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Abstract

This paper investigates the design of a recent regulatory proposal aimed at favoring the emergence of a battery recycling industry in Europe. Electric mobility is deemed necessary to cut CO_2 emissions in the transport sector but the industrial and environmental impacts of lithium-ion battery manufacturing are controversial. A recent regulatory proposal from the European Commission introduces the obligation to attain a series of minimum thresholds of recycled materials for the new batteries to be manufactured after 2030. This paper discusses the conditions required for that obligation to be fulfilled. It develops a material flow model that projects battery wastes and their recycling potential. Our findings indicate that the feasibility of proposed thresholds is not very sensitive to changes of material intensities from battery technology shifts, recycling efficiencies, or the faster uptake of demand. On the contrary, battery lifetimes are the most crucial parameters for recycling potential. We believe that this result could jeopardize avenues for extending battery lifetimes such as second-battery usage. Our policy recommendations are twofold. First, we recommend lower thresholds to improve the regulation credibility. Second, the regulation should integrate other objectives that address the lifetime of batteries.

Keywords: Recycling, Lithium-ion Batteries, Electric Vehicles, Environmental Policy

1. Introduction

In a recent proposal for a regulation, the European Commission (EC) has introduced recycling as a key element for the development of an industry for electric vehicle (EV) and especially the battery industry (European Union: European Commission, 2020). It is supposed to be a central part of the European Union (EU) industrial strategy covering economic, social and environmental goals. It establishes a legislative framework for a more sustainable life-cycle of lithium-ion (Li-ion) batteries. One of its main initiative is the introduction of minimum thresholds for recycled material sourcing in new batteries.

This paper aims to assess the conditions under which these thresholds may physically be reached. Our analysis of these conditions follows two steps. First, we set up a framework to qualitatively discuss

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the main characteristic trends of the battery sector and how these should affect sourcing from recycled materials. It allows us to separate the different mechanisms driving the amount of recycled material that can be incorporated in new batteries. The share of demand that can be covered by recycled materials in new batteries will be reduced by higher demand growth of electromobility, lower recycling efficiencies, longer lifetimes of batteries and technological changes that increase material use. Second, we estimate the sensitivity of recycling potentials to these mechanisms through a quantitative model. We set up a dynamic material flow analysis, calibrated using data from different reports from the International Energy Agency (IEA) and from the academic literature. For all materials, we find that battery lifespan is the most sensitive parameter driving the thresholds proposed by the EC. On the contrary, the growth rate of demand in batteries appears to bring little sensitivity. Regarding battery technological change, we find that only the recycling potential of cobalt is likely to be significantly impacted. Furthermore, the improvement of recycling processes is crucial to guarantee the sourcing in recycled lithium. Overall, our results indicate that the thresholds of recycled materials proposed by the EC may be difficult to comply with. At the light of this result, we discuss the eventual conflict in environmental goals that these minimum thresholds could cause. For instance, we highlight a trade-off between this instrument and the development of a second life for batteries.

More generally, the proposal of regulation from the EC is motivated by the ongoing transformation of the automobile industry. Indeed, the penetration of EVs has grown steadily for a few years, with EU market shares increased from 0.4% in 2014 up to 4.6% in 2020. EVs have been advocated as one of the main technological option to decarbonize the transport sector and to decrease urban air pollution. This led government to provide a large policy support for electromobility. In parallel, Li-ion batteries - the central components of EVs - have been subject to remarkable technological progress. As a result, their costs have fallen from USD 1 100 per kilowatt-hour (kWh) in 2010 to USD 156/kWh in 2020 (Nykvist et al., 2019; IEA, 2020). In this context, the growing importance of the Li-ion batteries also brings sustainability and strategic concerns. These include the carbon footprint of the life-cycle and waste management (Dai et al., 2019). These also include concerns regarding the availability of raw material, social impacts of the metal extraction as well as supply chain risk management (Hache et al., 2019; IEA, 2021b). Since 2008, the EU has taken into account this component of its industrial sectors. It mainly focuses on sustaining the access to those materials in the EU and worldwide, and developing recycling as well as resource efficiency. To address these issues, the EU has developed several initiatives, such as the European Battery Alliance[1] and the Raw Materials Initiative.[2] The proposal of the EC intends to bring a legislative framework to these initiatives.

Beyond the discussion of the regulation proposal of the European Commission, we contribute to

[1] The European Battery Alliance is a consortium of industrial actors that aims at developing a European battery industry (https://www.eba250.com/).

[2] https://ec.europa.eu/growth/sectors/raw-materials/policy-and-strategy-raw-materials_fr

two main strands of literature. First, we relate to the literature exploring the material usage for the development of electromobility. Ballinger et al. (2019) explore the risks for the EV sector related to material supply, in particular for graphite, lithium and cobalt used in batteries. Xu et al. (2020) and Sato and Nakata (2019) propose a long term analysis of the material demand for batteries. While the former show that the role of recycling remains minor while the market is in expansion, the latter find between 30 and 50% of mineral being supplied by recovery in 2035 in Japan. More generally, some articles address the broad topic of mineral criticity in the energy transition. A thorough literature study from Watari et al. (2020) covers the criticality of a wide range of material up to 2050. They highlight the lack of both socio-environmental analysis and inclusion of recycling strategies. While doing so, they link metal availability challenges to the key technologies of the energy transition. In the same spirit, Seck et al. (2020) examine the importance of copper use in the transition. They test different scenarios in a world model representing transport and energy sectors and find that the increase in copper demand could lead to an important stress on known mining resources. They use the same model for lithium and cobalt demand (Hache et al., 2019; Seck et al., 2022). While they do not find the same stress on mineral resources as for copper, they do highlight the risks caused by geographically concentrated resources, geopolitical strategies, lack of investments and environmental consequences of extraction. Helbig et al. (2018) also address risks in the supply chain of material used in Li-ion batteries. They compute a level of risk for a range of battery technologies, depending on their mineral composition. From the grey literature, reports from the IEA (IEA, 2020, 2021a) present the global trends of EV markets. They also tackle issues of metal scarcity in the energy transition, highlighting the important role that could be played by recycling in the following years in order to ensure the sustainability of material supply chains IEA (2021b). We contribute to this literature by disentangling the key-mechanisms of recycling potentials and by estimating the relative magnitude of those effects. We also focus on the European context.

Second, we relate to the literature on the aspects of the end of life of EV batteries. A review from Lv et al. (2018) lists the different recycling technologies for lithium, and discusses technological, environmental and economic perspectives for pyro-metallurgical and hydro-metallurgical processes. Other authors have investigated on the possibility of extending battery lifetimes through the re-utilization of used batteries. Such second life of batteries could indeed provide stationary storage for the power grid and thus reducing their costs (Few et al., 2018; Gur et al., 2018; Martinez-Laserna et al., 2018; Wu et al., 2020). We contribute to this literature by showing potential incompatibilities when considering at the same time recycled sourcing of materials and other sustainability objectives such as the reuse of EV batteries.

The rest of this paper is organized as follows. Section 2 presents the proposal of the EC and its context. Section 3 gives qualitative insights on the drivers of the level of recycled materials content from used batteries. Section 4 and 5 respectively present the methods and the results of the quantitative analysis. Sections 6 concludes.

2. Proposal of the European Commission

The current EU regulatory framework on batteries is established by a directive from the European Commission in 2006 (Council of European Union, 2006).[3] This directive aims at providing common rules across the EU market that would limit environmental impacts of battery wastes.[4] It distinguishes three kinds of battery types to be regulated: portable (electronic equipment), automotive (for starting, lighting and ignition) and industrial (traction for vehicles and other industrial applications). The directive applies from manufacturing to end of life. It enforces the extended producer responsibility principle. More precisely, it defines targets for the collection of portable battery wastes,[5] and maximum contents of cadmium and mercury in new batteries.

In the late 2020, the EC has proposed a new regulation for the regulation of batteries that would replace the 2006 directive (European Union: European Commission, 2020).[6] Indeed, the disruption of Li-ion batteries fueled by the development of electromobility has outdated made the former directive. Within the context of EU's Green New Deal, this proposal joins other measures pursuing the development of the sector in Europe, such as the initiative of the European Battery Alliance. It aims at providing a legislative framework that would gather industrial, strategical and environmental objectives. The proposal of the EC defines several environmental objectives that spread on the period 2025-2035. These objectives comprise the development of recycling, the limitation of the carbon footprint and the transparency of the supply chain.

		Cobalt	Copper	Lead	Lithium	Nickel
Minimum recycled content in new batteries	2030	12%	NA	85%	4%	4%
	2035	20%	NA	85%	10%	12%
Recovery rate from scrapped batteries	2026	90%	90%	90%	35%	90%
	2030	95%	95%	95%	70%	95%

Table 1: Targets on battery recycling of the 2020 EC proposal

This paper focuses on the objectives regarding recycling. The main elements from the proposal establish minimum recycled contents for several materials in new batteries. These constraints only apply to cobalt, lithium and nickel for the Li-ion technology, and lead for other battery technologies. Minimum thresholds are defined in 2030 and 2035. Table 1 displays them. The proposal also defines mandatory target levels of recovered materials from scrapped batteries for cobalt, copper, lead, lithium and nickel,

[3]The 2006 directive is not limited to Li-ion batteries, but the whole battery sector.
[4]Targeted sources of pollution involved cadmium, mercury and lead
[5]25% by 2012, 45% by 2016
[6]Unlike directives, regulations are automatically applied in EU members, without any transposition into national law. It results in a uniform effect for all the Union, in line with the objective of creating a coherent industrial sector at EU scale. See `https://europa.eu/european-union/law/legal-acts_en` for more details.

as displayed in Table 1. It is expressed in shares of these minerals as well as on total weight of the batteries.[7]

To the best of our knowledge, most of the proposal and in particular the minimum thresholds on recycling come from a feasibility study ordered by the EC (European Union: European Commission et al., 2021a,b). They present a number of measures to improve the 2006 directive. They are based on a modelling assessment complemented with interviews with stakeholders. To compute the thresholds, authors set up a material flow model to assess the availability of minerals to be recycled in the upcoming years. By doing so, the proposed thresholds later used by the EC are set to match available materials for recycling. It appears that the proposed minimum thresholds of recycled contents match high estimates considering the availability of recycled material.[8] Furthermore, the impact of different parameters stemming from the technological and economical context given by IEA reports are not quantitatively discussed in the report (IEA, 2020, 2021a,b). In this paper, we propose to fill this gap by investigating in particular the impact of demand growth, lifespan of batteries, recycling efficiency and technological changes.

3. Qualitative Insights

Having clarified the European context, we now provide the intuitions that will serve the reasoning presented in the quantitative sections which follow. Assessing the minimum thresholds of incorporated recycled materials given by the EC proposal can be done by computing the maximum ratio of recycled waste material over demand (RMD ratio hereafter).[9] As in the impact studies that inspired the EC proposal, such ratios can be estimated with complex dynamic material flow analysis, which requires a large number of hypothesis and data. We argue that a simplified version of such models is useful to draw the essential drivers of this dynamics.

We compute the RMD ratio in a two-period model ($t = 0, 1$). Each period, a quantity Q_t of batteries for electric vehicles are produced (in kWh), given a technology mix that requires an average intensity $w_{k,t}$ for each material k (in kg/kWh). At period 1, a quantity $P_{0,1}Q_0$ of battery is scrapped. These wastes are recovered and recycled with an overall efficiency $\epsilon_{k,1}$. For each material k, we define $RMD_{k,1}$ as the ratio of recycled material from battery wastes over demand at period 1. Such ratio can be decomposed as follows:

[7] After 2025, 75% of lead batteries, 65% of Li-ion batteries and 50% of other battery waste.

[8] Note a lower recovery rate for lithium. Indeed, the current state of lithium recycling technologies make it harder to recover it (a baseline of 10% in 2018 according to European Union: European Commission et al. (2021b), matching other studies such as (Hache et al., 2019) mentioning low effective rates), thus involving lower recovery targets than nickel and cobalt.

[9] Such ratio corresponds to the maximum amount of material that can be recycled from yearly scrapped batteries and incorporated in new manufactured batteries.

$$RMD_{k,1} = \underbrace{P_{0,1}}_{\text{Scrapping probability}} \underbrace{\frac{Q_0}{Q_1}}_{\text{Demand change}} \underbrace{\frac{w_{k,0}}{w_{k,1}}}_{\text{Technological change}} \underbrace{\epsilon_{k,1}}_{\text{Recycling efficiency}} \tag{1}$$

Such decomposition, shown in equation (1) involves four terms, two of which being material-specific, while the other two are material-neutral.

- $P_{0,1}$ is the fraction of battery turned into waste and scrapped between the two periods. It is mainly linked to the average lifetime of batteries through the stochastic process of battery degradation. In particular, this fraction is reduced with higher average lifetimes, which can be caused by technological improvements or by the re-utilisation of used battery for other purpose.

- ratio Q_0/Q_1 of battery capacity demand at period 0 over period 1 relates to the evolution of demand for battery capacity. The larger is the development of electromobility,[10] the lower this ratio is. This ratio is supposed to be large during the uptake of electromobility, and converge to one as fossil fuel cars are phased out.

- ratio $w_{k,0}/w_{k,1}$ in material intensities k in period 0 over period 1 relates to the technological change of batteries. Such ratio decreases as battery technology requires lesser quantities of material k. Material footprint may decrease as a whole and there may be material substitutions, as displayed later when discussing our data (see Tables 3 and 4).

- $\epsilon_{k,1}$ is the fraction of recovered material from battery wastes. It encompasses both the collection of battery wastes and the efficiency of recycling processes. Contrary to the other components, this parameter may be the most crucial in economic terms as collecting a high share of disposed batteries or recycling at higher rates can involve very large marginal costs on recycling. Also, it has been indicated that it can be difficult to reach high recycling efficiencies for some material, such as lithium, with the same recycling process. One recycling process can foster the recovery of a material at the expense of another (Xu et al., 2020).

This decomposition can be illustrated with a numerical example. Let's consider a 10 years time lapse. During this period, consider that demand quintuples ($Q_0/Q_1 \approx 0.2$), material intensities remain steady $w_{k,0}/w_{k,1} \approx 1$, recycling is almost perfect ($\epsilon_k \approx 1$), and 40% of batteries produced in year 0 are scrapped in year 10 ($P_{0,1} \approx 0.4$). In this case, the ratio $RMD_{k,1} \approx 0.08$. Such ratio is in the range of the minimum thresholds given by the EC proposal.

[10]Such development includes both the number of vehicles and battery size. Battery size will increase with the autonomy of electric vehicles, and should converge once autonomy of electric and thermal vehicles become close.

4. Quantitative Analysis: Methods

4.1. Model

The previous section exhibited the main drivers for the ratios of recycled material over demand. This following section aims at quantitatively estimating these levels and confronting them to the EC targets. We model the material flow of Li-ion batteries in the EU at both extremities of the lifecycle with yearly periods corresponding to 2020-2035: the demand of batteries (by extension related to the market for EVs) and the waste aggregation following the end-of-life. Note that this model can be seen as a sophisticated extension of the decomposition previously discussed. The underlying variable for the flow of batteries is the aggregate flow $F_{k,t}$ (in kg) for a specific material k at year t:

$$F_{k,t} = \sum_i \sum_j Q_{i,t} m_{j,t} w_{j,k} \tag{2}$$

This flow is summed for all types of EVs i and all technologies of Li-ion batteries j. $Q_{i,t}$ is the aggregated capacity (in kWh) from EVs of type i sold each year, and is computed as the product of the number of vehicle of type i with their related average battery size. $m_{j,t}$ is the market share of a battery technology and $w_{j,k}$ is the material k intensity of a specific technology j (kg/kWh).[11] The definition of indexes $\{i, j, k, t\}$ is summed up in Table 2. Differences between Li-ion battery technologies mainly stem from the conception of the cathode.

Index	Name	Description
i	EV types	cars BEV, cars PHEV, vans BEV, vans PHEV[a]
j	Li-ion battery technology	ASSB, LMO, LFP, NMC333, NMC532, NMC622, NMC811, NCA+[b]
k	material	copper, lithium, nickel, manganese, cobalt, graphite
t	time	2020 to 2035

[a] BEV: battery electric vehicle; PHEV: plug-in hybrid electric vehicle
[b] ASSB: solid-state; LMO: Lithium-Manganese-Oxyde; LFP: Lithium-Iron-Phosphate; NMC: Nickel-Manganese-Cobalt; NCA: Nickel-Cobalt-Aluminium

Table 2: Indexes of the model

Each battery (i, j) in use has a probability $P_{i,j,\tau,t-\tau}$ to be scrapped, where τ is the year of production of the battery, hence $t - \tau$ is the age of the battery. This allows us to compute for each year t the flow of waste from production year τ for material k when no decay or recycling takes place:

$$B_{k,\tau,t} = \sum_i \sum_j V_{i,\tau} b_{i,\tau} m_{j,t} w_{j,k} P_{i,j,\tau,t-\tau} \tag{3}$$

[11] Contrary to the qualitative analysis, material intensity $w_{j,k}$ is not time related, as it relates to a specific technology whose market share will evolve through time.

The probability $P_{i,j,\tau,t-\tau}$ follows a Weibull distribution calibrated with minimum, maximum and most likely lifespans of Li-ion batteries. We use a Weibull distribution as the literature shows that it fits well the lifecycle of durable goods (Xu et al., 2020; Elshkaki, 2005; Melo, 1999; Spatari et al., 2005).[12] Finally, we can compute for each year t the aggregated waste flow of material k:

$$W_{k,t} = \sum_{\tau=0}^{t-1} (B_{k,\tau,t} - B_{k,\tau,t-1}) \tag{4}$$

Finally, the ratio of recycled material over demand (RMD ratio) for each material k can be computed as follows:

$$RMD_{k,t} = \frac{\epsilon_{k,t} W_{k,t}}{F_{k,t}} \tag{5}$$

with $\epsilon_{k,t}$ the efficiency of the material recovery process. It includes physical collection of used batteries from used cars as well as the efficiency of recycling processes.[13]

Following the decomposition from the qualitative analysis, we elaborate several scenarii that aim at investigating the influence of demand evolution, battery lifespans, technological change and recycling efficiencies.

4.2. Data

The main source of data for the calibration of the model comes from recent IEA reports (IEA, 2020, 2021a). Projections of the EV market in 2025 and 2030 comes from (IEA, 2020). We use a quadratic interpolation to get the evolution of the total EV battery demand (in kWh) for the range 2020-2035, with the two different scenarii studied in IEA reports. Battery sizes are also calibrated using these reports. The Stated Policies Scenario (*STEPS*) relies on already existing and announced policies and their expected consequences on the development of electromobility. On the other hand, the Sustainable Development Scenario (*SDS*) is more ambitious and built in order to meet the Paris Agreement objectives. The extension of the demand curve up to 2035 is made with the hypothesis that the EV fleet does not yet reach its final deployment. Figure 1 shows the projections for battery demand. Note that a growing divergence between scenarii occurs after 2025, resulting for the *SDS* scenario in a twice larger demand in 2030 than for *STEPS*, and even more for 2035. Comparing these two scenarii allows to assess the effect of demand dynamics, which was the first component of the decomposition of the qualitative analysis.

Material intensities of each battery cell technology $w_{j,k}$ are taken from IEA reports and (Xu et al., 2020) and shown on Table 3. We linearly interpolate projected market shares $m_{j,t}$ of battery technologies

[12] We also computed our model with a gamma function, with very little difference in the results that do not alter the policy implications.

[13] Due to the lack of data, we neglect material losses from the use of batteries.

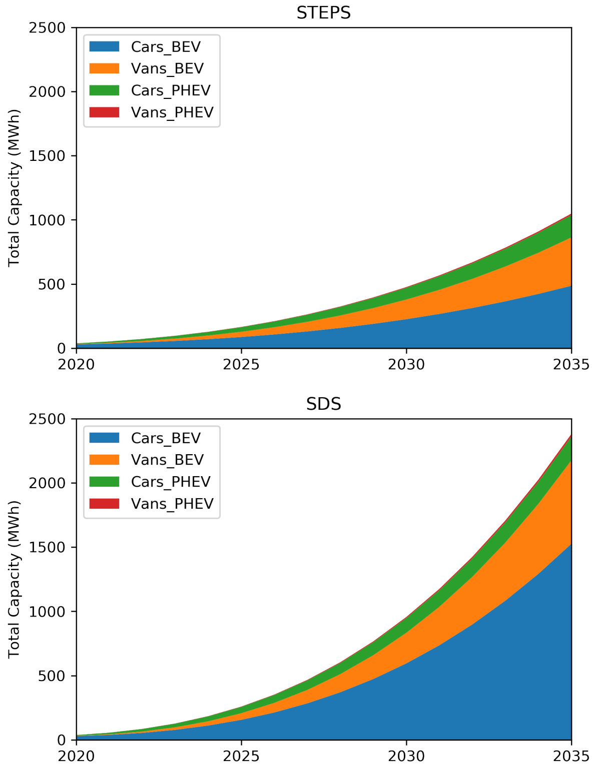

Figure 1: Projected EV batteries growth for two demand scenarii (extrapolated from IEA)

from the IEA (2021b) as shown in Table 4, given for up to 2040, consisting in the main technological scenario.

The projections of the IEA in Table 4 show a technological change that shifts from cobalt/manganese-based toward nickel-based batteries. This is caused by the phase-out of NMC333 batteries in favor of NMC811 with higher nickel incorporation rates. Another key feature of this technological change is the rise of solid-state batteries (ASSB), with an important reduction in material use among which cobalt and nickel.

Battery Type	Lithium	Nickel	Cobalt	Manganese	Graphite	Copper
ASSB	0.174	0.000	0.000	0.000	0.000	0.293
LMO	0.107	0.000	0.000	1.400	0.867	1.040
LFP	0.093	0.000	0.000	0.000	1.027	1.067
NMC811	0.093	0.587	0.080	0.067	0.907	0.853
NMC622	0.107	0.533	0.187	0.160	0.907	0.880
NMC532	0.160	0.507	0.200	0.280	0.907	0.907
NMC333	0.160	0.347	0.360	0.307	0.907	0.933
NCA+	0.107	0.773	0.027	0.000	0.907	0.853

Table 3: Battery Composition for each battery type. Values are given in kg/kWh.

In order to assess the impact of the evolution of material intensities, due to technological change, alternative scenarii are developed and summarized in Table 4, all considering a demand from the *STEPS* scenario. First, in scenario *status-quo*, market shares are maintained at their 2020 levels. Within it, battery manufacturing remains intensive in cobalt. Second, the scenario *ASSB+* simulates a large

Scenario	Historic	*main*		*status quo*		*ASSB+*		*LFP+*	
Year	2020	2030	2040	2030	2040	2030	2040	2030	2040
ASSB	0	0.7	31	0	0	1.4	62	0.4	21.8
LMO	2	0	0	2	2	0	0	0	0
LFP	6	10	9	6	6	9.9	5	40	36
NMC811	15	60	53	15	15	59.6	29.2	40	37.3
NMC622	29	11	4	29	29	10.9	2.2	7.3	2.8
NMC532	22	7.6	0	22	22	7.5	0	5.1	0
NMC333	6	1	0	6	6	1	0	0.7	0
NCA+	20	9.7	3	20	20	9.7	1.6	6.5	2.1

Description of technological scenarii:
- *main*: Main scenario given used in IEA reports
- *status-quo*: market shares stay at the 2020 level
- *ASSB+*: Strong breakthrough of solid-state batteries (doubled market share)
- *LFP+*: Strong breakthrough of LFP batteries in 2030-2035 (four fold increase)

Table 4: Description technological scenarii with their respective market shares (in %).

penetration of ASSB batteries. It leads to an important decrease in material use, especially nickel, manganese and cobalt, due to the technological breakthrough. Third, the scenario *LFP+* is built to show an important market share of LFP batteries. It shows lower needs for nickel, manganese and cobalt. For the last two scenarii, proportions for other market shares are kept the same.

The Weibull distribution function is calibrated with the most likely lifetime for the battery, and minimum/maximum set at 99,7% of the distribution. There is a lack of knowledge regarding the lifespan of EV batteries, as the market is still at its early stage of development. For the specific case of electric vehicle, we find shorter lifespans in the literature, with 8 to 10 years (Casals et al., 2017, 2019). Lifespans of batteries are often high estimates in studies, with the example of Xu et al. (2020) who take an average of 15 years based on generic studies on automobiles. Our main scenario follows a most likely lifetime of 10 years. For sensitivity purposes, we also test scenarii with shorter lifespans, as described in Table 5, as well as longer as some emerging uses of batteries such as second life could postpone the year of recycled material availability (Martinez-Laserna et al., 2018). We use demand from the *STEPS* scenario for these ones.

Scenario	Minimum	Most likely	Maximum $(99,7\%)$
shorter lifetime	1	8	18
main	1	10	20
longer lifetime	1	12	22

Table 5: Description of scenarii on lifespans and other relevant parameter for the Weibull function of batteries (in years)

Recycling efficiencies $\epsilon_{k,t}$ are set with the targets of the proposal of the EC (Table 1), and linearly interpolated between 2020 and 2026, and between 2026 and 2030, and are constant after 2030. Note that the EC aims at a recovery rate for lithium going from 35% in 2026 to 70% in 2030, while it is around 10% in 2020 (European Union: European Commission et al., 2021b), hence an optimistic seven-fold increase in a decade. We also test a scenario *low efficiency*, with demand from *STEPS*, where we maintain recycling efficiencies at their current 2020 levels, with 80% efficiency for both cobalt and nickel, and 10% for lithium.[14]

5. Quantitative Analysis: Results

This section presents the results of the quantitative analysis. It focuses on the computation of the ratios of recycled materials over demand in new batteries (RMD ratios) up to 2035. First, it presents the evolution of these shares for each material for the two IEA scenarii *STEPS* and *SDS*. Then, it successively shows the impacts of battery lifespans, battery technological change and recycling efficiencies on RMD ratios.

5.1. Evolution of RMD Ratios and Effect of Demand Growth

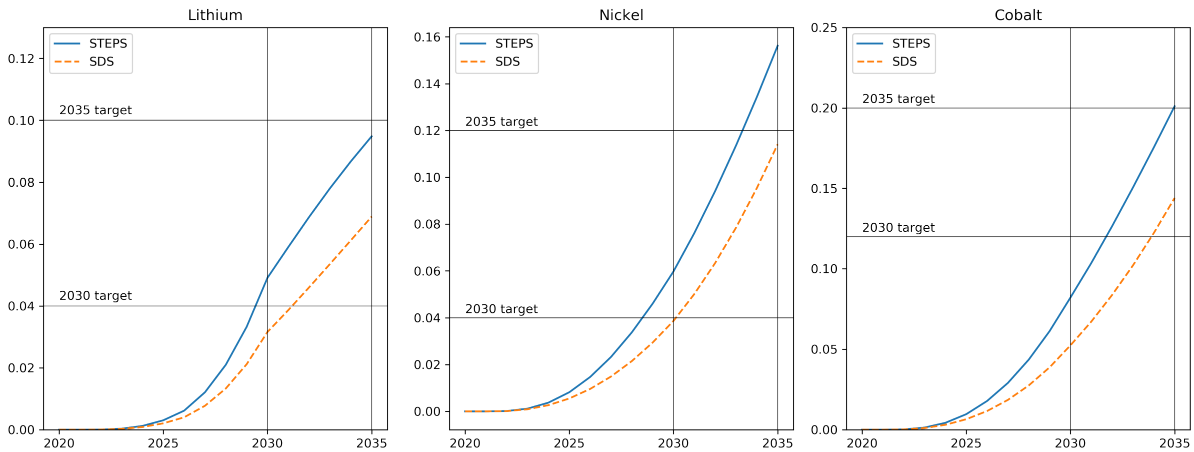

Figure 2: Ratios for Li, Ni and Co (policy objectives in dashed lines)

Evolutions of RMD ratios are displayed for lithium, nickel and cobalt on Figure 2. For both demand scenarii, all RMD ratios are increasing. It indicates that the amount of available waste that can get recycled grows faster than the demand in new batteries. Indeed, demand grows at a fairly constant rate, while available wastes grow faster due to the specificity of the degradation process, where the probability of becoming wastes grows up to the most likely lifetime, around ten years here, then decreases.

Figure 2 also displays EC minimum thresholds for 2030 and 2035. These targets are only partially met. Regarding lithium, targets are only reached in 2030 under the *STEPS* scenario. It results from a combination of low recycling efficiency compared to other materials (70% after 2030) and the use of lithium intensive technologies. In the case of nickel, targets are met under *STEPS* scenario for both 2030 and 2035 targets, while under *SDS* they are barely met in 2030 and below the objective in 2035. Cobalt targets, which are much higher than for nickel and lithium, are in both cases not reached in 2030 and 2035, despite the early shift from cobalt/manganese to nickel. This transition makes relatively high

[14] As indicated as the 2020 baseline for material recovery rate in (European Union: European Commission et al., 2021b).

amounts of cobalt available later in 2035 thanks to a decreasing demand, which explains that targets are almost reached for the *STEPS* scenario.

The comparison of *STEPS* and *SDS* scenarii highlights a conflict between a faster growth of electromobility and material sourcing from recycling. Faster demand growth in minerals makes it harder to achieve relatively high amounts of recycled inputs in new batteries. This indicates that while demand grows much faster in the SDS scenario than in STEPS, the difference between waste production growth is less significant.

5.2. Effect of the Battery Lifespan

	Lithium		Nickel		Cobalt	
Lifetime	2030	2035	2030	2035	2030	2035
8 years	**0,10**	**0,14**	**0,12**	**0.24**	**0.16**	**0.29**
10 years	**0.05**	0.09	**0.06**	**0.16**	0,08	**0,20**
12 years	0.02	0.06	0.03	0.09	0.04	0.13

Table 6: Ratios of recycled materials over demand (RMD ratios) for alternative battery lifetimes with the *STEPS* demand scenario. Values of RMD ratios above the respective EC minimum threshold are written in bold.

We perform a sensitivity analysis on the most likely lifespan of batteries, according to Table 5. Results are shown in Tables 6 for the *STEPS* demand scenario. RMD ratios are very sensitive to average lifetime changes. For a lifespan up to 12 years, available metals for recycling barely reach 4% in 2030 for all metal inputs. Indeed, longer lifetimes impliy lower waste rates on the short run, as secondary materials are later available for recycling.

Oppositely, with shorter lifespans (8 years), meaning that batteries are more often replaced, EC targets can more easily be met.[15] Hence, the impact of battery lifespans seems much larger than the effect of demand growth, while differences between *STEPS* and *SDS* scenarii were up to a factor two impact on the demand. In the case of lifespans, a 20% increase or decrease (from 12 to 8 years) leads to much larger differences in RMD ratios.

This result has implications regarding the development of second life of batteries. In this scenario, EV batteries are being refurbished when they do not meet EV power standards and are used for stationary storage, which could increase the economic value of batteries (IEA, 2020; Martinez-Laserna et al., 2018). A well developed second-life sector significantly extends battery lifetimes, and therefore limits the availability of recycled materials for reaching their sustainability objectives. Furthermore, lifespans of batteries could be increased a lot more than 12 years according to Martinez-Laserna et al. (2018), with technical requirements and economic profitability being the main drivers of life durations. However, this demand for second-life should be nuanced as stationary energy storage is expected to be a minor share of the overall EU demand in capacity in the following years (Martinez-Laserna et al., 2018).

[15] Here we examine this effect *ceteris paribus*, meaning we do not consider an impact of lifespans on demand growth of batteries.

5.3. *Effect of Technological Change*

	Lithium		Nickel		Cobalt	
Scenario	2030	2035	2030	2035	2030	2035
status-quo	**0.04**	**0.10**	**0.06**	**0.13**	0.06	0.13
main	**0.05**	0.09	**0.06**	**0.16**	0.08	**0.20**
ASSB+	**0.05**	0.09	**0.06**	**0.19**	0.08	**0.24**
LFP+	**0.05**	**0.10**	**0.08**	**0.18**	0.11	**0.25**

Table 7: Ratios of recycled materials over demand (RMD ratios) for alternative technological scenarii with the *STEPS* demand scenario. Values of RMD ratios above the respective EC minimum threshold are written in bold.

After having discussed the influence of demand evolution and battery lifespans on the different RMD ratios, this section discusses alternative technological scenarii. Detailed in Table 4, each alternative scenario represents a characteristic trend, with demand following the *STEPS* scenario. Results show little differences in RMD ratios across scenarii as soon as batteries become less cobalt-intensive. This contrasts with the large sensitivity shown by battery lifespans.

As stated in the qualitative section, the effect of technological change is heterogeneous between materials. Indeed, all RMD ratios for lithium (resp. nickel) are in the range 0.04-0.05 (resp. 0.06-0.08) in 2030 and 0.09-0.10 (resp. 0.13-0.19) in 2035. In particular, despite the lithium intensity of ASSB batteries, similar RMD ratios are reached in 2035 for *ASSB+* and *main*, explainable by the early use of NMC333/532 with high lithium contents. The only deviation happens for the RMD ratio of cobalt under the *status-quo* scenario. In 2035, the RMD ratio is 0.13 compared to 0.20-0.25 for the other scenarii. Indeed, the *main* scenario as well as the *ASSB+* and *LFP+* scenarii show a significant decrease in cobalt intensity, especially after 2030. As this transition reduces its demand, RMD ratios for cobalt increase.

5.4. *Effect of Recycling Efficiencies*

	Lithium		Nickel		Cobalt	
Scenario	2030	2035	2030	2035	2030	2035
low efficiency	0.01	0.01	**0.05**	**0.13**	0.07	0.17
main	**0.05**	0.09	**0.06**	**0.16**	0.08	**0.20**

Table 8: Ratios of recycled materials over demand (RMD ratios) for an alternative recycling efficiency scenarii with the *STEPS* demand scenario. Values of RMD ratios above the respective EC minimum threshold are written in bold.

Finally, we also estimate the influence of recycling efficiencies in our results. As explained above, our *main* scenario is based on the EC targets for recovery rates in 2026 and 2030, with *STEPS* demand. They can include a very high increase, in particular for lithium (from 10% efficiency in 2020 to 70% in 2030). It implies key developments in terms of technology and cost reductions. With scenario *low efficiency* (with *STEPS* demand too), we compute RMD ratios when recycling efficiencies do not change after 2020 (10% for lithium and 80% for both nickel and cobalt), thus remaining especially low for lithium . As expected, given the linearity of the recycling efficiency in the model (in equation (5)) important change occurs for lithium, with RMD ratios dropping to 0.01 (Table 8). To a lesser extent, RMD ratios for nickel and cobalt also drop, though recycling efficiencies were not expected to increase with the same magnitude.

6. Conclusion and Policy Implications

With its regulation proposal, the EC tries to cope with the fast-paced evolution of innovation and market development of Li-ion batteries. The ambition of the EC is to create conditions for the development of a local industry for electric vehicles while securing the different stages of its supply chain and limiting the life-cycle environmental impacts. This implies securing the sourcing of the necessary critical minerals to produce batteries. Developing a recycling industry would be a way to limit risks of geological scarcity and geopolitical tensions. This paper discusses one of the main features of the proposal, which aims at enforcing the incorporation of minimum shares of recycled material in new batteries from 2030. Our approach is to disentangle the different key-assumptions for the calculations of such targets. Using a material flow model, we find that the targets given by the proposal are physically attainable under very specific assumptions on characteristics of battery technologies, recycling processes, and the evolution of demand. In particular, most of the targets given by the European Commission are not met for average battery lifetimes beyond 10 years. Keeping average battery lifetimes at 10 years might be unrealistic given the technological progress in the battery sector. To a lesser extent, we notice that meeting this target is even more difficult when the demand growth rate is high and recycling efficiencies are low. Heterogeneity between materials is also observed due to technological change and specific recycling efficiencies.

This study sheds light on several consequences of EC regulation. First, the targets set by the EC are very likely to be too high to be realistic, given market growth, battery usage, and the expected technological framework. On the one hand, setting optimistic targets gives a powerful signal to industrial stakeholders, from battery and car manufacturers to the recycling industry. For instance, it guarantees producers of recycled material the existence of a demand for recycled input, thus encouraging a needed investment in the sector. On the other hand, setting unrealistic targets undermines the readability and stability of the regulation. We believe that too optimistic targets will severely increase the risk of needing downwards revisions, which would alter the credibility of the regulation. This study indicates that battery lifetime is the most sensitive parameter driving recycling. Hence, setting high targets could give incentives to decrease battery lifetimes. Indeed, shorter lifetimes would allow a faster circulation of material in the economy, thus increasing the potential use of recycled material. However, increasing lifetimes could be an objective in itself, as it would decrease material use.

Therefore, the policy recommendations of this study are twofold. First, we believe that the regulations should incorporate robust targets. Although it is stated that targets may be changed in the future, industrial actors of the sectors (battery and cars manufacturers, recycling industry) would need readable and credible regulations to make the right investments and technology choices. While this study indicates that the proposed targets may be difficult to reach, we believe it would be appropriate to propose lower targets for each material. Second, we believe the regulation could include other complementary indicators. Indeed, developing a sustainable battery sector should not rely on recycling and recycled content targets only. As our results indicate that battery lifetime is the main driver of recycled material incorporation in new batteries, we believe it would be adequate to set quantitative objectives on this matter. It could include precise targets on the lifetime of the battery, either regarding the lifetime in the electric vehicle only, or the total lifetime, which could include eventual repurposing of used batteries.

Further research could complete our analysis in three directions. First, an analysis that incorporates strategies from the supply side to comply with the regulation can be made. For instance, battery wastes or recycled materials could be accumulated years before the start of the regulation and be incorporated in new batteries only once the regulation applies. There could also be strategies to meet recycling targets by extending the source of recovered material to other industries or geographical areas. However, this reasoning bears several limits: a significant part of total production of lithium and cobalt is already used for the battery industry, leaving relatively small amounts for recycling from other industries, especially with an exponentially growing sector; it is not in the spirit of the EC proposal which aims at regulating a specific sector, in this case the battery sector; it suggests coordination between different industries and the possibility of incompatible usage of materials; and, regarding environmental considerations, it would only result in a displacement of the material sourcing problem. Second, our sensitivity analysis could be enriched by accounting for the different links between the main parameters. For instance, larger battery lifetimes should also decrease battery renewal, hence new battery demand. Battery lifetimes should also differ between technologies. Third, the analysis could be improved by a resource economics approach, in order to assess how imposing recycling contents forces a demand for recycled material and how it affects prices on markets for primary and secondary materials.

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