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Electrification of the French automotive industry: modeling the influence of main parameters of the lithium extraction and electric vehicle industries

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Abstract

This study models the evolution of the French electric vehicles fleet depending on different parameters, such as production or recycling capacities, average lithium amount per vehicle, using system dynamics. 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 target growth of the French electric vehicles fleet, lithium extraction from a newly established mine, and recycling rates mandated by European regulations. The results show that reaching the 2050 target is not the only issue: maintaining the fleet at a stable state is not evident if the three parameters mentioned above are not balanced. This study concludes that the European Union's legal targets are not enough to ensure the perennity of the electric vehicles fleet.

Keywords: lithium supply; electric vehicles; recycling; critical raw materials; extraction; system dynamics

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 accounted 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 (EoL) 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]. This mine will exclusively supply the automotive industry, to make 100% electric vehicles (EVs) [8]. That is why we only include BEVs and not plug-in hybrid electric vehicles (PHEVs) in the study. At the same time, several “gigafactories” (large-scale battery production plants) are taking shape in northern France, benefiting from considerable public subsidies [9], 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 EVs a year in France and Europe [8]. 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 6% in 2031, rising to 12% in 2036 [13]. For the time being, the evolution of know-how in the recycling of critical metals is quite unpredictable: manufacturers are facing major obstacles, such as fires in their EoL battery stockpiles. Indeed, these fires doubled between 2022 and 2023 in France (41 referenced events) [14]. 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 influence of different recycling and production industries parameters 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, and perpetuate it. Even if the targets are defined for 2050, the choice to model until 2100 is useful to understand how the different parameters of the system can impact the perennity of the EV fleet. The years between now and 2050 are transitional, and the period after 2050 can be either characterized by a steady state or a collapsing of the EV fleet.

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 the art

2.1. Methods used in the literature to quantify material demand

Different methods can be found in the literature to quantify future material demand. System dynamics (SD) is used several times to quantify the evolution of the demand of critical materials. Material flow analysis (MFA) is also popular to describe the different paths travelled by the materials and the proportion of each path in the overall flow. Moreover, some articles use the shared socio-economic pathways (SSPs) [15] to consider different scenarios of the role of electromobility in the society.

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 [16]. 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 [17], [18], [19]. 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. 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.

MFA is an analytical method to quantify flows and stocks in a defined system [20]. This method is used to study material, substance or product flows across different industrial sectors or within ecosystems. The system is defined by its boundaries, and its internal relations and elements. Another important step of the MFA is to quantify the metabolism of each element of the system. Then, this method enables to see how a system metabolizes depending on its inputs.

2.2. Studies using MFA and SD

Ginster et al. [21] used a combination of SD and LCA to evaluate the material flows and environmental impacts of a circular battery production system in the EU27. The SD aims to quantify the material flows. The main conclusion given by this study concerning the lithium supply need in the EU is that it is highly dependent on the chosen scenario: the most the lifetime is improved, the most the supply need is reduced. For the "reduced lifetime" scenarios, the supply need is reaching a 50% higher value in 2050.

Calculations made by Maisel et al. [6] on future raw material demand are based on different scenarios: the SSPs. These are used to create prospective scenarios describing parameters that are beyond the automotive market, such as the vehicle dimensions and weight. The evolution of the demand is calculated with the number of new registrations of vehicles per segment given by the mobility scenarios. Moreover, to estimate the cathode shares of EV LIBs technologies (LCO, NMC, NCA, LFP...) up to 2040, Maisel et al. [6] considered 11 market studies and technology scenarios already existing. They formed 2 different scenarios based on this literature to describe the evolution of the tension on each critical material. This study conclusion about lithium supply is mainly about giving order of magnitude of lithium need depending on the SSP. We can see how the lithium supply need is sobriety-dependent.

MFA were used by Abdelbaky et al. [22] to calculate the probability of failure a manufactured battery depending on its age. With this result, they calculate the composition on the waste stream returning to recycling and the part of EoL batteries that are used for a second life. In this case, MFA is used to see if the batteries are mostly recycled or reused, and what was the reason of its EoL. A result of this study is that lithium recycled stream is included between 8% and 33% of the demand in 2040, depending on the scenario. Even with the most favorable scenarios, the recycled part does not exceed the third of the need.

Bobba et al. [23] also use MFA, with the same goal as Abdelbaky et al. [22], but their model is more detailed: it includes sub-path that are not mentioned in the precedent model. They end at the same conclusion: lithium recycling will not enough supply the automotive industry needs. It also gives another conclusion about the quantity of lithium used for a second life. The trend is exponential and is way higher than the need.

MFA is used in an even more detailed way by Xu et al. [24]. Indeed, they added in this method different scenarios describing the proportion of different battery technologies. They reach the same conclusions giving details about each battery technology.

2.3. Research gaps

These studies only focus on the transitory aspect of the electrification of the automotive industry, but does not evaluate the sustainability of the production regimes proposed by the scenarios. Indeed, the latest horizon of calculation chosen by these articles is 2050.

Moreover, they mention the lithium supply needs without considering the physical limits that the industries will face if they do not limit their lithium consumption. Coupled to the fact that countries compete against each other for raw materials supply, it is interesting to evaluate the physical limits that industries will face in a context of increased sovereignty.

2.4. Contribution to the literature

Considering the research gaps and the fact that multiple non-linearities derive from the electrification of the automotive fleet (e.g. delays, saturations), SD appears to be a great modelling option for our study. Therefore, we chose this method for our study.

The aim of this study is therefore to evaluate how the physical limits concerning lithium stocks, production capacities, recycling capacities and lithium amount in each vehicle can influence the dynamic, the stable state and the sustainability of the EV fleet.

3. Method

3.1. Modeling choices

Several main points should be mentioned before detailing the SD model:

- 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 [8];
- The recycling sector is intended to be a very important ecosystem in securing a critical resource such as lithium.

We will not consider conventional batteries as a lithium source in the model because around 80% of the tonnage of batteries collected in France comes from the automotive sector, and this has been the case constantly since 2009 [25]. In addition, it is even more difficult to collect small batteries and accumulators, given consumers' freedom to return or keep these products.

3.2. Structure of the SD model

The model is built on the software *Vensim PLE*. In view of the political choices mentioned in the introduction, an SD model divided in two parts, one concerning EVs and one concerning lithium supply chain dedicated to the automotive industry, is used to model the evolution of lithium demand in France according to the target growth of the French electric vehicle fleet (Fig. 1). 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 transformation time is neglected in this model. That is why the model is based directly on lithium hydroxide monohydrate (LHM), which is the raw material used to make batteries. All following descriptions of the model can be observed on Fig. 1. Variables and links are defined in the following paragraphs, numerical values and formulas are defined in Table 1.

The first part of the model is dedicated to the lithium supply chain. Considering that we only focus on the French mining industry, the lithium is only dedicated to the automotive industry [8]. Therefore, all flows will directly get into the automotive part of the model. This industry is mainly represented by two stocks:

- *Potential LHM deposit in the mine*: available lithium stock remaining in the mine. The initial value is 716,000 tons [8];
- *LHM available for the automotive industry*: transformed lithium ore usable by battery manufacturers. We consider that the stock is empty at the beginning.

The lithium industry is supplied by 3 inflows:

- *Foreign LHM imports*: lithium imports before 2028. After 2028, imports are stopped. It is driven by the EV industry needs;
- *French LHM extraction*: Échassières mining flow. The project starts in 2028 and reaches its cruising pace in 2030. The extraction pace is considered as an exogenous parameter, the industry extracts the maximum possible material quantity;
- *LHM recycling*: lithium recycling sector flow. It is driven by the outflow of EoL EVs and the battery production scrap.

The outflow of the lithium industry is *LHM consumption*, representing the lithium flow used by the automotive industry to make EVs. It is driven by the *EV manufacturing* flow, the *Average lithium amount per vehicle* and the *Production scrap rate*.

The second part of the model represents the EV industry, detailed by the different life stages of a vehicle. Two stocks represent the different life stages of the EVs:

- *EV fleet*: currently operational EVs in France;
- *EVs awaiting processing*: EoL EVs waiting for recycling or reuse.

These stocks are linearly linked by flows:

- *EV manufacturing*: EVs made and injected in the French fleet. This inflow is designed to match as best as possible the *EV fleet target* variable;
- *EV end-of-life*: obsoletes EVs injected in the awaiting processing stock. The flow is driven by a delay on *EV manufacturing*. DELAY3 function has been used on *Vensim PLE* with a 10 years duration to characterize with continuity the life duration of EVs;

- *EV processing*: EoL EVs going to recycling or reusing. It is designed to process the maximum EV amount possible at each time step.

3.3. Definition of exogenous variables

To keep the continuity of the calculations made by the program, all following exogenous variables are interpolated as sigmoid functions. The choice of sigmoid function is justified by the fact that it characterizes the transition between 2 stable states, which matches well with the situation that mining and automotive French industries are facing. The logistic regressions have been made with Python, and are available in the attached resources.

The model's input is driven by the actual evolution of the electric vehicle fleet from 2010 to the present day. According to a scenario proposed by ENEDIS (French electricity distributor) [26], the EV fleet should match a target of 18 million vehicles in 2035. Then, we consider as a target for 2050 the full replacing of the present ICEV fleet, i.e. 40 million EVs [27].

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 65% 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. As seen in the literature review, these values are already very optimists, even if these are legal objectives.

To make realistic calculations, we have to define a *Maximum EV processing capacity*. The two main French EV recycling actors are Veolia, and Suez/Eramet partnership. They expect a recycling capacity of respectively 20.000 [28] and 200.000 [29] vehicles/year. Considering that we want to study the impact of the recycling capacities on the system, we interpolated a sigmoid function for the expected recycling capacities, and we added another one, representing future investments on this.

We also define the production capacities planned by the French government and the French automotive constructors for 2030. The two main French EV constructors are Stellantis and Renault. They expect a production capacity of 1M [30] and 480.000 [31] vehicles/year respectively in 2024 and 2025. Considering that we want to study the impact of the production capacities on the system, we interpolated a sigmoid function for each constructor, and we added another one, representing future investments on this.

3.4. Definition of exogenous constants

The most used exogenous constant in the model is the *Average LHM amount per vehicle*. This constant has a significant impact on the results returned by the model, as it represents the very important factor of vehicle mass. Considering that we want to evaluate the impact of this value on the system, we need to determine the relation between this amount and the battery capacity of the EVs that we study. Global EV Outlook 2024 by IEA [32] gives a value near 0.1 kg/kWh for each battery technology. Depending on the battery capacity scenario, we will change the amount of lithium per vehicle, considering this value.

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% [33] (Table 1).

Due to the lack of information concerning the second life of EV batteries, we assume a *Second life rate* of 10% (Table 1). This value does not have much impact on the system, because it only adds a 5-year delay from the EV EoL and to the recycling. We used the DELAY3 function of *Vensim PLE* to keep the continuity in the recycling supply.

Finally, the *Processability rate* is set at 90% during all the simulation (Table 1). For the moment, we do not have much information about this topic because the sector is not structured yet. The value of 90% enables the representation of the accidented vehicles, and the fires that affect the battery recycling companies. Moreover, the EU legislation expects the producers to manage their EV waste [13]. Therefore, we can suppose that most of the EV fleet will be treated by the recycling industry.

Table 1. Summary of constant exogenous variables.

Variable	Value	Unit
Production scrap rate [33]	0.1	Dimensionless
Second life rate	0.1	Dimensionless
Processability rate	0.9	Dimensionless

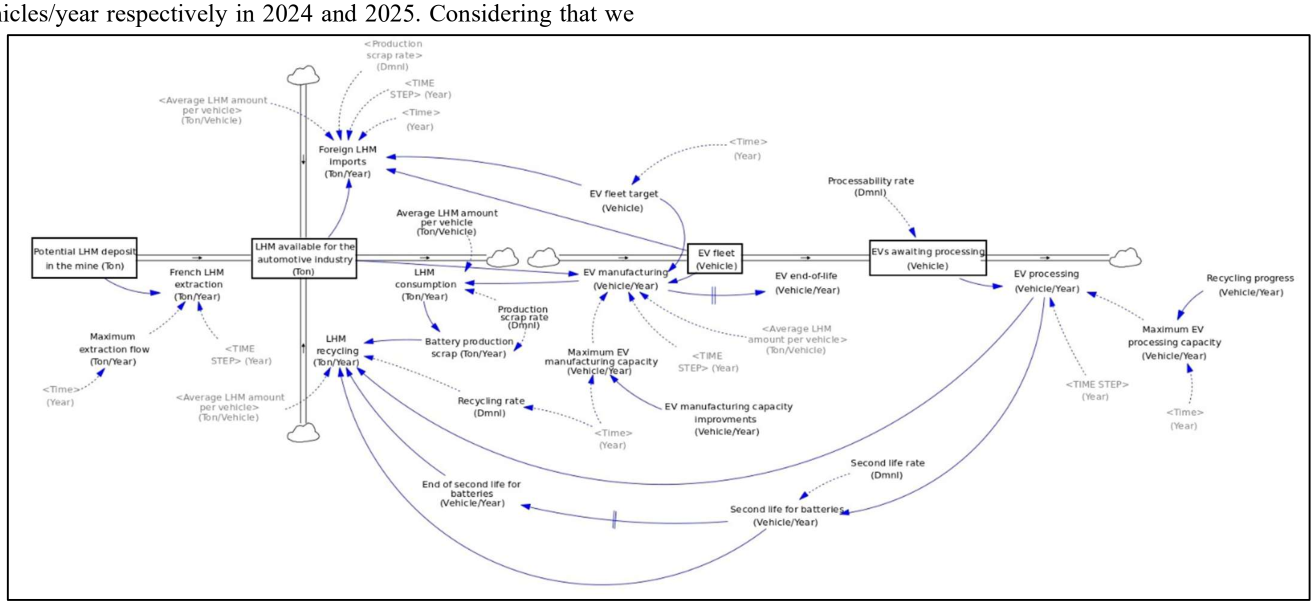

Fig. 1. Stock-flow diagram (SFD) of the model, made with *Vensim PLE*. Exogenous factors linked with dotted arrows.

4. Results

The following results show the influence of the *Maximum EV manufacturing capacity*, the *Maximum EV processing capacity*, and the *Average LHM amount per vehicle*. For each case, all parameters except the studied one are fixed.

4.1. Maximum EV manufacturing capacity influence

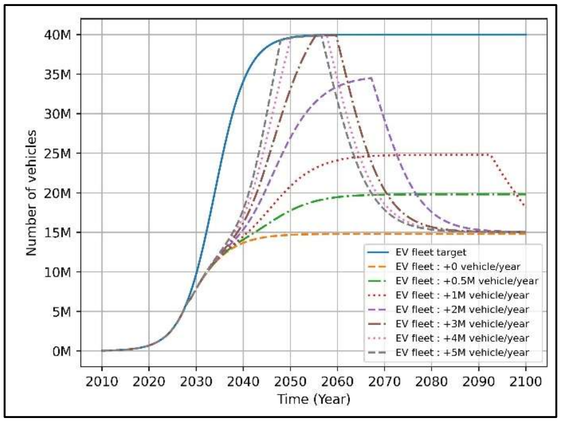

Fig. 2. Evolution of the EV fleet depending on the EV manufacturing capacity improvements

The variation of the *Maximum EV manufacturing capacity* parameter shows that it has an impact on the transition speed and the final stable state. Indeed, the more this parameter grows, the more the final state is reached fast, and the more final EV fleet is large. In this case, *Recycling progress* is set at +2M vehicle/year, and *Average LHM per vehicle* is set at 0.01 ton/vehicle.

4.2. Maximum EV processing capacity influence

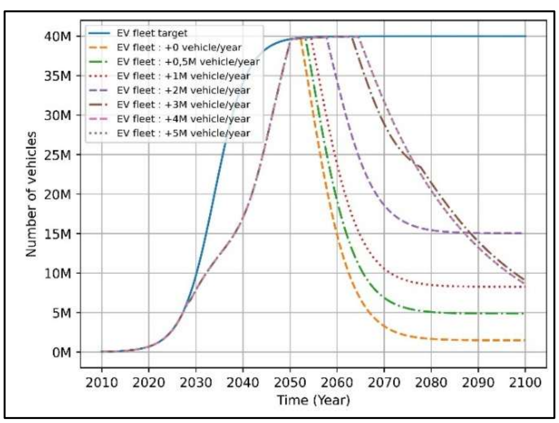

Fig. 3. Evolution of the EV fleet depending on the EoL processing influence

The variation of the *Maximum EV processing capacity* parameter shows that it has an impact on the perennity of the stable state. Indeed, we see that a collapse of the *EV fleet* happens between 5 and 15 years after 2050. Moreover, we can see that the more the recycling industry is developed, the more the post-collapse stable state is large, until it reaches a limit. We can see that after the +3M vehicle/year processed gap, the post-collapse stable state is reached way later and is way lower. This can be explained by the fact that the recycling industry is processing too fast the EoL EVs stock to keep it over 0. Then, the recycling industry does not have enough EVs to supply to LHM stock. In this case, *Maximum EV manufacturing improvements* is set at +4M vehicle/year, which is the value necessary to reach the 2050 objective on time. The *Average LHM amount per vehicle* is set at 0.01 ton/vehicle.

4.3. Average LHM amount per vehicle influence

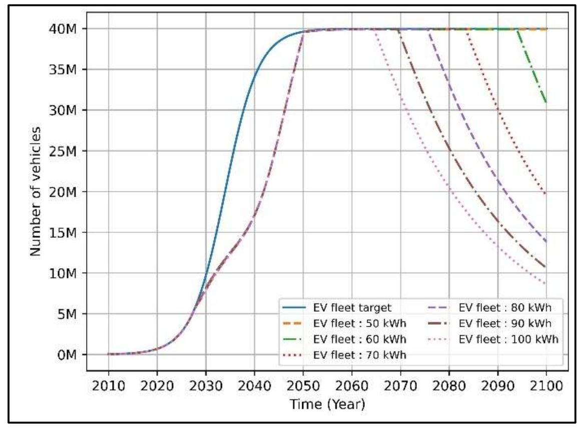

Fig. 4. Evolution of the EV fleet depending on the average LHM amount per vehicle

The variation of the *Average LHM amount per vehicle* parameter shows that it has an impact on the perennity of the stable state after reaching the objective. We can see that the curves after the beginning of the collapse, has the same profiles. We just see a time translation between each case.

5. Discussion

The results show clearly the different influences of these 3 parameters. These impacts can be summarized in the following figure:

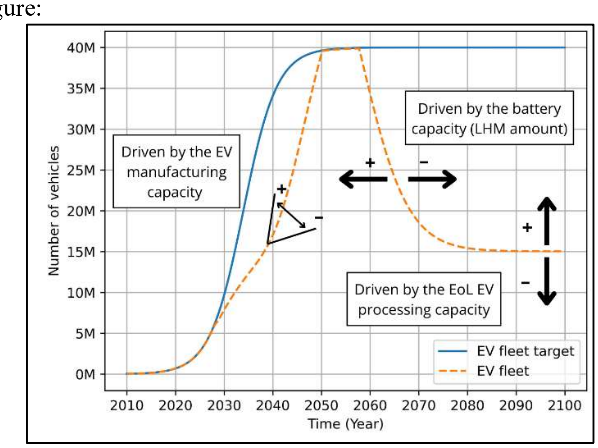

Fig. 5. Summary of the influence of each studied parameter

We can deduct from this figure that the feasibility of the electrification of the automotive industry is not only a question of reaching the 2050 objective, but also perpetuate the new fleet to a sustainable stable state. Otherwise, reaching a peak to return to a way lower stable state only few years later will just highly impact the lithium criticality without resolving the mobility issues.

This work is adopting a different view that the ones used in the state of art. Indeed, the state of art studies only focus on the transitional aspect of the electrification. But we see that the limits do not only reside in the finiteness of the resources, but also in the industrial capacities. In our case, we also consider the sustainability and the maintainability of the system. Therefore, this paper contributes to evaluate which scenarios should be chosen to reduce fluctuations and reach a robust state (as insensitive as possible to the exogenous factors fluctuations).

The first reservation we can make is that the model considers that when an investment choice is made by the policies, there is no return back on this choice.

Another big review we can make on the model is that it considers a stable economic and environmental world: there is no external brake on the system that can occur in this modelling. To include this aspect, it would be possible to include variables that can randomly deteriorate the production or recycling capacities.

A future study could quantify precisely the relation with the studied parameters and the objective-match speed, the perennity and the post-collapsing stable state level.

Conclusion

This study proposes a SD model to evaluate the impact of the production capacity, the recycling capacity and the average lithium amount per vehicle on the global EV fleet between 2010 and 2100. The model links the lithium extraction and recycling industry, and the EV industry. The results show that:

- The EV manufacturing capacity influences the speed at which the EV fleet reaches the objective;
- The EV processing capacity influences the perennity of the target stable state and the level of the post-collapsing stable state;
- The LHM amount per vehicle influences the perennity of the target stable state.

We can therefore conclude that policies should consider to find a balance between these parameters to make the EV fleet the most sustainable, without only focusing on the 2050 defined targets. Indeed, the EV fleet collapse that could occur if the policies only focus on reaching the target could be very problematic concerning environmental, economic and social aspects.

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