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Electrification of the French automotive industry: modeling the evolution of lithium demand

Edouard Millet[a], Tom Bauer[a]*, Gabriel Banvillet[a], Tatiana Reyes[a]

[a]*Arts et Metiers Institute of Technology, CNRS, Univ. Bordeaux, Bordeaux INP, I2M, UMR 5295, Institut de Chambéry F-73375 Le Bourget-du-Lac, France*
* Corresponding author. *E-mail address:* tom.bauer@ensam.eu

Abstract

This study models the evolution of lithium demand in France's electric vehicle sector through 2100, using system dynamics to account for the interplay of extraction, recycling, and production projects. Following the European Union's 2023 decision to ban internal combustion engine vehicles by 2035, France has focused on securing critical raw materials, including lithium, to support its electrification goals. The system dynamics model incorporates the growth of the French electric vehicles fleet, lithium extraction from a newly established mine, and recycling rates mandated by European regulations. The results compare the scenario with the simulation and show when the electric vehicle industry will not be self-sufficient in lithium.

Keywords: lithium supply, electric vehicles, recycling, critical raw materials, extraction

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1. **Introduction**

1.1. Political background

In 2023, the European Union (EU) voted to ban the sale of new internal combustion engine vehicles (ICEV) from 2035 [1]. This measure was voted through with the aim of drastically reducing greenhouse gases (GHG) emissions and urban air pollution from the transport sector in Europe, as well as reducing dependence on fossil fuels, particularly oil. According to the European Environment Agency (EEA), the transport sector will account for 23.8% of EU GHG emissions by 2022 [2]. New European legislation also aims to reduce GHG emissions by 55% by 2030 ("Fit for 55" plan), the first intermediate step on the road to carbon neutrality in 2050 [3].

1.2. The growing challenge of industrial sovereignty

Against the backdrop of this ban and the EU's climate ambitions, the electric car sector is booming in Europe, despite strong competition from other global players such as China and the USA [4]. To ensure its sovereignty in the face of growing demand for mining resources, the EU has introduced regulations governing the use of critical raw materials to its ecological transition. As a result, new mining operations will emerge in Europe, generating impacts that the EU has not directly endorsed for years. The continent aims to develop an extraction capacity of at least 10% of its own annual consumption by 2030, a refining capacity of at least 40% and a recycling capacity of at least 25% [5]. On the other hand, no structural change in usage is currently planned to reduce demand for critical metals, particularly lithium [6]. In view of the very strong growth in demand for critical metals, end-of-life issues, and in particular recycling, will be crucial to ensuring the industrial sovereignty of European countries.

1.3. Development of extraction and manufacturing projects in France

More specifically, France has recognized the "major national interest" of a lithium mine project on its mainland, at Échassières, and is positioning itself as one of the key players in European automotive battery production [7]. At the same time, several "gigafactories" (large-scale battery production plants) are taking shape in northern France, benefiting from considerable public subsidies [8], to be able to produce most automotive batteries in France. As France is not currently self-sufficient in lithium production, present and future "gigafactories" are currently supplied with lithium from abroad. The target production rate for this mine is to equip 700,000 electric vehicles (EV) a year in France and Europe [9]. In 2022, the battery sector will account for 74% of global lithium consumption [10], compared with 23% in 2010 [11]. According to the International Energy Agency (IEA), the EV sector will account for around 90% of growth in lithium demand between now and 2050 [12]. In view of this strong future growth, France is strongly developing its recycling sector to reduce the strain on this future mine and promote resource circularity as much as possible. European regulations are encouraging these initiatives by setting a mandatory minimum quantity of recycled material for battery manufacture from 2030, rising to 2035 [13]. For the time being, there are very few studies forecasting the evolution of know-how in the recycling of critical metals. In addition, manufacturers are facing major obstacles, such as fires in their end-of-life battery stockpiles. This makes the development of recycling capacities for these materials even more unpredictable.

1.4. Aim and scope of the study

The aim of this study is to model the evolution of France's lithium demand between now and 2100, based on prospective scenarios, considering the extraction and recycling projects being developed on its territory, to meet the objective of electrifying its vehicle fleet.

System dynamics (SD) is a modeling technique whose main advantages are its use of time-varying parameters, its ability to take precise account of the evolution of a technology, and its ability to consider changes in production systems and market dynamics [14]. It can be used to address a wide range of interdependent fields: engineering, economics, politics, ecosystems; modeling supply chains as well as financial markets at given points in time, and the long-term impacts of political choices [15], [16], [17]. Systems are modeled using feedback loops, time delays, stocks and flows, and are simulated through the prism of various pre-defined prospective scenarios. These models show how changes in one variable can impact the whole system and destabilize it. Thus, SD is a tool that meets the needs of this study, given that we know the targets for mining and EV manufacturing, as well as the desired evolution of lithium recycling capacities in France. On the other hand, this modeling technique also has several drawbacks. One of the risks is an oversimplification of reality. In our case, the economic aspect is not considered at all, even though it would have a definite impact on market trends. On the other hand, modeling is highly dependent on the quality of the causal link assumptions and values used in the system.

With a view to responding to the issues raised above, this article first presents an overview of the work already carried out on the subject. It will then describe the method used for the study. It will detail the choices made in the modeling, then present the results, before discussing them.

2. State of art

Guo et al. [18] combined SD and life cycle assessment (LCA) to evaluate the evolution of GHG emissions from thermal and EV fleets in China from 2016 to 2035. Reading this article initially suggested a return to the use of the SD model of ICEV and EV fleet evolution. This implied not considering a fleet evolution scenario, but letting the system self-regulate by considering the vehicle replacement rate and new demands. However, the disadvantage of using this model is that it is based on an arbitrary evolution of market shares between electric and combustion-powered cars, and on a growth in new demand that is difficult to assess because it is highly dependent on economic fluctuations, of which there are more and more. Furthermore, as lithium consumption depends exclusively on sales of EVs, there's no need to complicate the model by considering the ICEV fleet. We therefore end up with a model in which the EV fleet is driven by a set scenario, and directly influences lithium extraction to meet demand for EV manufacturing.

Shared socio-economic pathways (SSPs) [19] were used by Maisel et al. [6] as prospective scenarios describing the evolution of the electromobility market worldwide to assess the evolution of demand for lithium, cobalt, nickel and manganese. The main limitation to the use of SSPs is that they do not adapt to the state of the system. In other words, the input conditions are fixed by the SSP, and the output does not influence the input conditions, which may however be output dependent.

Berthet et al. [20] have used a multi-regional input-output analysis [21] to determine the socio-economic impacts of switching from thermal to electric power. The main advantage of this method is that it takes account of market dynamics, which we neglect in our SD model. On the other hand, a study such as this one is not concerned with the physical limits that may constrain the system.

Andersen et al. [22] used the same input-output analysis method as Berthet et al. to assess the impact of Europe's ecological transition on demand for critical raw materials.

Existing literature is mainly concerned with factors that are exogenous to the EV industry, such as fossil fuel extraction, the energy mix or changes in market share between ICEV and EV. On the other hand, it rarely examines both endogenous factors such as the reduction in weight of batteries and vehicles, progress in battery production or the structuring and development of a recycling industry, and the physical limits imposed by raw material extraction and recycling capacities.

The aim of this study is therefore to refine the results proposed in the above-mentioned literature, by employing a dynamic method in which the parameters can vary according to the state of the system, and by including factors endogenous to the electromobility sector in the model, as well as the evolution of the extraction and recycling sectors.

3. Method

3.1. Structure of the SD model

In view of the political choices mentioned in the introduction, an SD model with two stocks, one of electric vehicles and one of lithium available to the automotive industry, is used to model the evolution of lithium demand in France according to the growth of the French electric vehicle fleet. There are various physical interdependencies between these two stocks: the manufacture of vehicles increases demand for lithium, which can be met by extracting primary raw materials (imported or produced locally) or by producing secondary raw materials (from recycling channels). The lithium transformations are neglected in this model. That’s why the model is based directly on lithium hydroxide monohydrate (LHM), which is the raw material used to make batteries.

The inflow from the *EV fleet* is *EV manufacturing*. Since we don't consider the lithium extraction time (considered negligible compared to the times involved), this flow directly influences the *Foreign LHM imports*, at the same time as the *LHM consumption* outflow. Given that we wish to drive the model with a growing fleet of electric vehicles, the inflow *EV manufacturing* is defined by the following expression:

$$EV\ manufacturing = \frac{EV\ fleet\ scenario - EV\ fleet}{Time\ step}$$

This makes it possible to adjust the number of vehicles entering the fleet in real time to keep up with the scenario. In addition, the outgoing flow *EV end-of-life* is equivalent to the incoming flow *EV manufacturing* with a delay of 10 years, corresponding to the life of a single-life battery [23].

The *LHM available for the automotive industry* stock represents the total amount of LHM usable by the industry at a given time to make EV. That is why the inflows of this stock are *Foreign LHM imports*, *French LHM extraction* and *LHM recycling*. First, *LHM imports* are triggered when there is a demand of LHM to make EV, by comparing the value of the stock with the amount of LHM needed. The imports are stopped in 2028 because the local mine opens. Considering the values shared by the mining company, the extraction will reach 34 kt/year after 2.5 years of exploitation [9]. Thus, the inflow *French LHM extraction* follows this trend. This inflow is also an outflow for the stock *Potential LHM deposit in the mine*, representing the potential available LHM in the mine. Initially, its value is 716,000 tons [9]. When its value reaches 0, it stops the flow *French LHM extraction*. Finally, the inflow *LHM recycling* represents all the flows of recycled lithium: recycled vehicles, recycled second life batteries, and battery production scrap. The second life batteries have a lifetime of 5 years [23].

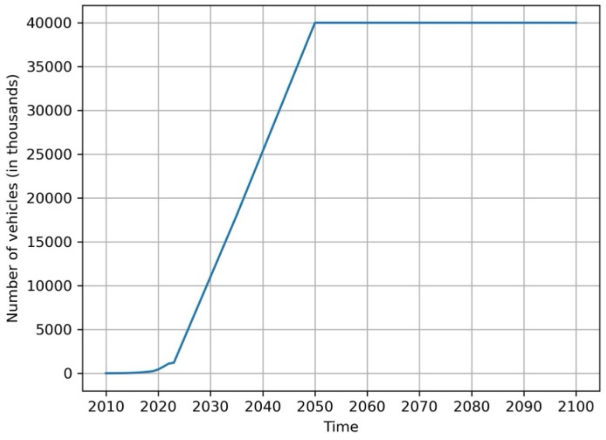

Fig. 1 EV fleet evolution scenario

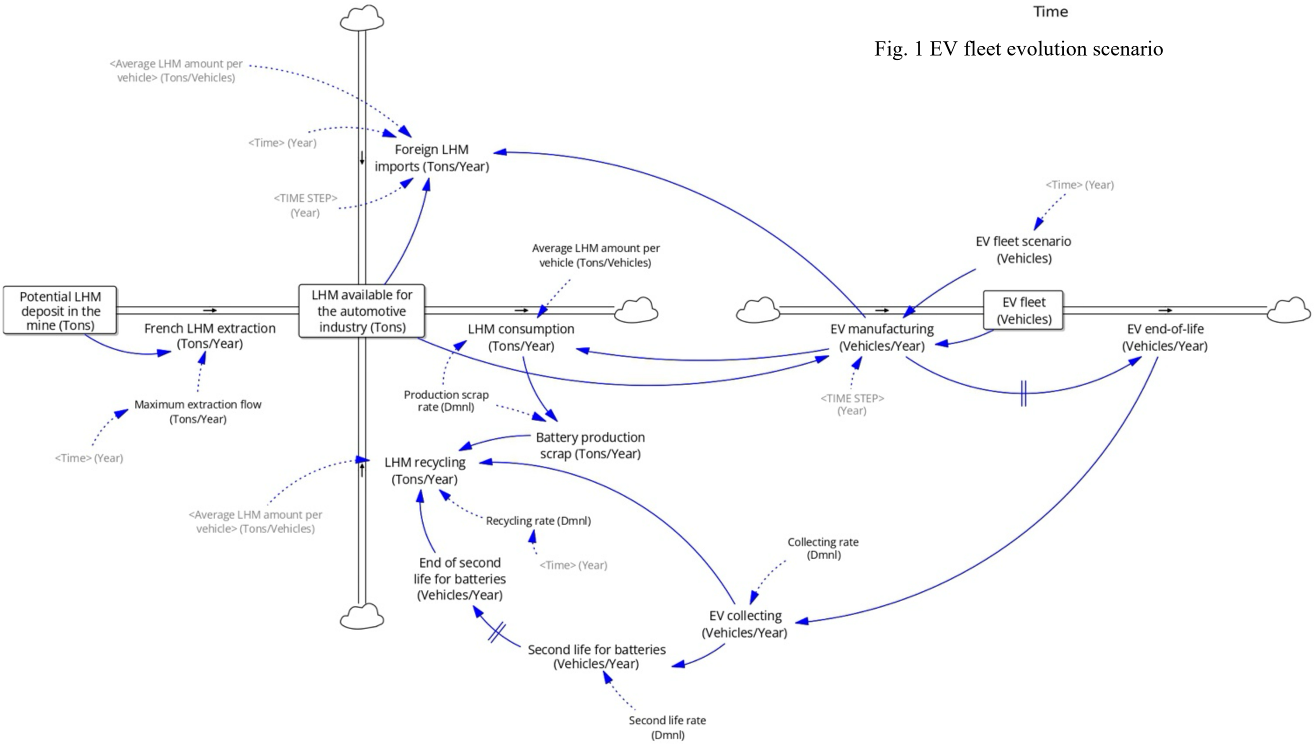

Fig. 2 Stock-flow diagram (SFD) of the model

3.2. Definition of exogenous variables from a scenario

The model's input is driven by the actual evolution of the electric vehicle fleet from 2010 to the present day, then by a quasi-constant evolution of the fleet up to 2028 (opening of the mine). From 2028 to 2035, the trend is linear until we reach the target of 18 million electric vehicles in the national fleet, proposed by ENEDIS (French electricity distributor) scenario [24]. Finally, from 2035 to 2050, we propose to study the scenario of total electrification of the French ICEV fleet in 2050, with linear growth over the entire period. We therefore project linear growth from 18 million electric vehicles in 2035 to 40 million vehicles in 2050 [25].

The second exogenous variable defined by a scenario is the *Recycling rate*. Recycling technologies and processes are not yet mature. To constrain progress in the critical metals recycling sector, the EU is imposing recycling efficiency targets of 35% and 70% in 2025 and 2030 respectively [13]. It is then assumed that the recycling rate will remain unchanged to reflect the physical realities of recycling (process losses, efficiency of recycling methods). Finally, we assume that the recycling sector is non-existent in 2010, when the first EVs are sold.

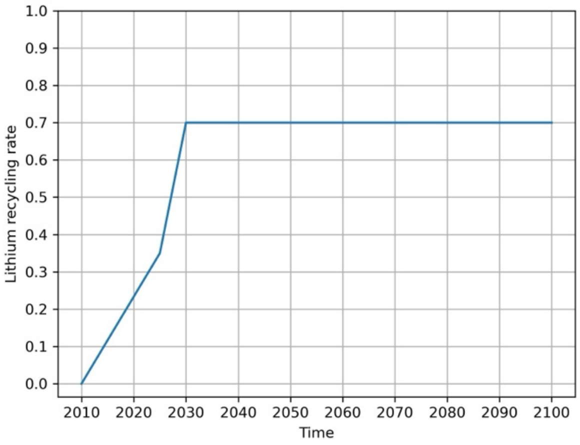

Fig. 3 Lithium recycling rate evolution scenario

3.3. Definition of constant exogenous variables

The exogenous variable most used in the model is the *Average LHM amount per vehicle*. This variable has a significant impact on the results returned by the model, as it represents the very important factor of vehicle mass. For the sake of simplicity, we assume that the batteries manufactured have a capacity of 75 kWh. This allows us to estimate that manufactured batteries will contain an average quantity of lithium of the order of 10 kg [26].

As mentioned above, the amount of production scrap is not negligible in relation to the total amount of recycled lithium. The literature suggests a *Production scrap rate* of 10% [23].

Due to the lack of information concerning the second life of EV batteries, we assume a *Second life rate* of 10%. This value doesn't have much impact on the system, because it only adds a 5-year delay from the EV end of life and to the recycling.

Finally, the *Collecting rate* is set at 70% during all the simulation. For the moment, we don't have much information about this topic because the sector is not structured yet. The value of 70% enables the representation of the accidented vehicles, and the fires that affect the battery recycling companies.

Variable	Value	Unit
Average LHM amount per vehicle [26]	0.01	t/vehicle
Production scrap rate [23]	0.1	-
Second life rate	0.1	-
Collecting rate	0.7	-

Table 1 Summary of constant exogenous variables

4. Proposal

4.1. Modeling choices

As the electromobility sector is currently undergoing major changes, there are many changes to consider, both dependent on and independent of the sector. Considering variables that can vary over time and according to the state of the system is fully in line with the tools proposed by SD. Indeed, the system under study is multi-factorial, depending on several sectors driven by different policies. The great flexibility offered by SD in the definition of the various parameters was therefore an important criterion in the choice of models. More specifically, the lithium extraction, battery manufacturing and battery recycling industries are in the process of being structured. The transient regimes these industries are undergoing are potential sources of error for static modeling methods such as LCA. SD also makes it possible to implement in the system the various temporal milestones already defined by industry players: the opening of the lithium mine, the end of sales of new combustion-powered vehicles. In addition, SD enables us to propose a scenario to follow, but the system can deviate from it if it is unable to meet the requirements imposed by the scenario. In this case, it is vital that we know whether the mine will be sufficient to supplement the recycling channels to meet the demand for lithium.

4.2. Choice of variables

As regards the various channels of influence between electric vehicle and lithium flows, the choice of summarizing them as an import channel, a local extraction channel and a recycling channel is justified by several aspects:

- France does not currently exploit any lithium deposits on its territory, and therefore imports some.
- The lithium from the Échassières mine, due to open in 2028, will be used exclusively to manufacture automotive batteries.
- The recycling sector is intended to be a very important ecosystem in securing a critical resource such as lithium.

The decision not to consider conventional batteries as a lithium source in the model is explained by the fact that around 80% of the tonnage of batteries collected in France comes from the automotive sector, and this has been the case constantly since 2009 [27]. In addition, it is even more difficult to collect small batteries and accumulators, given consumers' freedom to return or keep these products. Conversely, a car battery must be collected by the producer, in accordance with the regulations on extended producer responsibility.

5. Results

The first result concerns the comparison between the target imposed by the scenario and the actual evolution of the EV fleet.

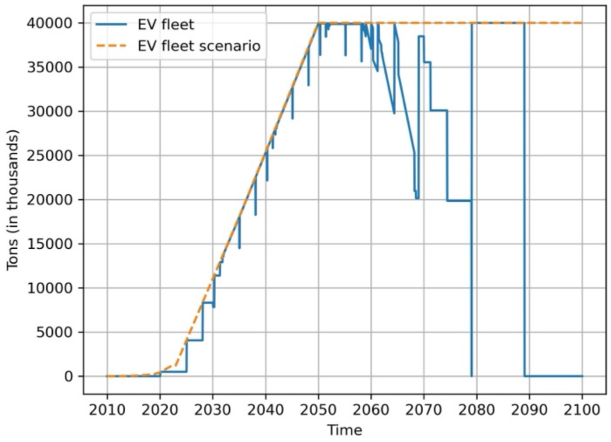

Fig. 4 Comparison between the EV fleet scenario and the simulation

From 2010 to 2060, the *EV fleet* manages to follow the scenario quite well, excepted few falls which are corrected by the system. From 2060 onwards, the *EV fleet* starts collapsing, which ends with a stock of 0 vehicle in 2088.

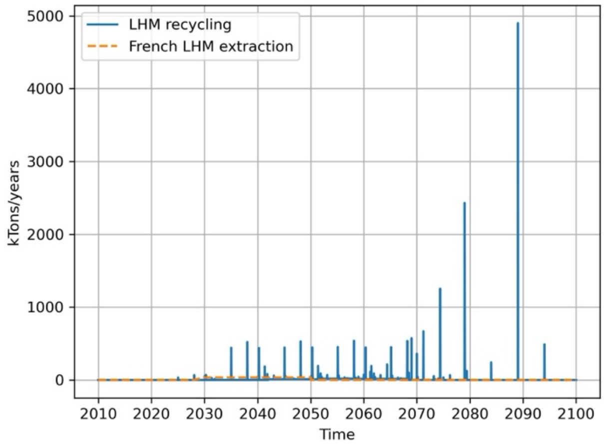

Fig. 5 LHM recycling evolution

The second result deals with the evolution of the LHM recycling, stacked with the French LHM extraction.

6. Discussion

The first remark concerns the shape of the curve: the *EV fleet* evolution varies sharply. This can be explained by the fact that the model doesn't consider the EV production capacity and the LHM recycling capacity of France. This means that the recycling system of the model will recycle the batteries instantly and will send the recycled lithium to the factories to make new EV. Nevertheless, these results can be interpreted as an indicator of when the EV sector will not be self-sufficient in LHM any more. It's notable that from 2060, the EV fleet is starting its degrowth. This means that only 10 years after the end of the LHM extractions, there is a need of new extractions to make up the recycling losses (if France decides to keep its EV vehicle fleet at the same level).

Considering that the scenario used in this model is shared by the French electricity distributor, and that the French government is considerably investing in the EV industry, this scenario is quite realistic and matches with the French ambitions. However, it is essential to consider that this simulation is based on a model working in a stable world, industry, economy, and a constant production capacity. Therefore, a way to improve the current model would be to include new variables and relations, for the system to depict more precisely the growing instabilities.

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