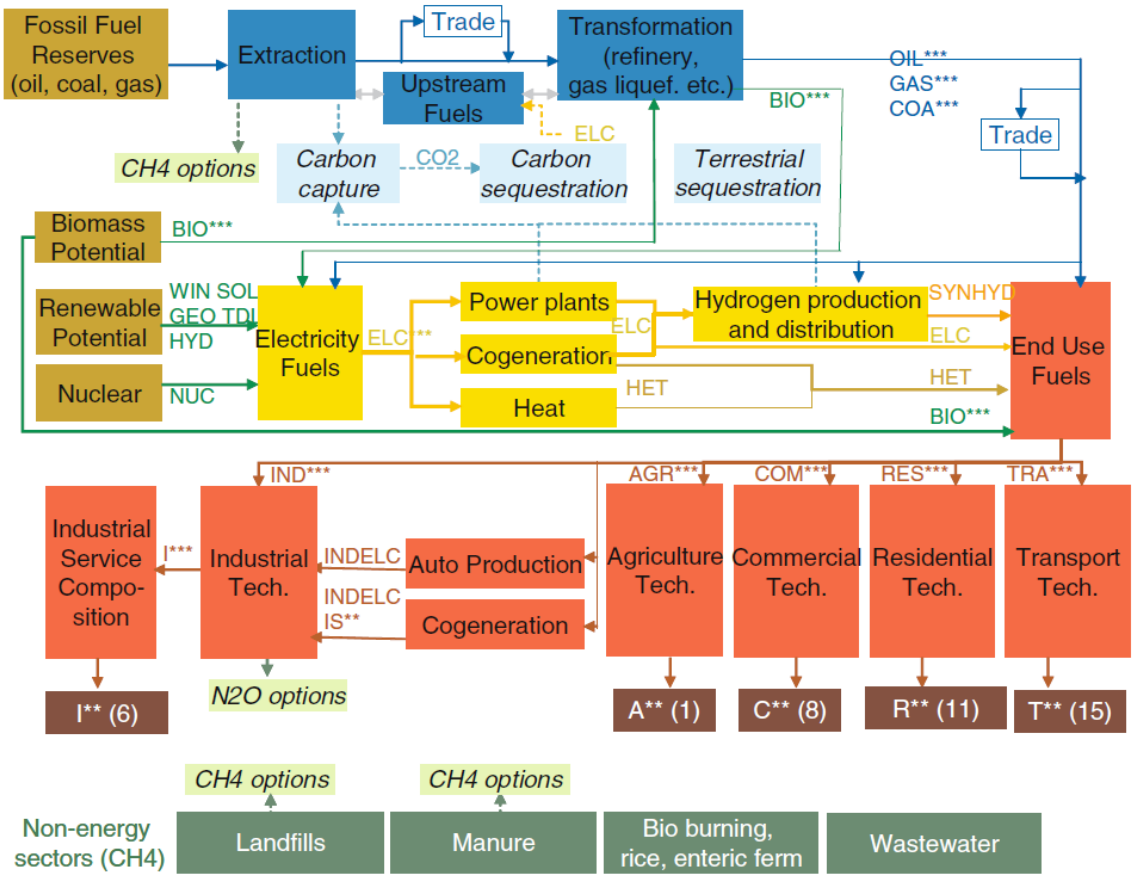
TIAM-IFPEN (TIMES[4] Integrated Assessment Model) model [82-84] is a technology rich bottom-up cost optimization belonging to the MARKAL[5] family model [85-89]. Energy supply, demand and market dynamics are modelled in order to represent energy dynamics over a long-term, multi-period time horizon at a local, national, multi-regional, or global level. A detailed description of the model with its main features (technical, economic and policy parameters, scenarios...) is provided in the following subsections.

2.1 TIAM-IFPEN structure

TIAM-IFPEN is a linear optimization programming inherited from the ETSAP[6]-TIAM model which is the global multiregional model simulating the dynamics of the global energy system from resource extraction to energy end-use over a long-term period of over 100 years. It is a version of the TIAM model, developed in 1997 by one of the IEA implementing agreements IEA-ETSAP, which is the global incarnation of the TIMES model, the successor of the former generators MARKAL and EFOM[7] [90], but implemented with new features for enlarging its field of application and providing greater flexibility [91].

[4] The Integrated MARKAL-EFOM System
[5] MARKet Allocation model
[6] Energy Technology Systems Analysis Program.
Created in 1976, it is one of the longest running Technology Collaboration Programme of the International Energy Agency (IEA). https://iea-etsap.org/
[7] Energy Flow Optimization Model

Fig. 1: TIAM model's Reference Energy System [91]



As seen above, all main sectors of the economy are represented in the TIAM-IFPEN: industry, residential, agriculture, commercial, transport and electricity generation. It computes a partial equilibrium which means that the suppliers of energy produce the quantity to meet the exogenous demand services considered. This equilibrium feature is present at every stage of the energy system. While computing the equilibrium, a TIAM run configures the energy system over a certain time horizon, in such a way as to minimize the objective function of the system, while satisfying a number of constraints. This objective function represents the total discounted cost of the system over the selected planning horizon. All components of the system cost are specified yearly in the study horizon in contrary to the constraints and variables which are related to period for a better representation of the payment flows. The main cost components included in the objective function are the investment costs, fixed and variable operation and

maintenance (O&M) costs. Other cost components such as costs incurred for exogenous imports, revenues from exogenous exports, taxes and subsidies associated with commodity flows and process activities or investments are also included. All costs are discounting to the base year 2005 which is the reference year at which our TIAM-IFPEN is calibrated. A complete description of the TIMES equations appears in ETSAP documentation [83].

As a technology explicit model, TIAM is based on a Reference Energy System which is a network of processes linked by their inputs and outputs, going from the energy supply sector to the energy consumption sector, through energy trade, transformation and conversion (Fig. 1). The existing and future technologies in the sectors over a given time horizon are considered with techno-economic parameters (capacity, energy intensity, conversion efficiencies, availability factor, investment costs, fixed and variable costs, future cost changes, maximum penetration rates, economic and technical life, etc.) and their related strategic orientation parameters (taxes, subsidies, etc.).

As reminded in all ETSAP documentation, solving the model means finding for each time period the optimum Reference Energy System by selecting the set of technologies and feedstock that provides the optimal energy-technology pathways. Thus, the model determines the optimal mix of technologies (capacity and activity) and feedstock at each period, the associated emissions, the mining and trading activities, the quantity and prices of all commodities, the equilibrium level of the demand for energy services, all in times series from the base year 2005 to the time horizon 2050 of the model.

2.2 Regional assumptions

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

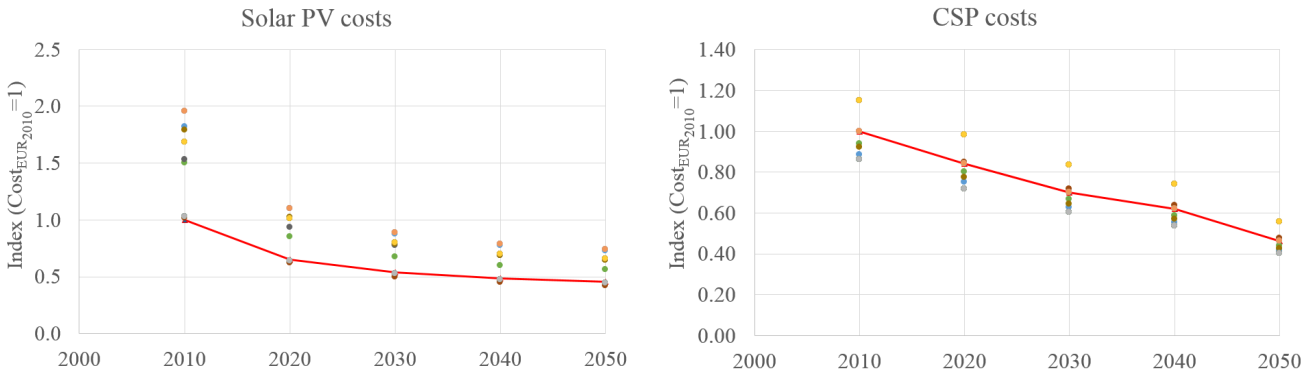
Table 1 : Regions of the TIAM-IFPEN

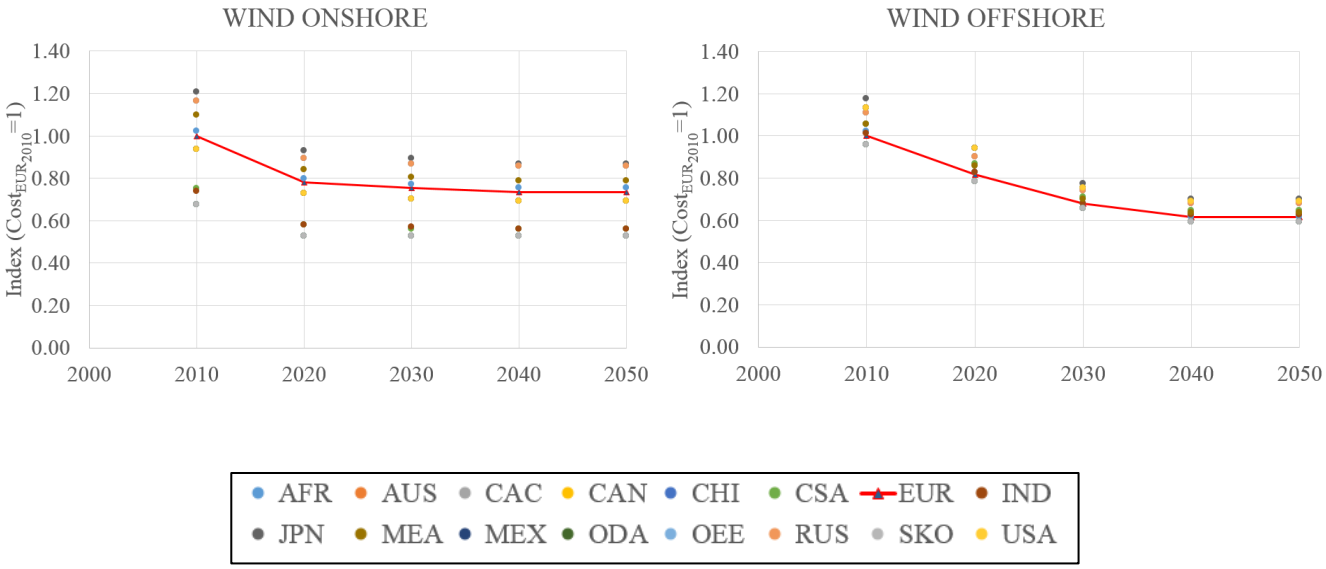
TIAM name	Region
AFR	Africa
AUS	Australia, New Zealand and Oceania
CAN	Canada
CHI	China
CSA	Central and South America
IND	India
JAP	Japan
MEA	Middle-east
MEX	Mexico
ODA	Other Developing Asia
SKO	South Korea
USA	United States of America
EUR	Europe 28+
RUS	Russia
CAC	Central Asia and Caucase (Armenia,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

The model is disaggregated into 16 regions (Table 1). Each region has its own energy system with its main demand sectors. Each region can trade fossil resources, biomass, materials or emission permits with other regions or in a centralized market. Thus, the model fully describes within each region all existing and future technologies from supply (primary resources) through the different conversion steps up to end-use demands.

The following power generation technologies have been covered by the model: renewable energy technologies (RETs) (solar PV and CSP, wind onshore and offshore, hydro, biomass), fossil-based technologies (coal, natural gas, oil) and nuclear. Most techno-economic parameters (capacity, energy intensity, efficiency, availability factor, investment costs, fixed and variable costs, economic and technical life, etc.) and the inventories of the existing and future generation technologies were taken from the World Energy Outlook 2016 [92], IRENA [93] and the European Commission database. An evolution of regional investment costs of the main technologies has been displayed in Fig. 2 and Fig. 3. The investment cost of a technology in Europe region in 2010 is considered as the reference index for regional comparison. We assumed a continuing decrease of the RETs costs over the studied period till 2050 in line with IRENA and IEA.

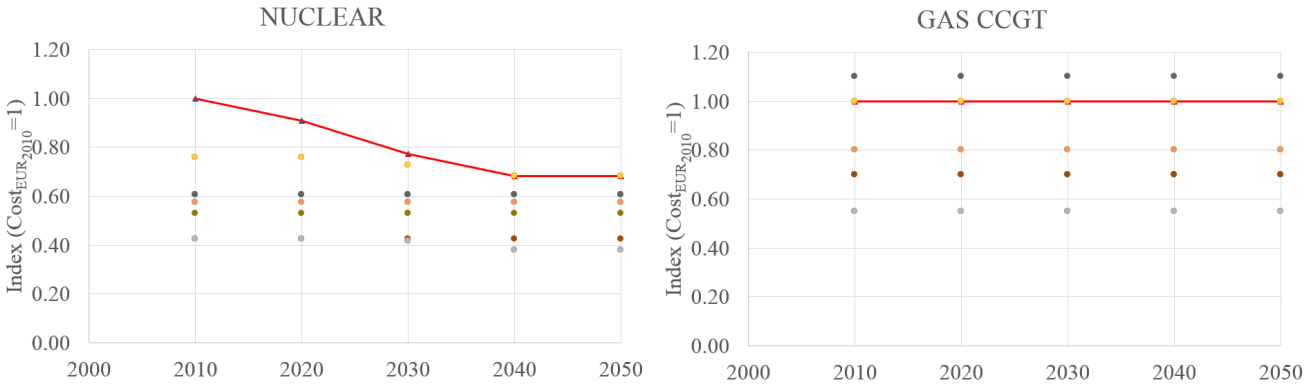
Fig. 2 : Average renewable energy technology (RET) investment costs at regional level between 2010-2050 (Index CostEUR$_{2010}$=1, red line)

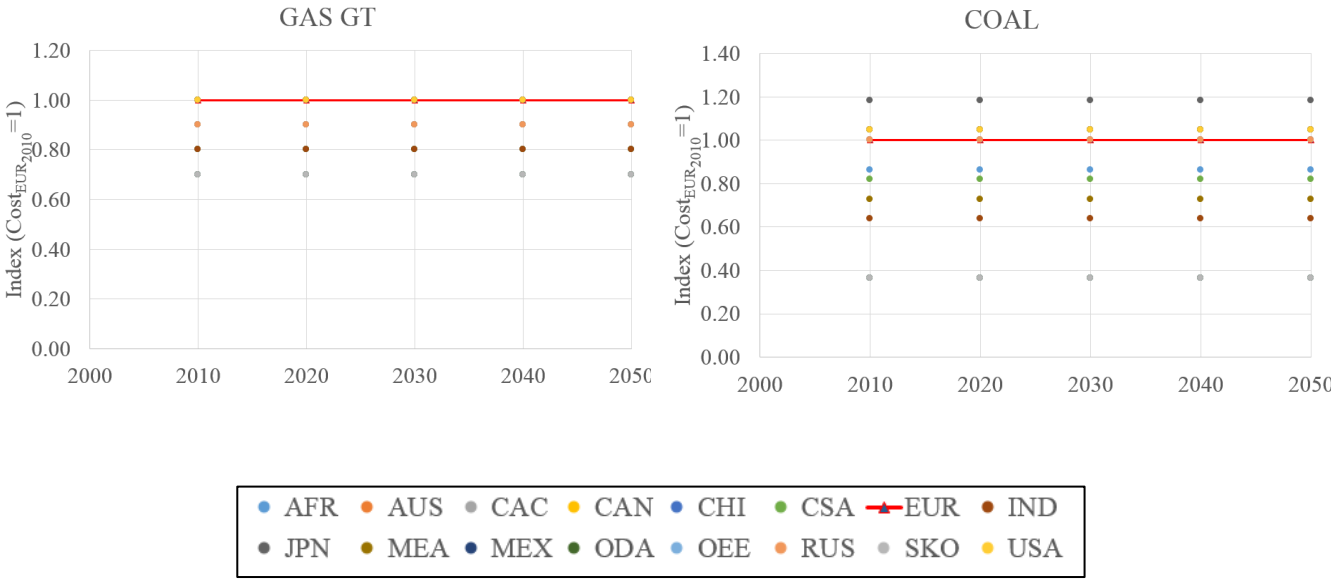




On the contrary, the regionalized fossil-based power plants costs remain constant over the same period. As with any model, the results of TIAM-IFPEN scenario runs are sensitive to the input parameters values.

Fig. 3 : Average technology investment costs at regional level between 2010-2050 (Index CostEUR$_{2010}$=1, red line)





CCGT: Combined Cycle Gas Turbine, GT: Gas Turbine

As perfectly reminded by Schimpf et al., it is important to understand that a scenario is neither a mere forecast - in the sense of an unsurprising projection of the present – nor is it expressing a vision, i.e. a desired future [94]. Therefore our results should not be considered as forecasts but rather as projections of the possible pathways of a future energy system development. All energy demand projections have been done considering macro-economic drivers such as the GDP, the population growth, etc. (Statistics/outlook of the IMF[8], results from GEMINI-E3 or GEM-E3 macro-economic models). All assumptions related to regional fossil fuel reserves and trade capacities have also been implemented along with the regional renewable energy potentials ([95], World Energy Council, BP Statistics, US Geological Survey, specialized literature and experts involved in the projects). For the power generation, the general sources of data are the National Renewable Energy Laboratory (NREL), PLATTS database, IRENA, WEO IEA and specialized literature.

[8] International Monetary Fund

2.3 The lithium chain structure

The lithium supply chain has been built from ore deposits to its end-use via various transformation processes and trade flows (Fig. 4). Two types of trade are included in the model: the first one is about lithium ore from the mineral deposits to the refining sites. As of today, the main flow is from Australia to China. The second type concerns the main lithium-based chemicals (LiOH and Li_2CO_3). Both products are aggregated in the same trade flows as they are not differentiated according to their specific end-use. Taking into account the trade capabilities will allow analysing future international lithium exchanges according to the each regional needs and growth.

Fig. 4 : Detailed description of lithium in each TIAM region

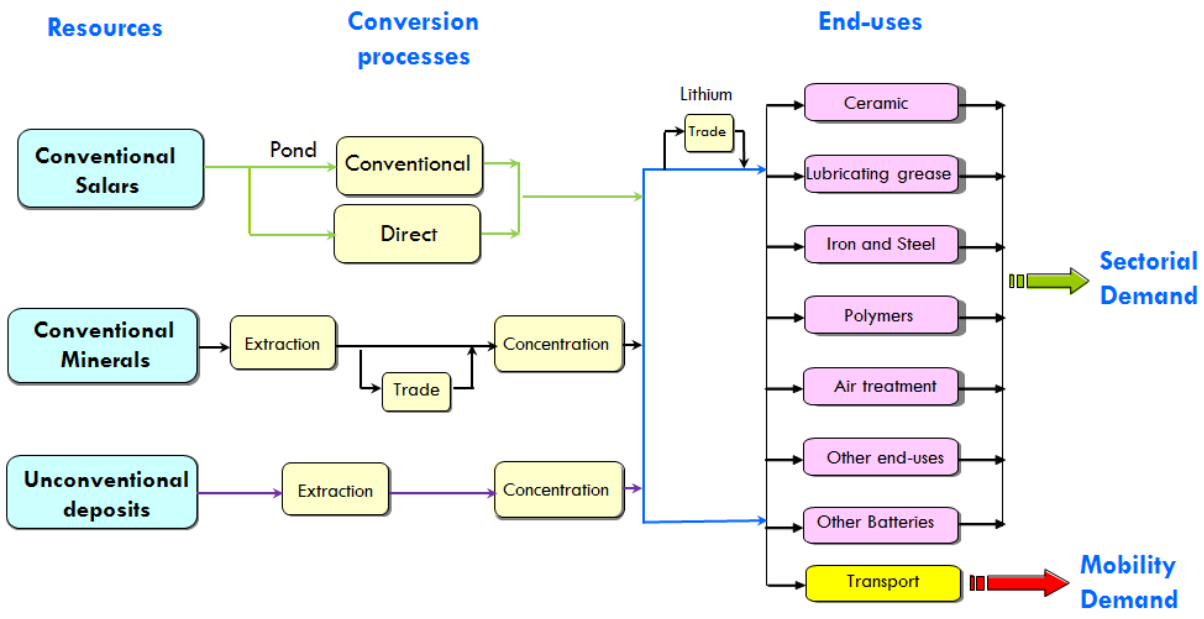
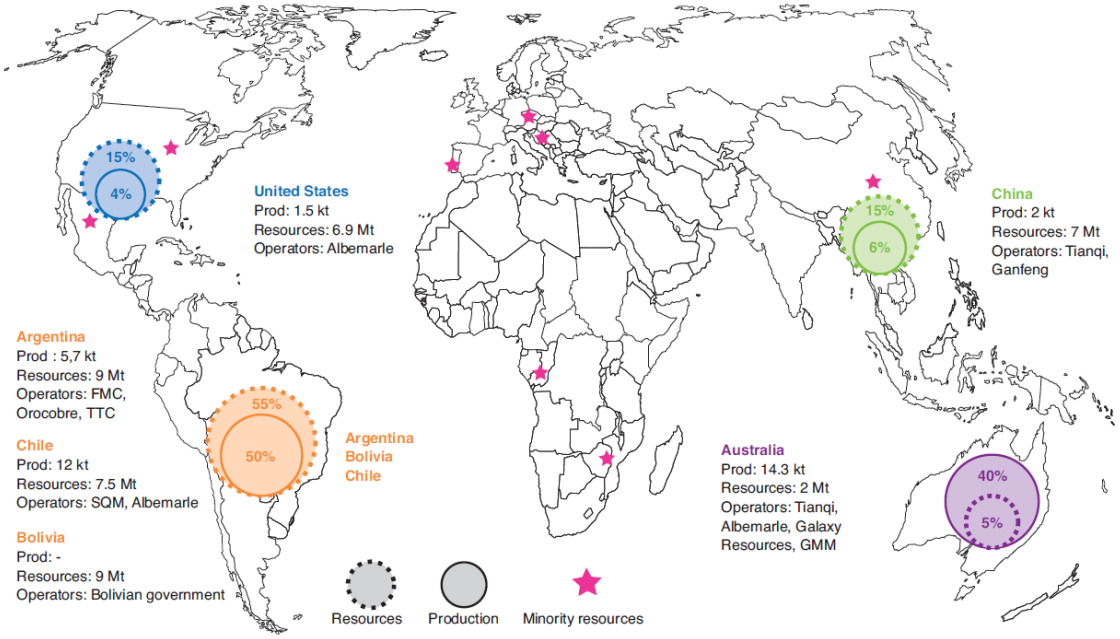


Fig. 5 : Distribution of resources (dotted line) and primary production (solid line) worldwide, with the main companies operating at current production sites and ongoing projects (Data 2017)



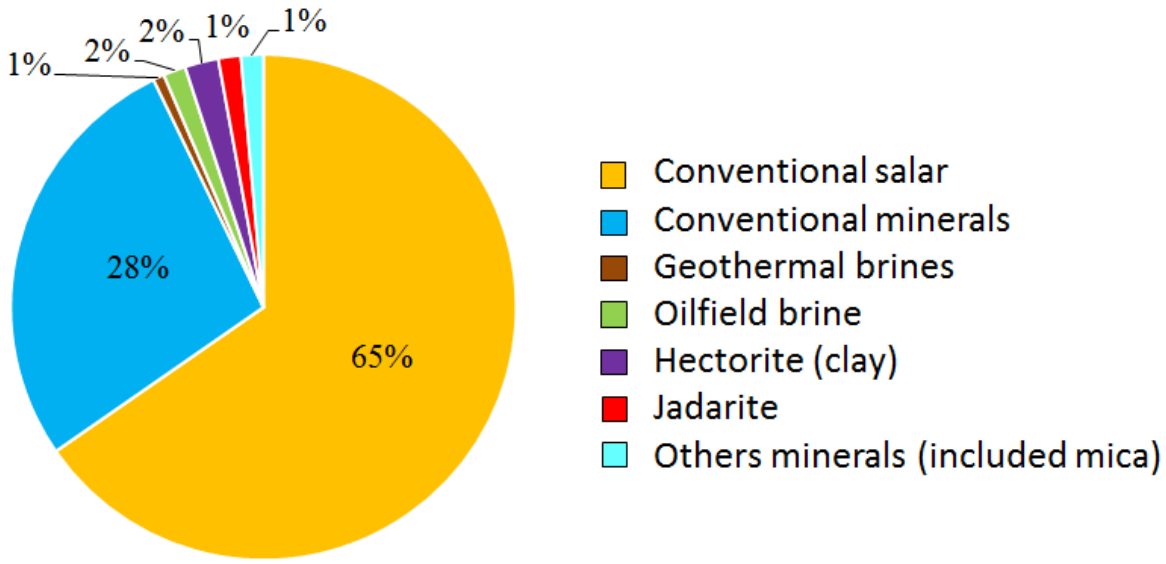
Source: USGS (2017), producer announcements

Table 2 : Regional disaggregation of the lithium resources (in Mt) by type of deposits

	AFR	AUS	CAC	CAN	CHI	CSA	EUR	IND	JPN	MEA	MEX	ODA	OEE	RUS	SKO	USA
Brine					5.25	25.5										2.07
Mineral	1.2	2		2	1.75	0.2	0.01			1.5				1		4.14
Clay							1.033				0.845		1.033			0.69

Source: USGS 2017

Fig. 6 : The various lithium deposits



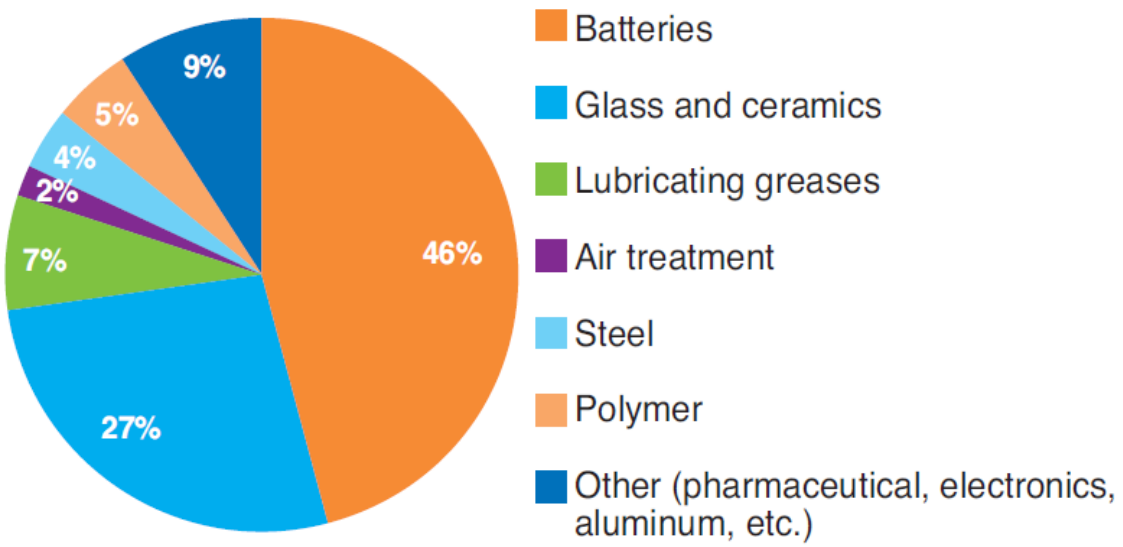
Source: USGS 2017

Three different deposits have been considered (Table 2) in the model: two conventional deposits (brine from salars and minerals[9]) and an unconventional lithium one (Fig. 6)[10] according to their regional reserves and resources. The associated technology is then described and differentiated by region in terms of investment, operations and maintenance costs, capacity of production and efficiency. Note that at present, less than 1% of lithium is recycled. Various studies address this concern for lithium-ion batteries, from technological [96-98], geopolitical (Zeng et al. for China [69] ; Miedema and Moll for EU27 [80]) or economic [99] point of views. If lithium recovery from Li-ion batteries is technically feasible with high recovery rate (about 80% at the laboratory scale) it seems that lithium recycling would be far from widespread. Considering the low percentage by mass (about 3%) and the current lithium price, strong political incentives are needed for widely deploying this sector. For instance, based on the 2006/66/EC European directive, where the minimum recycling efficiency of NMC batteries is 50 % by average weight, there is little incentive to recover lithium compared with cobalt for

[9] lithium-bearing rock (specifically spodumene).
[10] Several unconventional lithium deposits have been identified including hectorite (clay), jadarite, geothermal brine, oilfield brine, and even ocean brine.

example. The latter is much more profitable because lithium recycling requires the use of highly-complex processes, which are not currently economically viable [100]. Even though batteries are partly recycled to recover higher-value metals such as cobalt, there is currently no specific recycling system for lithium. In the future, lithium recycling would certainly rely more on supply security strategies than on a competitive economic model. Therefore, we did not take into account the recycling parameter in the model.

Fig. 7 : Share of lithium consumption by various end-use sectors in 2017



Source: USGS 2018

In the transport sector, Li-ion based technology is considered for all the lifetime period. The Li content is based on the NMC technology with an energy intensity per kWh increasing over the period. The battery sector is now the primary outlet, with one-third of this lithium use applied to EV (Fig. 7).

A positive growth has been observed in recent years for all end-use sectors (except for the lubricants), especially batteries, where lithium consumption is increasing by about 20% per year. Therefore, when considering future demand in lithium, all end-uses might be considered in the modelling exercise. Based on literature and producers' data [61,64], estimated growth rates have been considered from nowadays up to 2030 and beyond for

all end-use sectors except for transport (**Table 2**). Under these assumptions, the model is then able to account for the structural effect into the lithium demand evolution.

Table 2: Lithium consumption growth annual rates according to the existing end-uses

End-sector use	Annual growth rates	
	Now to 2030	**2030-2050**
Batteries (excluding transport)	8 %	2,5 %
Glass and ceramics	5 %	2 %
Lubricating greases	3 %	2 %
Iron and steel	5 %	1 %
Polymers	3 %	0 %
Air treatment	2 %	2 %
Other (pharmaceutical, electronics, aluminium, etc.)	5 %	4 %

Sources : [64], Dakota Minerals, USGS, auteurs (2017)

2.4 Scenarios assumptions

Our scenarios have been defined to observe the evolution of the transportation sector in response to environmental constraints at global level, lithium resource availabilities and the implications of future mainstream in road passenger transport mobility. The demand for travel and motorization has increased dramatically over the past few decades along with economic development and population growth [101]. In recent years, a change of

individual travel behaviour in road passenger transport has been observed due to the promotion of the use of alternative forms of transport (walking, cycling, shared mobility and public transport). As acknowledged by the UN-Habitat, while the global trends of the implications of the unfolding events of rapid urbanization, hyper-mobility and the health and climate hazards associated with car-dependencies pose uncertainties and risks, there are also unprecedented opportunities for advancing sustainable urban mobility [102]. Many governments around the world have been constantly adjusting its transport policies overtime through an integrated approach to land use and transport planning, transport pricing (congestion pricing schemes, road tolls), parking restrictions to challenge car attractiveness while providing alternative modes of transport[11] [103-104]. Therefore, for the purpose of the present study, we run four scenarios where we have considered two climate scenarios[12] with two different type of mobility each in order to assess the impact on the lithium market along with the transportation electrification:

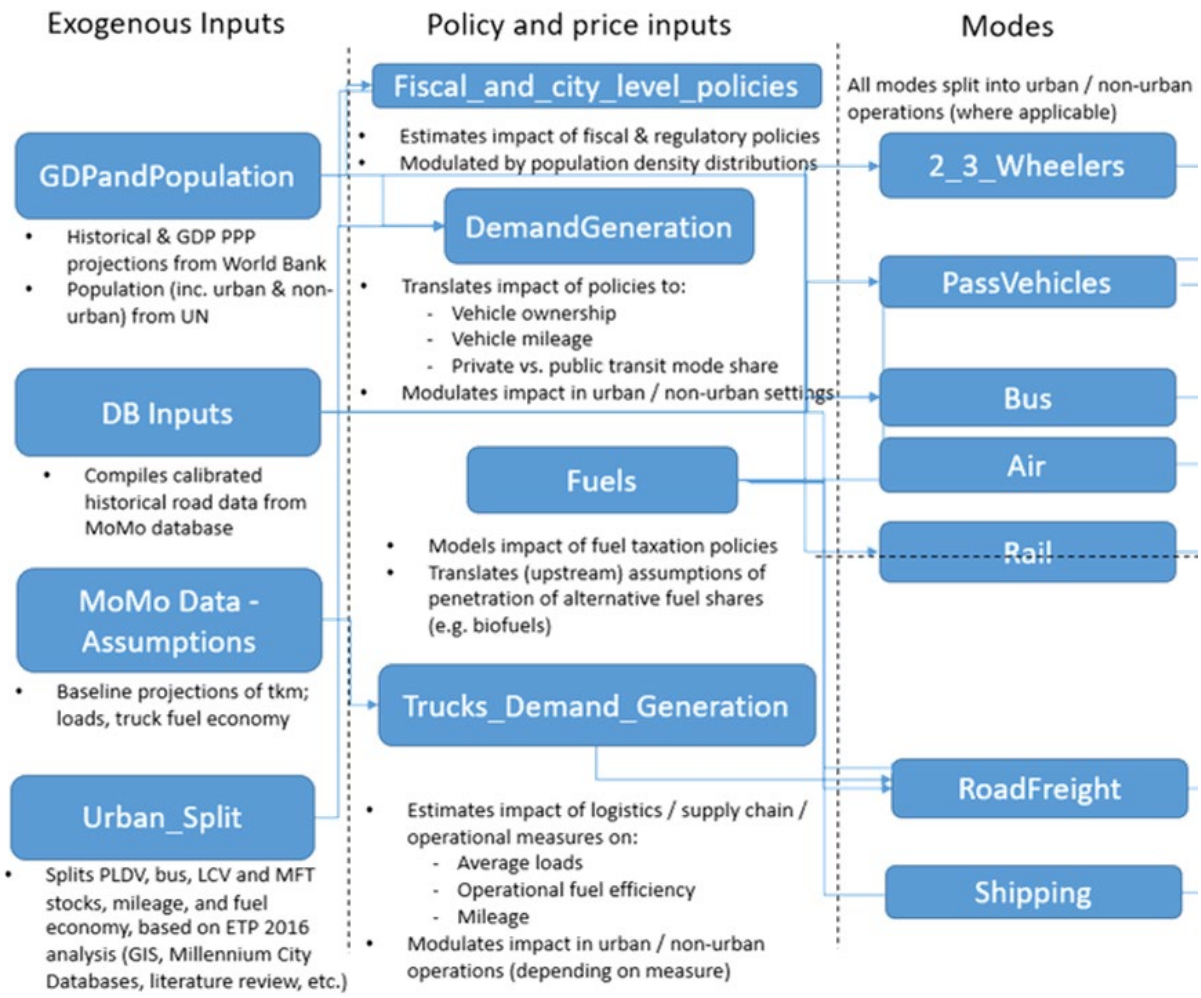
- Scen 4D which is consistent with limiting the expected global average temperature increase to 4°C above pre-industrial levels by 2100.
- Scen 2D which is a more ambitious scenario, which translates the climate objectives of limiting global warming to 2°C by 2100.

In each climate scenario, different future shapes of mobility have been assumed and taken from the IEA Mobility Model (MoMo Model). The MoMo model is a technical-economic database spreadsheet and simulation model that enables detailed projections of transport activity according to user-defined policy scenarios to 2060. The model covers 29 countries and regions including a urban/non-urban split, and the potential for municipal-level policies to reduce transport energy use. As explained by the IEA, "the MoMo model includes key elasticities, based upon representative "consensus" literature values, are used to model vehicle activity and fuel consumption responses to changes in fuel prices – which are themselves driven by projections and policy scenarios (i.e. GHG or fuel taxes). Elasticities also enable

[11] Cycle lanes, pedestrian areas and public transport coverage have been expanded while new mobility options such as bike- and car-sharing schemes have been introduced, underpinned by the development of the ICT (information and communication technology).
[12] The climate module per se is directly inspired by Nordhaus-Noyer model.

vehicle ownership to vary according to fuel prices and income, as proxied by GDP per capita". Thus, they derived two future shape of mobility which would take into account the evolution of the ownership rates (number of vehicles per inhabitants), evolution of city density (density of cities with potential access public transport) according to their size. The research strategy of the MoMo project is detailed on the Fig. 8

Fig. 8 : The network of spreadsheets of the IEA Mobility Model (MoMo model) (Source IEA MoMo team)

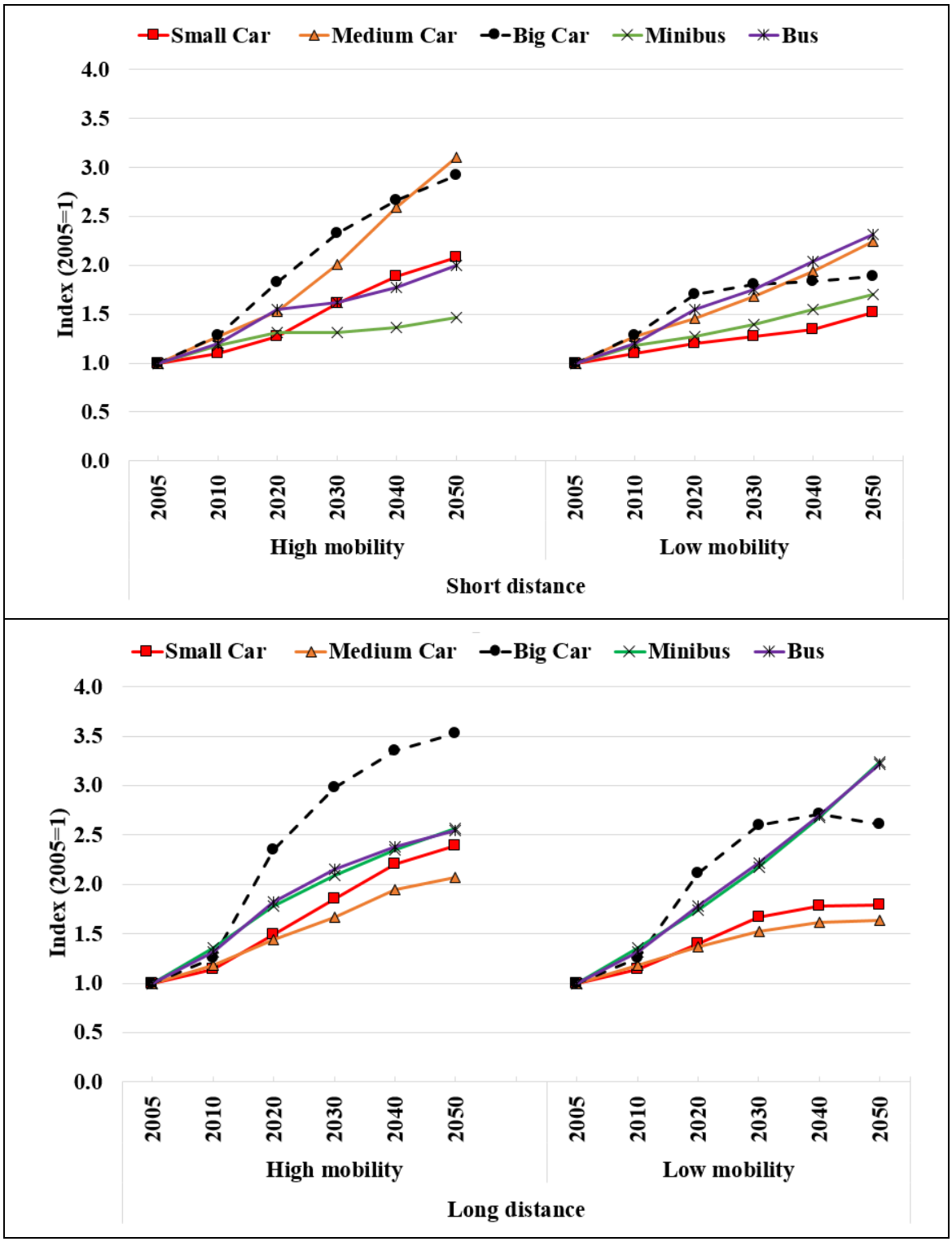


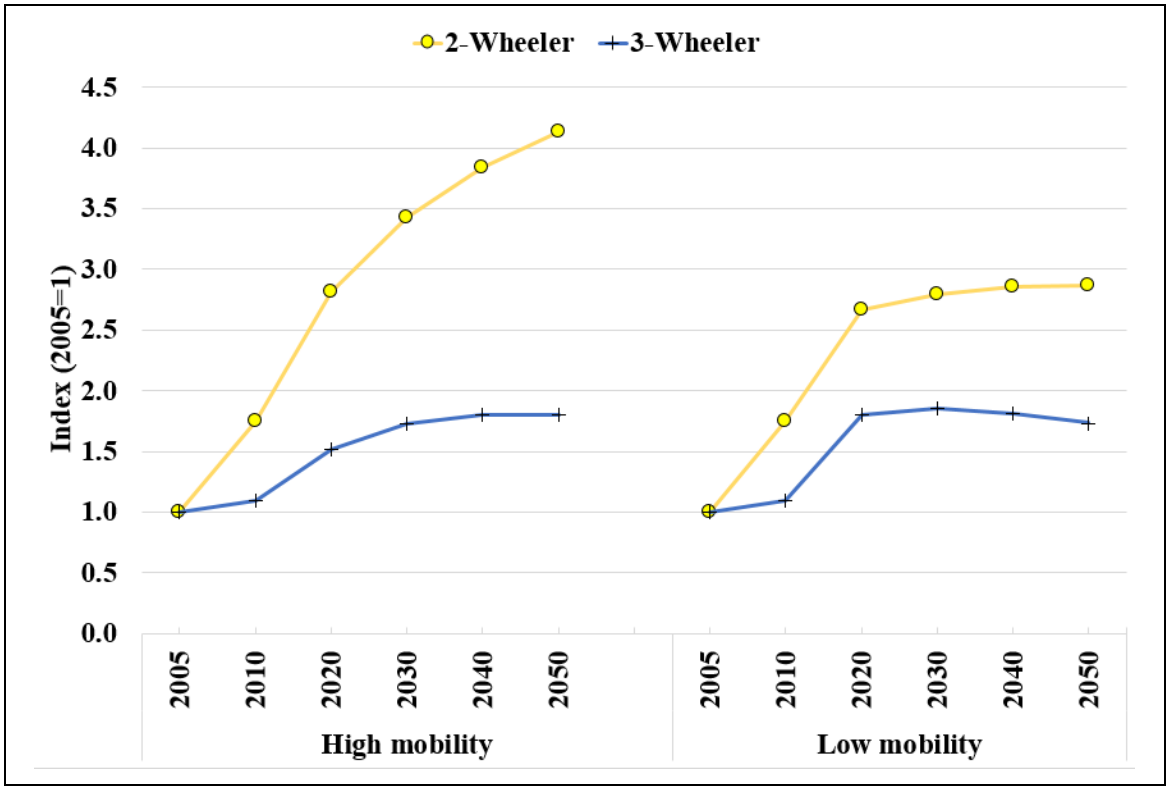
In this paper, we incorporate the outputs of the MoMo model as inputs of transport mobility in our TIAM-IFPEN, there are two mobility scenarios for each climate scenario (Fig. 9):

- A High mobility shape equivalent to a continuing increase of the ownership rate, more private transit mode share and lower city densities. It is assumed an impact of urban dispersal, a worldwide phenomenon, on mobility and travel as well as the influence of urban land coverage on travel where we keep on having a huge car dependency and usage. As acknowledged by the UN, urban dispersal has an unmistakable and profound influence on travel because of the fact that spread-out growth increases the use of private motorized vehicles. Nowadays, this "urban sprawl"[13] is increasingly widespread in developing countries and should be considered in transport modelling.
- Hypothesis of a Low mobility shape where the idea of a sustainability in mobility is assumed. This assumption implies more compact cities, underpins an integrated approach to urban land-use and transport planning and investment, and gives priority to sustainable modes of mobility such as public and non-motorized transport as seen in Fig. 9 with the bus and minibus travel demands.

[13] The term "urban sprawl" describes low-density, dispersed, single-use, car-dependent built environments and settlement patterns that, critics charge, waste energy, land and other resources and divide people by race, ethnicity and income/wealth [84].

Fig. 9 : Evolution of the two different shape of mobility (high and low) according to the travel mode (short and long distance)





Source: IEA MoMo Model

As seen in Fig. 9, the travel demand has been also disaggregated into two types of vehicle usages: short distance (urban) and long distance (extra-urban) for all vehicles except for the heavy commercial vehicle (HCV) and the 2/3-wheelers. This paper aim to contribute to the transport policy literature by modeling the implications of different shape of mobility along with climate constraints, firstly on cars fleet evolution and secondly on the regional lithium needs in regards to the resource availability in the future.

III. RESULTS AND DISCUSSIONS

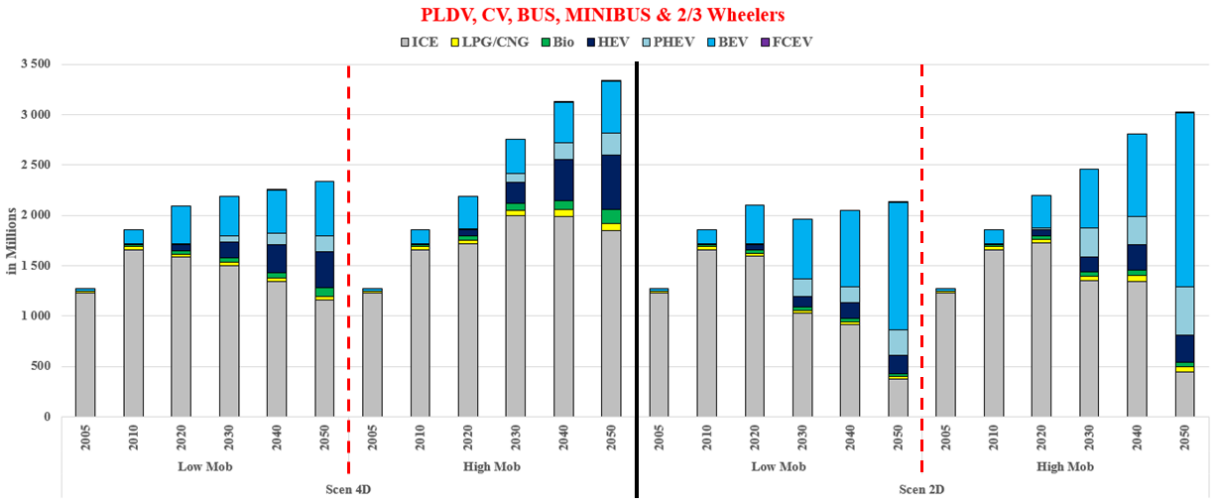
3.1 Model structure

Fig. 10 presents the changes in the global vehicle stock (including 2/3-wheelers) by power-train for the 4 scenarios we defined above. With a sustainable mobility, the worldwide fleet achieves 2.3 and 2.1 billion vehicles respectively in the 4°C and the 2°C scenarios by 2050. Meanwhile, it is more than 3.3 billion and around 3 billion

respectively in 4°C and 2°C scenarios with a hyper-mobility due to dispersal metropolis and therefore car usage to satisfy higher travel demand. A reduction in the global fleet is also observed when the climate constraints are more stringent.

There is a preponderance of internal combustion engine (ICE) vehicles (more than half of the global fleet) in the scenario 4°C both in high and low mobility with gradual penetration of EV. Meanwhile, in the 2°C scenario, they decrease to around 20% and 15% of the global fleet respectively under an hypothesis of low mobility and high mobility. Electric vehicles will increase steeply over the time horizon in both climate scenarios by 2050: between 30% and 22% of the global fleet in the 4°C scenario respectively in low and high mobility, while around 75% in the 2°C scenario in both mobility hypothesis.

Fig. 10 : Evolution of the global vehicle stock between 2005-2050

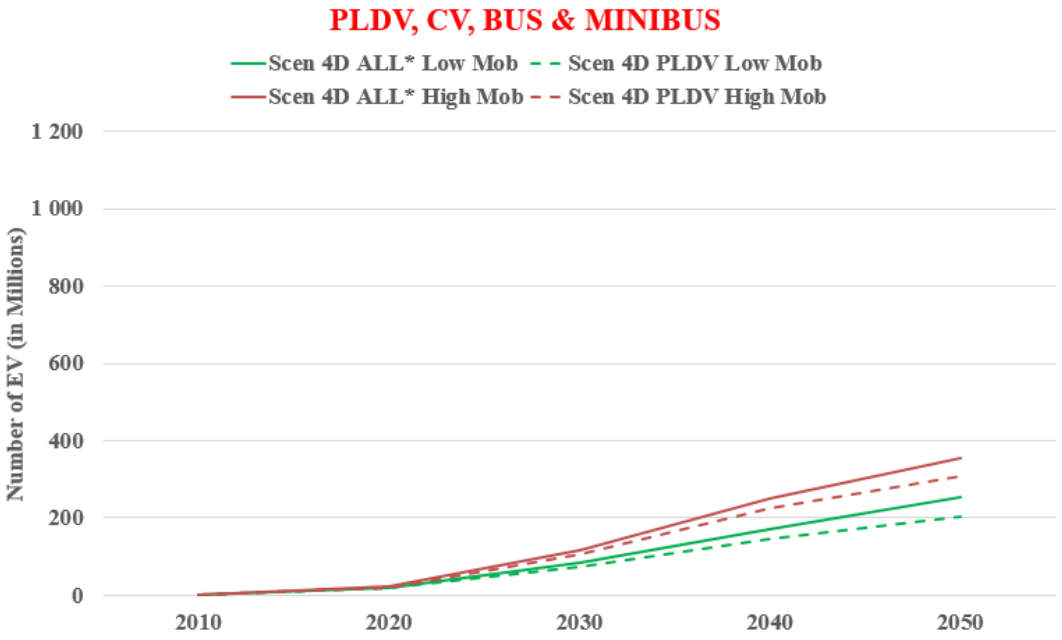


ICE: Internal combustion engine; HEV: Full hybrid vehicle; PHEV: Plug-in hybrid vehicle; BEV: Battery-powered electric vehicle; FCEV: Fuel cell electric vehicle

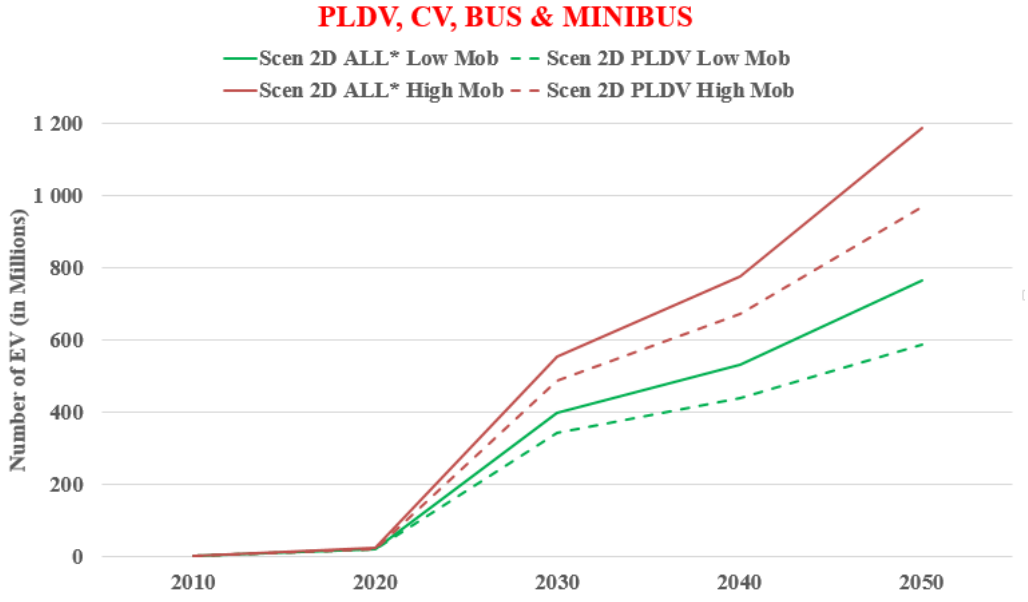
It should be highlighted that the EV fleet is mostly located in Asian countries (China, India and other developing countries in Asia) due to the large presence of two and three-wheelers that stand for more than half of the global EV fleet.

Fig. 11 : Evolution of the global EV stock (two and three-wheelers excluded) between 2005-2050. (a) 4°C scenario (b) 2°C scenario

(a)



(b)



PLDV: Passenger Light-duty vehicle; CV: Commercial vehicle

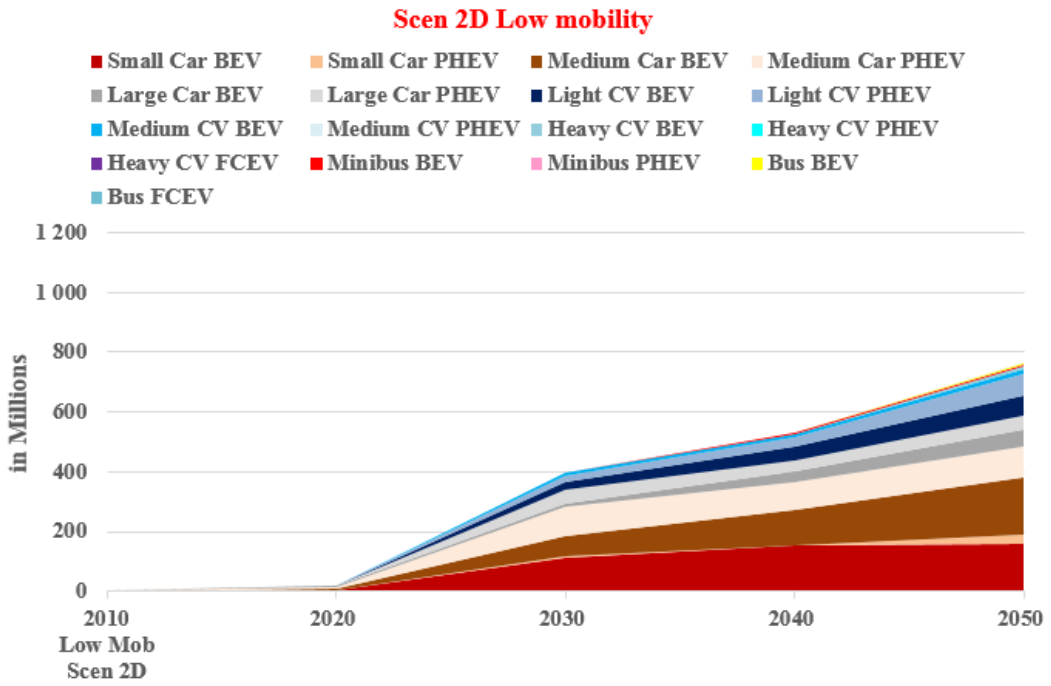
According to Fig. 11 (a) and (b) (solid lines), the global fleet of EV (two and three-wheelers excluded) should reach between 250 and 360 million units by 2050 in the 4°C

scenarios, while it could be as high as 760-1200 million units in the 2° scenarios. When considering passenger light-duty vehicles (PLDVs: small, medium and large cars) alone, they should reach 205 and 310 million units in circulation by 2050 in the 4°C scenarios respectively with the low and high mobility hypotheses (Fig. 11 (a) dotted lines). On the other hand in Fig. 11 (b) (dotted lines), it would be around 590 and 970 million units respectively in the low mobility and high mobility assumptions of the 2°C scenario.

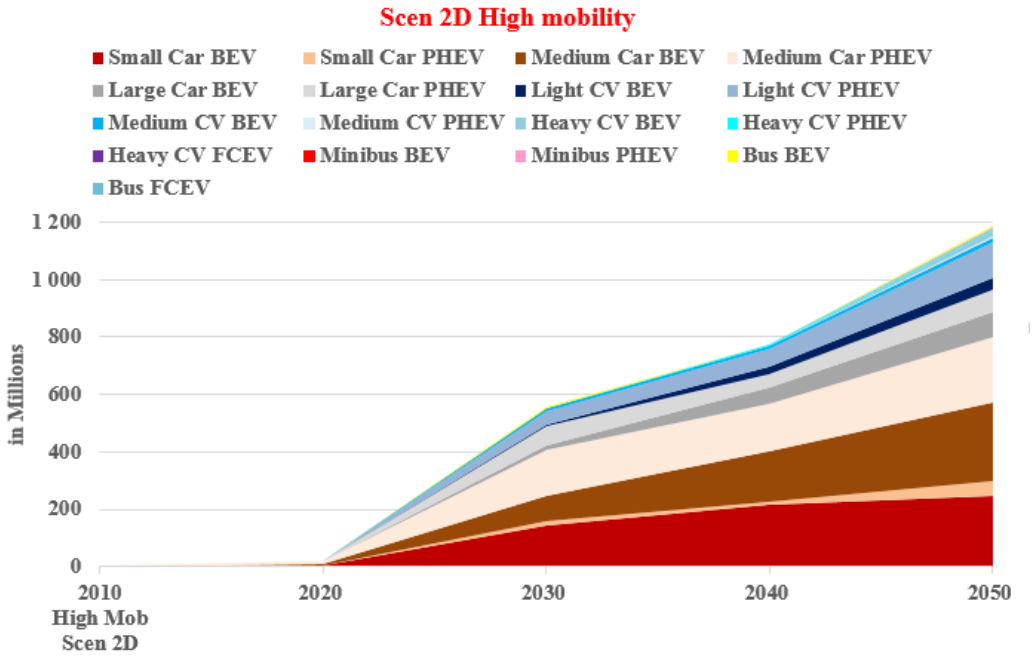
Analysing these graphs, we could acknowledge that our forecasts in the 4°C scenario with no change of individual travel behaviour in road passenger transport (high mobility), 115 million units by 2030, are similar in scope to the IEA's forecasts in the Global EV Outlook 2018 [59], which estimates the number of EV at between 130 and 230 million by 2030, depending on the scenario.

Fig. 12 : Evolution of the global EV stock by vehicle's category between 2005-2050 in the 2°C scenario

(a)



(b)

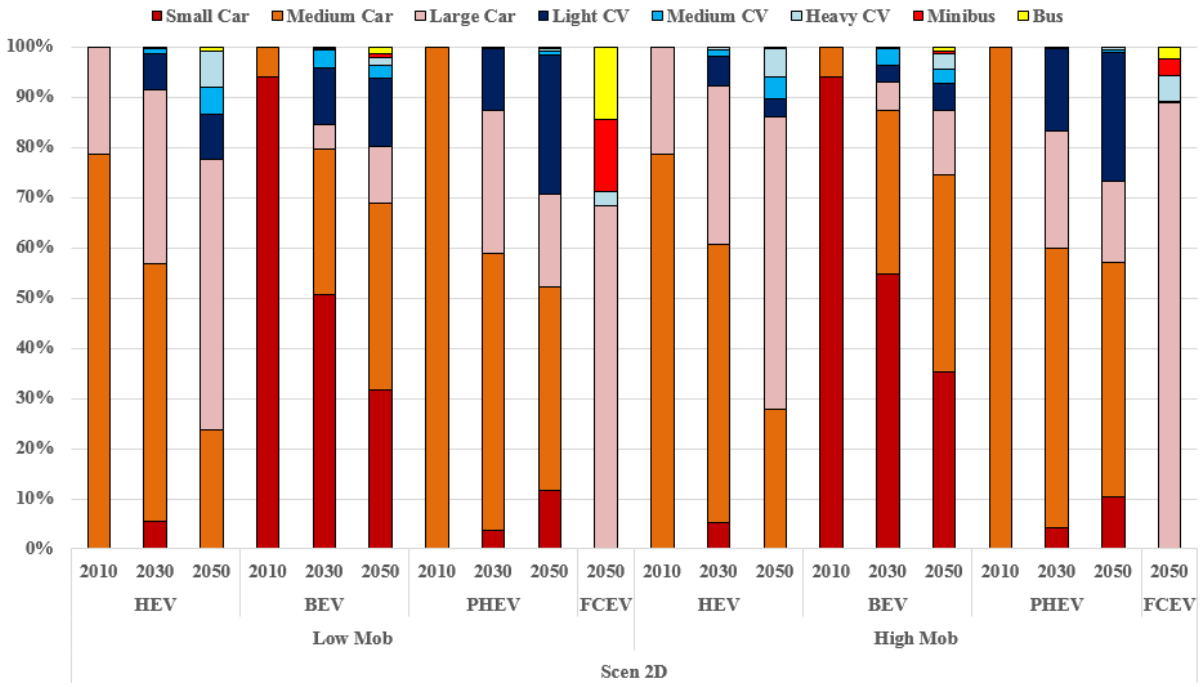


Our TIAM-IFPEN model could allow us representing in details the evolution of the EV stock by powertrain and by category. We have the example of the 2°C scenario with low mobility in Fig. 12 (a) and with high mobility in Fig. 12 (b).

It could be deduced that more than 25% of EV in circulation by 2050 are small cars (of which around 85% of battery-powered EV) while 40% and 15% are respectively medium and large cars. An uptake of the fuel cell electric vehicles (FCEV) has been observed in large cars, heavy CV, Minibuses and buses.

From the outcomes of the model, Fig. 13 displays another representation for a perfect visualisation of the evolution of some power-train uptake (Full hybrid HEV, Plug-in hybrid PHEV, Battery-powered electric vehicle BEV and Fuel cell electric vehicle FCEV) in each category over the time horizon in the 2°C scenario. Considering for example the battery-powered EV in the low mobility hypothesis, 95% of them were small cars category and 5% in medium size in 2010. However, from 2030, the penetration of EV in medium, large cars, light and medium commercial vehicles is observed. It could be explained by their higher usage and travel demand than small cars (Fig. 9). Therefore, these categories will need more low-emitter vehicles such as electric-powered vehicles with stringent climate scenarios.

Fig. 13 :Evolution of the vehicle's share by category in different power-trains (HEV, PHEV, BEV and FCEV)



3.2 Results and discussion of the impacts on lithium market

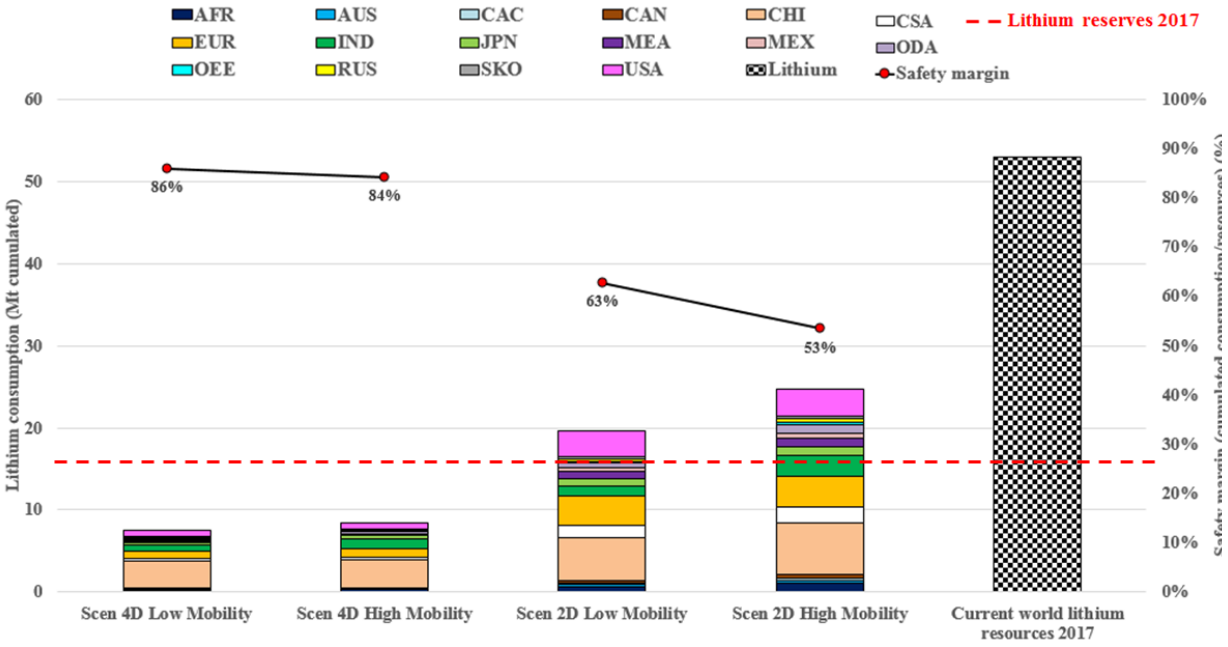
3.2.1 Impact of the global EV evolution on the lithium demand

Cumulative demand for lithium from 2005-2050 is estimated at 7.5 and 8.5 Mt respectively in the low and high mobility of the 4°C scenario, while it reaches 19.7 and 24.7 Mt in the case of the 2°C scenario (Fig. 14). Demand is driven globally by China, Europe, India and USA in both climate scenarios. They have respective shares estimated as high as at approximately 45%, 13.5%, 12%, 9% of total cumulated consumption in the 4°C scenario. High consumption by China is due to the big proportion of two and three-wheelers in addition to PLDVs. In the 2°C scenario, the share of China decreases due to more transport electrification in other regions of the world. It is observed that the share of China, Europe, India and USA reach respectively 26%, 16.5%, 8.5% and 15%.

A comparison of cumulative lithium consumption between 2005 and 2050 with current reserves (16 Mt in 2017) provides information about the level of criticality of lithium. Fig. 14 shows that only 2°C scenarios will certainly have a cumulative lithium

consumption higher than the current level of lithium reserves (red dotted line). On the contrary, in the 4°C for any shape of mobility, the cumulated lithium demand is far under the current dotted lines representing the lithium reserves 2017.

Fig. 14: Comparison between the cumulated lithium consumption (2005-2050) and the world lithium resources in 2017

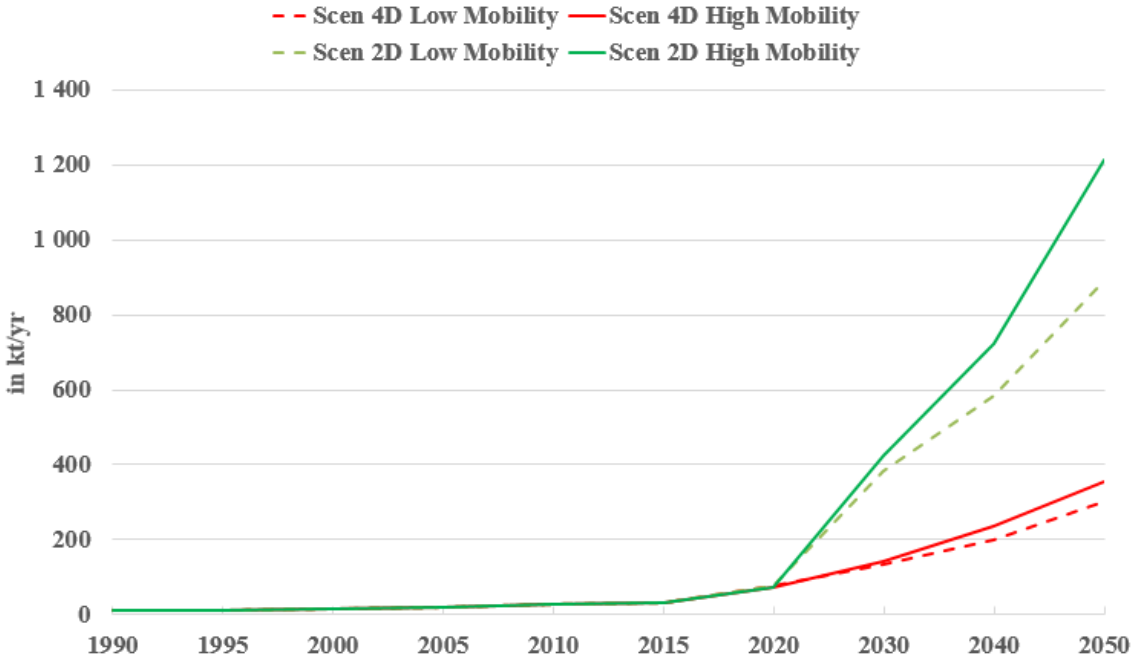


The safety margin (ratio of the cumulative consumption to the current resources) is decreasing in both climate scenarios as the lithium consumption follow the same trend as the penetration of EV. It fluctuates from 86% to 84% in the 4°C scenario according to the shape of mobility while it is falling from 63% to 53% in the most stringent climate scenario (2°C scenario).

3.2.2 Geological and technological implications

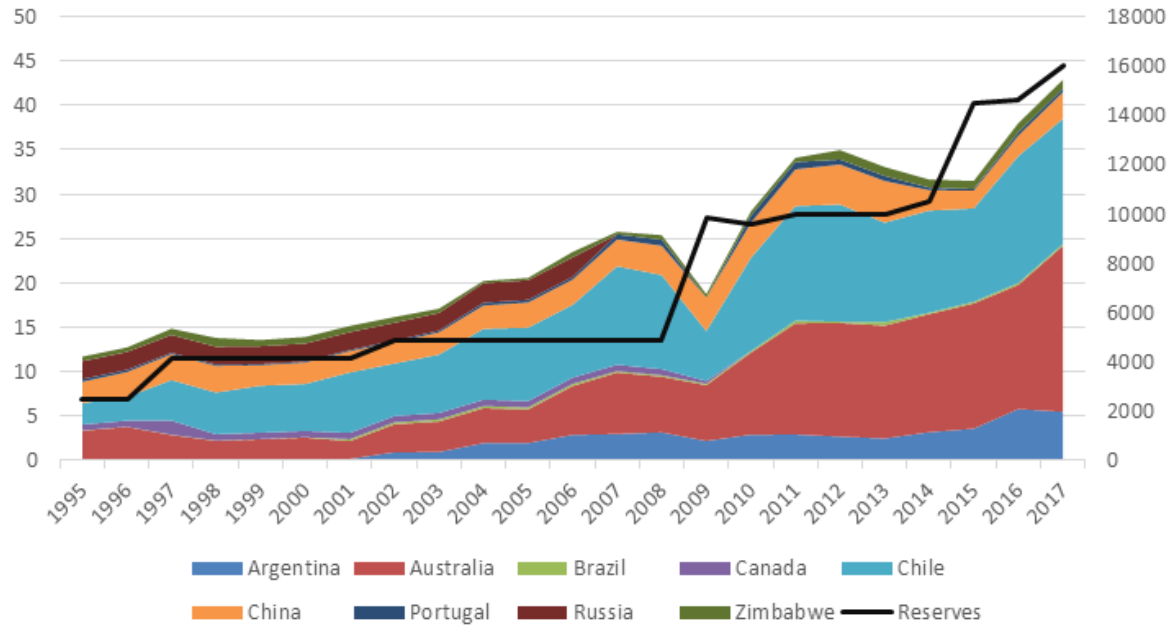
Fig. 15 shows the evolution of lithium demand according to each scenario described (4D scenario High Mobility, 4D scenario Low Mobility, 2D scenario Low Mobility, and 2D scenario Low Mobility).

Fig. 15: Evolution of lithium demand from 1990 to 2050 (historical data until 2016)



Unsurprisingly the lithium demand is higher in the most constrained climate scenarios where EV stock is higher in order to limit GES emissions, and therefore the global warming to 2°C. In the 2°C scenario with high mobility, the annual lithium production reaches around 1200 kt by 2050 while it is lesser in the case of a lower mobility at around 890 kt. Thus, the annual production by 2017 which is around 45 kt (Fig. 16), has been multiplied by 27 and 20 respectively. In the case of the 4°C scenarios, the expected annual production is obviously lesser than in the 2°C, regardless of the shape of mobility considered. Indeed, it increases as high as 300 kt by 2050 in the lower mobility while it is at around 360 kt with a high mobility assumption.

Fig. 16 : World lithium production per year and per country (kt, left axis) and global world reserve (right axis)



Source: USGS, 2018

With regard to resources, new exploration missions could lead to new deposits discovery and increasing resource volumes, especially for non-conventional resources (geothermal brines, clay, mica, etc.) which represent only about 10% of resources today (USGS, BRGM). Along with these unconventional land-resources, oceans also constitute a natural lithium resource. The lithium concentration is 0.18 mg/l which would represent an estimated resource between 230 and 260 billion tons of lithium [105-106]. Early projects were initiated in the 1970s (USGS) concluding on the technical feasibility but at a much higher cost than lithium current prices. Indeed, it is necessary to handle very important volumes of water which requires a considerable energy. The cost of recovering lithium via the oceans has been estimated between $15 and $22 per kilo of carbonate lithium [61], which is tenfold the cost of production of the Atacama's salar (Chile).

A significant share of the current and new resources could become profitable in the future, and therefore be taken into account as reserves, according to technological advances and new processes as well as higher prices on the market. Regarding brines,

process optimizations focus on the evaporation step which is expensive and weather constrained in addition to long recovery times (up to 18 months, low yields (40/50%) and huge negative landscape impact). New processes would extract directly lithium from the brines (see projects conducted by *ERAMET* or *POSCO,* etc.). Geothermal brines resources in the United States for instance could be explored in more depth when direct recovery of lithium technologies will be commercialized suggesting new deposits exploitable. Recent research at Stanford has also shown that lake sediments could host large lithium-rich clay deposits[14].

3.2.3 Uncertainty about supply despite adequate resources

Increasing lithium prices can make some resources affordable. Between 2014 and 2017, lithium carbonate prices more than double from 4.90$/kg to 10.60$/kg in average (IHS Market 2018) stimulating the mining sector and promoting new feasibility studies. In the same period the reserves have increased by more than 50% (Fig. 16).

The analysis of the evolution of the Reserves-to-Production ratio could be also interesting retrieving the annual production, an outcome of the model, over the time horizon (Fig. 17). In this graph, we have represented the annual lithium production (P) and thus different Reserves-to-Production ratios according to growth rate of the reserves' level:

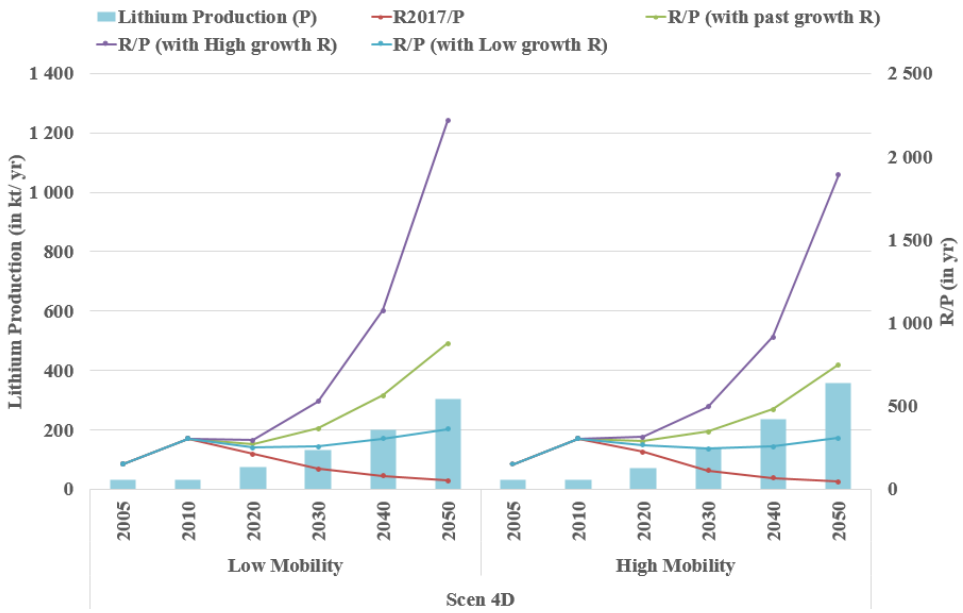
- R2017/P is the ratio where it is assumed that the reserves if kept at its level of 2017 and constant onwards (16 Mt). It means that it is the most pessimistic case where the level of reserves would no longer increase from 2017 to 2050.
- R/P (with past growth R): an assumption of an annual growth rate of the reserves between 2017-2050 is assumed equal to the historic growth rate between 1995-2017, which is 8.9%/yr. It could be considered as the "Business-As-Usual".
- R/P (with high growth R) and R/P (with low growth R): in these two scenarios, it is assumed two annual growth rate of the reserves defined by taking the growth

[14] https://news.stanford.edu/2017/08/16/supervolcanoes-key-americas-electric-future/

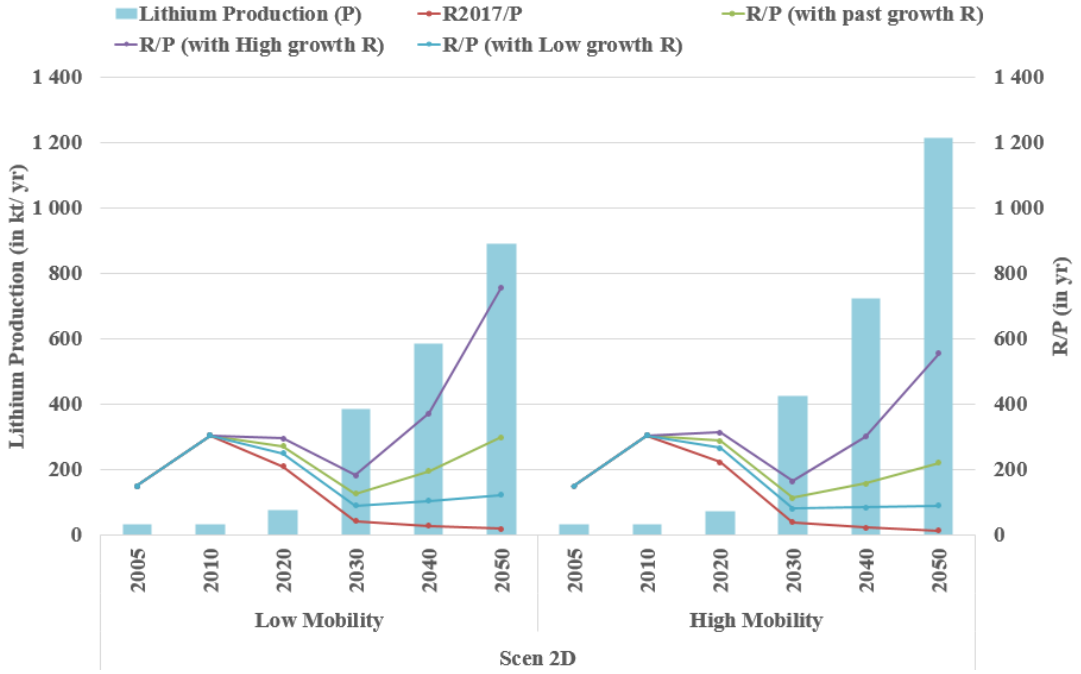
rate of the R/P (with past growth R) as median. The high growth rate is considered at 12%/yr and the low growth rate at 6%/yr between 2017-2050

Fig. 17: The evolution of the ratio R/P (reserves/Production) according to four assumptions: (a) 4°C scenarios (b) 2°C scenarios.

(a)



(b)



These ratios provide thus the remaining amount of lithium, expressed in time (year). For example in Fig. 17 (b), in the case of a 2°C scenario, it is observed that only 18 years remains by 2050 with a low mobility in the pessimistic scenario (R2017/P) while it could increase as high as 760 years in the highest annual growth rate of reserves (R/P high growth R). On the contrary, it is decreasing to 555 years when considering a high mobility and a Reserves-to-Production ratio with a fast growth of the reserves over the time horizon. This analysis is pinpointing the importance of the future exploration and production lead times.

The studied scenarios tend to show that no significant geological risk exists in the lithium market since, as with reserves, resources are substantial (around 52 Mt) and it is likely that they will be technologically accessible by 2050, at least in part. In the short term, it is important to have time to react between supply and demand, which could may be led to supply risks.

If some lithium mines can be extended and increase their production rate in the near future, new ones have to be implemented to meet the long term demand. When looking to the traditional schedule and steps prior to the production of a lithium mining deposit the entire process could take up to 10 years. Resource identification, exploration and then feasibility analysis could take few years as exploration companies have to raise capital for each steps. Negotiations are then initiated with the government and the population to determine the administrative terms and ensure the acceptability of a future mining project. In addition, a mine can be reached its ramp-up and be fully operated within 1 or 2 years. The investment cost for such projects is high and there are a lot of uncertainties over such long project durations. It is not uncommon for companies to go bankrupt before they have even completed feasibility studies.

As of today, taking into account announcements by mining companies, a dozen new deposits were expected to be mined in 2018 [81]. In the short terms, there is significant uncertainty surrounding production lead times, which are typically delayed for several years following producers' announcements. According to the figures announced by the new companies (based on 2016 annual reports), it would be between 65 and 85 kt of additional lithium which would be likely to arrive on the market between 2017 and

2020. Given the production published by the USGS in the year 2017 (45 kt of lithium) it could then already represent a threefold increase of production by the end of the decade. From the actors' point of view, most of the credible projects announced exceed 15 kt LCE[15]/year and are partly supported by juniors such as *Lithium Americas, Orocobre or Galaxy Resources*. Having a look to the past production planned and comparing it with effective current volume production leads to large error margins. Moreover, beyond the optimism of companies seeking financing, the volumes thus announced often concern capacity and not production volumes, which tends to overestimate future production.

In addition, in the short term what could be observed is a surplus of lithium ores and concentrates on the market due to a refining bottleneck thereafter if plants are already working at full capacity. Therefore, a reaction time between supply and demand would be required to achieve such a production leap.

3.2.4 Geopolitical consequences

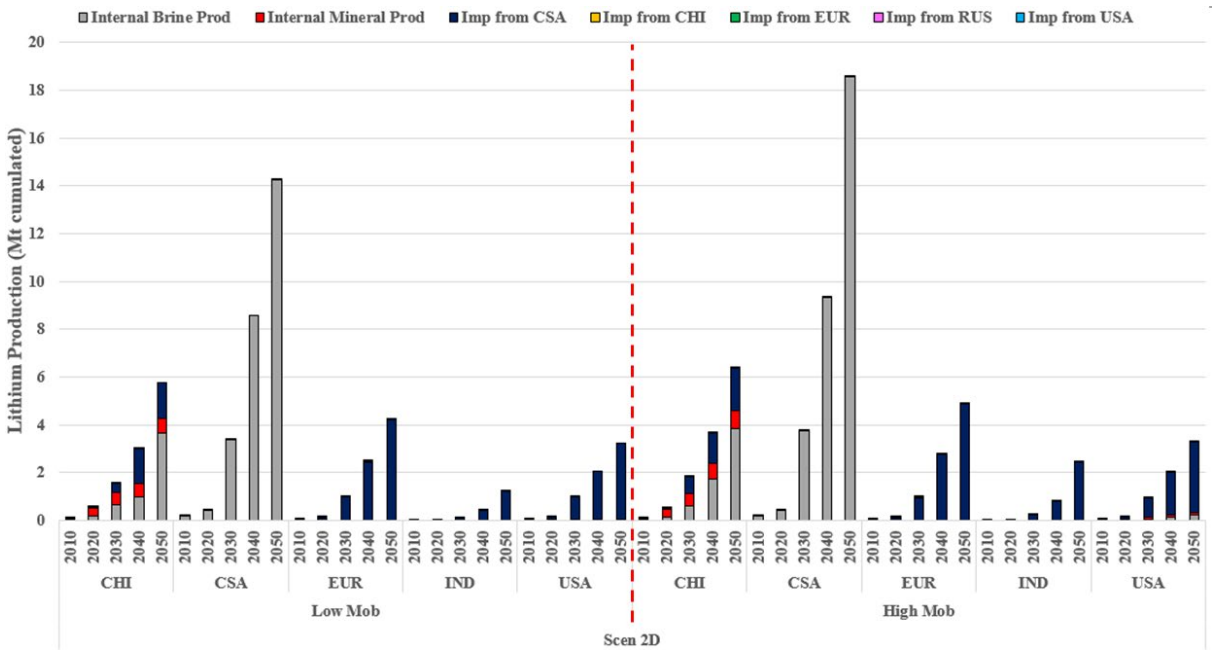
55% of global resources and nearly 50% of production are currently coming from the lithium triangle, composed of Argentina, Bolivia and Chile (USGS, 2017).

In Fig. 18, according to the results displayed, it can be observed that this region (Central and South America) will still be the largest exporter of lithium by 2050. However, national strategies currently vary significantly from one country to another in this region.

In Chile, deposit concession holders are subject to exploitation quotas and short-term leasing contracts. In Argentina, President Mauricio Macri's current economic policy in favour of foreign direct investment (FDI) raises questions about the sustainability of projects, in a country where foreign economic involvement is a national concern that shifts with political change.

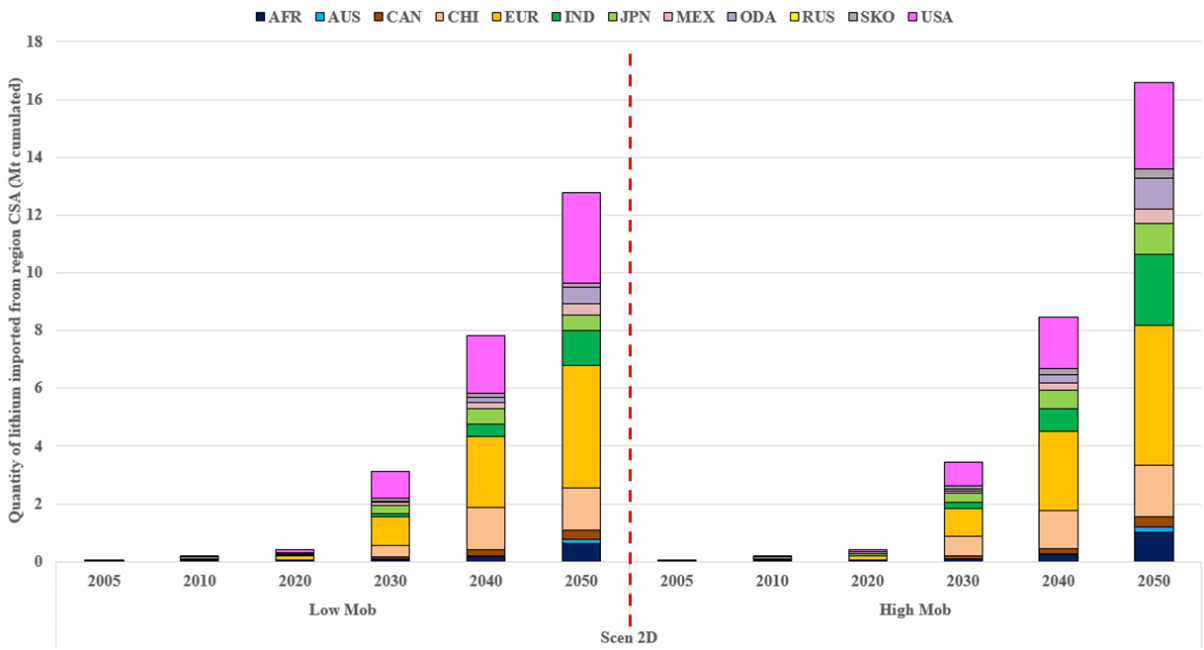
[15] LCE: lithium carbonate equivalent. 15 kt LCE equivalent to approximately 3 kt Li

Fig. 18 : Lithium consumption by region, internal production and imports in four major regions: China (CHI), Central and South America (CSA), India (IND), Europe (EUR).



Bolivia is a unique case in the commodities market: it has the world's largest lithium resources, located in the Uyuni salt flats, but is not currently producing lithium. Even though there is no real convergence among these three major countries, their national policies are key to understanding the lithium market in the coming years.

Fig. 19 : Profile of regionalized lithium imports from the Central and South America (CSA) region



By 2050, Europe, United States, India and China, the other regions in a lesser extent, would become predominantly dependent on imports from the lithium triangle (Fig. 18 & Fig. 19). However, China's resources are fairly substantial (around 15% of global resources), even though their production costs are higher than in the salt flats. China has also completed multiple acquisitions and acquired interests in deposits, both in Australia and in the lithium triangle. China is a net importer of lithium and a net exporter of lithium-based chemicals and processed lithium products (such as lithium cathodes). China imports resources, and refines it within its borders (including 75% of spodumene from Australia and 25% of brine from South America). A major player in the lithium sector with two significant companies, Tianqi Lithium and Ganfeng Lithium Co., Beijing has become the largest consumer of lithium and the largest producer of processed lithium. In this context, changes in Chinese trade policy must be analysed with respect to past transformations observed on other raw material markets (such as rare earths, etc.).

Despite the presence of new players in the exploration sector, the lithium market remains dominated by a few companies, including Chinese companies [107]. Given that instruments used to manage price volatility are not yet available on the commodities

markets (LME)[16], this concentration of players results in major uncertainty about future lithium prices. Price volatility may also weaken newcomers to the market and lead to further consolidation (mergers and acquisitions) among the players. Consolidations may also take place among companies further downstream in the value chain, such as the case of *Toyota Tshucho Corp.*, which invested in the Argentinian company *Orocobre Ltd*. The lithium market remains small compared with the non-ferrous metal markets[17]. It is characterized by a lack of identified buffer stocksin the markets, which can lead to far more volatile price movements and reduced cyclicality. Shifting demand may therefore lead to sudden reactions by players and high intrinsic volatility on the markets. However, it is important to note the relative role of the price of the commodity lithium in the overall cost of automobile battery manufacturing. Bloomberg[18] calculated that if the price of lithium tripled, it would only lead to a 2% increase in battery prices, while the increase would reach nearly 13% in the case of cobalt.

IV. CONCLUSION

The number of EV (two and three-wheelers excluded) on the road reaches between 250 and 360 million units by 2050 in the 4°C scenarios, while it is between 760 and 1200 million units in the 2°C scenarios according to the type of mobility assumed. In addition, the EV fleet is mostly located in Asian countries (China, India and other developing countries in Asia) due to the large presence of two and three-wheelers that stand for more than half of the global EV fleet. Should the policy ambitions continue to rise to meet climate goals and other sustainability targets, as in the 2°C scenario with a high mobility assumption, then the number of electric passenger light-duty vehicles on the road could be as high as 970 million units by 2050 while it would not be more than 310 million units in circulation by 2050 in the 4°C scenarios.

[16] The LME plans to propose new futures contracts including lithium, graphite and manganese. (all three used in automobile batteries), starting in January 2019.
[17] Production in the non-ferrous metals market (copper, aluminum, nickel, etc.) totals several Mt.
[18] Bloomberg 2017.

The scenarios developed in this article tend to show that a high penetration of the EV worldwide could lead to a decrease in the lithium safety margin in the 2°C, the most stringent climate scenario, and an hyper mobility. This leeway varies from 86% to 84% respectively in the 4°C scenario with low mobility and high mobility while it is falling from 63% to 53% in the 2°C according to the shape of mobility. Nevertheless, the massive deployment of Li-ion battery technology (small electronics with portable batteries and the first phase of electric vehicle penetration since 2010) has already resulted in a fourfold increase in reserves between 2005 and 2017. The demand of cumulated lithium in the 2°C with hyper mobility would reach by 2050 around 1.5 times the current level of lithium reserves. Therefore, it is likely that it will be technologically accessible by 2050 according to recent project announcements. However, long-term equilibrium dynamics in commodity markets tell us that the absence of geological criticality of reserves and resources does not hide different forms of vulnerability, whether economic, industrial, geopolitical or environmental.

Four major risks on the lithium market have been thus identified according to our modelling results:

- Uncertainties about the market's ability to meet the new and growing demand on time
- Uncertainties related to the environmental impacts of lithium production
- Uncertainties about the commercial strategy of large lithium consumers (especially China)
- Uncertainties about the consequences of national strategies in the lithium triangle

Concerning the first point above mentioned there are strong uncertainties in the short term linked in particular to production lead times which are generally delayed by several years compared to the estimated ramp-ups. As said before, these volumes announced also often concern capacity and not production volumes, which likely overestimate future production.

Uncertainties related to the environmental impacts of lithium production should be pinpointed as well. Such a future volume production in lithium triangle may bring potential issues related to the environmental impacts of lithium production. Beyond the destruction of fauna and flora or the degradation of landscapes for tourism, the need for fresh water and energy could be critical. Some processes for lithium extraction and purification are larger water consumers, which could be a problem given that water stress often already exist around salars and salt lakes.

Despite the presence of many new entrants in the exploration sector, the lithium market is still dominated by a limited number of companies, including the Chinese ones. Since there are no yet price volatility management instruments on commodity exchanges, this concentration of players is leading to considerable uncertainty about future lithium prices. However, the London Metal Exchange plans to offer new futures contracts including lithium, graphite and manganese (all three used in automotive batteries) from January 2019. Price volatility could weaken new market entrants and lead to new consolidation movements (mergers and acquisitions) between players.

Actor's consolidation is very significant, particularly at the level of Chinese players. Due to the importance of China in the lithium market, a more in-depth analysis of any change in China's trade policy (introduction of quotas, embargo) have to be done in the wake of historical patterns observed on other commodity markets (rare earths, etc.).

Although China owns about around 15% of world lithium resources, it is expected to be strongly dependent on supplies from South America (like the rest of the world's lithium consumers such as the United States, India or Europe). The lithium triangle between Argentina, Bolivia and Chile currently accounts for 55% of world resources and nearly 50% of production (USGS, 2018). According to our results this region should be the largest exporter of lithium by 2050. In the 2°C scenario with high mobility, therefore stringent climate constraint and more car dependencies, the region could account for around 90% of lithium supply. Therefore, the current contrasting national strategies within it could constitute future uncertainties about supply. In Chile, reservoir concession companies are subject to exploitation quotas, as well as limited-term lease contracts. Argentina is currently very favourable to foreign investments but Foreign

Direct Investment (FDI) policies are a national issue which may change with future country governance. In the case of Bolivia which endows one of the most important resources but has not yet started production, the Bolivian government is more in favour of a vertical integration of the local industry to position itself on the all value chain of the industry (including batteries production).

Other perspectives of our global model as further research on raw materials would be to implement and analyse as well, at the global scale, the impact of other strategic materials (nonferrous metals such as cobalt, nickel, copper and rare-earth metals such as neodymium, terbium, lanthanum, etc.) either in transport or in power sector with the increasing penetration rate of Renewables Energy Technologies (RETs). It could be very useful as a good decision-making tool for a better foresight within investments according to future raw material market stresses for a better sectorial screening. ■

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CRITICAL RAW MATERIALS AND TRANSPORTATION SECTOR ELECTRIFICATION: A detailed bottom-up analysis in world transport

BY Clément BONNET, Samuel CARCANAGUE, Emmanuel HACHE, Gondia Sokhna SECK, Marine SIMOËN

This article is part of the GENERATE (Renewable Energies Geopolitics and Future Studies on Energy Transition) Project.

GENERATE (Renewable Energies Geopolitics and Future Studies on Energy Transition) is a two years research project (2018-2020) on the Geopolitics of Renewable Energy, on behalf of the French National Research Agency, in a consortium with IFP Energies Nouvelles. The purpose of the project GENERATE is to analyse the geopolitical consequences of a spread of renewable energies worldwide. This project will focus particularly on three major issues, namely (1) the criticality of energy transition materials for energy technologies (electric vehicle, solar panel, wind turbine, etc.). (2) the new geography of patents for the renewable energy technologies and (3) the oil producing countries development model, and their places on the international energy scene.

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