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The EV transition: The impact of the EU battery directive on critical material supply, recycling and battery costs

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ABSTRACT

Lithium-ion batteries (LIBs) are central to the European Union's (EU) Net Zero strategies. Yet, rising regulatory pressures and geopolitical tensions have increased the risk of supply chain bottlenecks for strategic and critical materials such as nickel and cobalt, posing threats not only to the EU's decarbonisation agenda but also to global Net Zero ambitions. In response, EU policymakers have accelerated efforts to develop local battery ecosystems including the recycling of end-of-life LIBs. However, the potential impact of these interventions on material dependencies and battery economics is not well understood. This paper introduces a novel policy-economic framework to assess the prospective evolution of the LIB recycling sector in response to policy changes introduced by the EU Battery Regulation (Regulation (EU) 2023/1542). In particular, drawing on an industry-led survey, the framework evaluates the impact of the mandated minimum recycled content on material flow and battery costs. The results reveal that the Battery Regulation may increase battery cell costs by up to 15 %. While this study is EU-specific, its findings carry broader relevance for international battery policy and market dynamics and provides new evidence on how international policies may impact the future of the battery sector.

1. Introduction

As the EU continues to follow a path towards Net Zero, lithium-ion batteries (LIBs) have become a key enabler for the energy transition providing an opportunity for renewable energy integration and a faster adoption rate of electric vehicles (EVs) (Marty and Ruel, 2025; Schreiber et al., 2022). As such, LIB key materials such as lithium (Li), cobalt (Co), graphite, and nickel (Ni) have become instrumental. The EU commission considers materials critical if they are of high economic importance for the whole European economy and are facing supply risks and includes Co and Li.[1] Materials like Ni are considered strategic due to their importance in achieving the EU's strategic objectives of addressing global supply-demand imbalances and overcoming challenges with scaling up production (European Commission, 2024).[2] Therefore, the ability of countries to secure a supply of these strategic and critical raw materials is central to their push towards Net Zero (Sattar et al., 2020; Sommerville et al., 2021; World Economic Forum, 2019).

The urgency of the situation has been recognised by governments across the world leading to strategies, policies, and legislations aimed at securing access to critical materials. National policies include the UK's Critical Minerals Strategy (Department for Business and Trade and Department for Business, Energy & Industrial Strategy, 2022; IEA, 2025), the US Inflation Reduction Act (IEA, 2025; US Department of Energy, 2024), China's Industry Standard Conditions for Comprehensive Utilization of Waste Power Batteries of New Energy Vehicles (2024 Edition) (IEA, 2025; Ji and Hu, 2024), Australia's National Waste Policy Action Plan (Department of Industry Science and Resources, 2024; Federal Register of Legislation, 2024; IEA, 2025) and the EU's new

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[1] The Critical Raw Material Act identified materials considered critical and strategic for the European economy (European Commission, 2024).

[2] Strategic Raw Materials are a subset of Critical Raw Materials that are critical to achieving EU's strategic objectives (i.e. green transition, digital development and space and defence applications).

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Battery Regulation (Regulation (EU) 2023/1542 introduced in 2023) which is part of Europe's Green Deal and repeals Directive 2006/66/EC (European Commission, 2021; European Parliament, 2021; European Union, 2023; Santos, 2023).

Despite the importance of LIBs, there are only a limited number of assessment tools that allow stakeholders to evaluate the future implications of national policies for battery demand, supply chains, material recycling, and overall battery costs. The challenge is exacerbated by barriers to knowledge exchange between stakeholders such as battery manufacturers, automotive original equipment manufacturers (OEMs), recyclers, policy makers, and academia. The purpose of this paper is to help academics and policymakers to better understand the challenges within the LIB supply chain and the interactions between the various stakeholders as well as to analyse how policies can impact the economics of LIB battery manufacturing and recycling.

The contribution of this paper is three-fold. First, a novel policy-economic framework is introduced which links the EU battery legislation with a material flow analysis and battery price projections to enable researchers to estimate how battery markets may respond to policy changes. Second, by gathering and sharing valuable insights from world-leading battery industry representatives on the potential evolution of the battery recycling market, the analysis allows researchers, OEMs and policymakers to develop targeted strategies in response to future policy developments. Third, the EU Battery Regulation is used to demonstrate the applicability of the policy-economic framework approach and policy recommendations are provided.

The EU Battery Regulation is one of the more notable regional policies that covers LIBs and was introduced in 2023 to increase the resilience of the EU battery materials supply chain and to improve its sustainability (European Parliament, 2022; European Union, 2023). Most importantly, the Regulation sets recycling efficiency targets (80 % from 2031 onwards) and defines a mandatory minimum level of recycled content (16 % for Co, 6 % for Li and Ni, respectively) in newly manufactured battery cells produced for the EU market (Cobra, 2022; European Parliament, 2021, 2022; PreScouter, 2022; Santos, 2023). Consequently, the EU Battery Regulation has raised questions regarding the availability of recycled battery material needed to fulfil the required minimum recycled content. Such developments position recycled battery material as a new type of critical material.

The existing literature touches on the critical material supply chain for LIBs and several reports have highlighted potential supply chain bottlenecks for virgin materials. Olivetti et al. (2017) report that while the supply of virgin Li and Ni would be sufficient to meet the demand for LIBs in the near future, the demand for virgin Co could exceed supply. Similarly, Maisel et al. (2023) in their technology and growth scenarios, estimate that in 2040 the demand for virgin Li and Co could exceed today's supply by up to eight times. To estimate the impact on prices, Boer et al. (2023), evaluate demand shocks for LIB metals and predict that prices of virgin Co, Li, and Ni could increase by several hundred percent from their annual average levels in 2020. They further projected that prices would remain high for more than a decade, far longer than previous peak periods.

Previous studies of the Battery Regulation from a recycling perspective include Ginster et al. (2021) who assessed the impact on recycled materials availability and the environmental implications and identified that post-production waste would become an important recycling feedstock to meet the specified levels of recycled materials. Hoarau and Lorang (2022) investigated the conditions required to fulfil the minimum recycled content of the EU Battery Regulation using a material flow model and concluded that battery lifetime would a the key factor in achieving these mandated targets. The authors recommended lower regulatory targets and to consider battery lifetime in the regulations (Hoarau and Lorang, 2022). Wesselkämper et al. (2024) conducted a systematic analysis of the impact of various strategies on primary raw materials demand and recycled materials supply in order for the EU to reach full circularity. The strategies include accelerated electrification through EV sales, the reduction of EV battery size, second life applications, and using three different battery cathodes. The authors reveal that these strategies are essential to achieve cost savings in terms of mining and recycling investment and CO_2-equivalent emission reduction (Wesselkämper et al., 2024).

Besides the above-mentioned impacts, changes in the demand and supply of recycled materials caused by the EU Battery Regulation might also alter the prices of battery materials and hence battery costs. This aspect, however, has not yet been analysed in previous studies. This paper therefore seeks to build on these previous studies and takes a resource economics approach to assess the economic impact of the EU Battery Regulation on primary and secondary materials prices and battery costs. More specifically, this paper builds on the material flow analysis studies reviewed in Wesselkämper et al. (2024), extending their approach by combining it with additional analytical tools to assess the potential economic impact of the minimum recycled content and mandated recycling efficiencies on EV batteries in the EU.

Central to this paper is that the impact of the EU Battery Regulation on the battery recycling market remains unclear due to both changes in demand and supply dynamics of virgin and recycled materials. This means that there are considerable materials price uncertainties and unknown knock-on effects of price changes. For example, the relatively volatile prices of virgin materials may make incorporating recycled materials into the supply chain more attractive and further stimulate demand (Zhou et al., 2022). On the other hand, the prices of recycled materials may closely track the prices of virgin materials and offer no significant price benefits other than being a more secure source of supply.

To answer these key questions, first, an updated and detailed material flow analysis is conducted to assess the supply-demand gap of recycled materials within the EU. Second, we combine projections of raw material prices, derived from a selected econometric model, with expert elicitations to develop different price scenarios for recycled materials. Then, specialised techno-economic models, namely BatPaC and EverBatt, are used to translate these evolutions into changes in the costs of battery cathodes, cells, and packs of various LIB cell chemistries ($LiFePO_4$ (LFP), $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA) and $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811)), which conform with the EU Battery Regulation (Argonne National Laboratory, 2024; Nelson et al., 2019).

Of importance for the community is that the novel policy-economic framework introduced here can be extended beyond battery recycling and is applicable to other technologies, legislations and regions beyond the EU, supporting industry stakeholders, OEMs, and policy makers in their decision-making process.

The paper applied the following research approach: First, the policy-economic framework is presented (Section 2) detailing the three main policy assessment steps. Second, in Section 2.1, the supply of recycled Li, Ni, and Co in the EU compared to the projected demand is assessed including a sensitivity analysis of the impact of recycling efficiency and collection rate on the amount of available recycled materials. Third, Section 2.2 discusses and analyses the findings of the industry-led survey, which informed the development of four price scenarios for recycled materials by 2030 (Section 2.2.b). Finally, based on the predicted prices of the recycled materials, battery cell and pack costs containing the required minimum recycled materials content are assessed (Sections 2.3). Sections 3 and 4 describe the results and discuss the potential implications.

2. Methodology and objective

The objective of this study is to assess the possible impact of recycling policies on first, the battery supply chain (i.e. supply-demand gap), second, prices for primary and secondary materials, and third, battery cathode, cell and pack costs. To this end, an integrated approach combining a material flow analysis, a material price assessment, and an industry survey was applied.

Fig. 1 illustrates the three key steps the policy-economic framework developed in this paper follows to assess the potential effects of the EU Battery Regulation on its local battery market.

The framework includes following steps:

1. Supply and demand analysis: With the EU Battery Regulation pushing for the use of recycled metals in new batteries by 2030, the demand for recycled materials is expected to see a steep increase. However, the question remains whether supply will be sufficient to meet this demand. Furthermore, it is important to understand whether the EU recycling industry is ready to meet the expected increase in demand. Step 1 assesses the supply and demand of virgin and recycled battery materials. A potential supply-demand mismatch serves as the rationale for the price analysis in Step 2. The supply and demand analysis for recycled Li, Ni and Co is based on cathode demand and the amount of End-of-life (EOL) LIBs such as EV, manufacturing scraps and portable batteries, available for recycling. Data is obtained from the Advanced Propulsion Centre (APC) and Circular Energy Storage Online (CES Online) (with an assumed 80 % recovery efficiency).
2. Price projection and scenario analysis: Assessing how battery materials prices will evolve with an increase in demand as demonstrated in Step 1 is key as it could impact how the battery and recycling industries develop. Scenarios are proposed to demonstrate possible market directions. The price analysis in this step provides the input parameters for Step 3 where recycled metal prices are used to assess how cell and pack costs will develop. This analysis is based on price data from the International Monetary Fund (IMF) and US Geographical Survey commodity prices. Recycled material prices are estimated as a percentage of virgin material prices.
3. Battery cell and pack cost: The study models systemic battery price effects by conducting a techno-economic assessment of how the mandated minimum recycled content influences the overall cost of battery cells and packs, compared to configurations using 100 % virgin materials. To this end, BatPaC and EverBatt were used (Argonne National Laboratory, 2024; Nelson et al., 2019) to simulate cost outcomes across three battery chemistries: NCA, NMC811, and LFP. While the analysis does not explicitly model producer compliance costs (such as fees paid to join producer responsibility organisations or compliance schemes, registration, reporting, and auditing costs or consulting costs for regulatory monitoring and compliance management) it assumes some of them are embedded in the green premium between recycled and virgin materials. This premium feeds into the modelled cost channel and indirectly affects battery cell and pack prices.

2.1. Material flow analysis

2.1.1. Supply-demand analysis of recycled materials

The first part of the paper aims to answer the question whether there will be sufficient recycled material available in Europe to fulfil the demand induced by the minimum recycled content targets set in the EU Battery Regulation. Understanding the criticality of the situation with regards to supply and demand dynamics in the EU battery market provides the rationale for the prediction and evolution of battery metal prices in the future (discussed in Section 2.2 for Step 2).

Here, the projected battery demand by battery chemistry and metal (Li, Ni, and Co) in 2030 is evaluated against the availability of the respective recycled material. Assessed battery chemistries include $LiNi_{1-x-y}Mn_xCo_yO_2$ (NMC) in various compositions (NMC111, NMC622, NMC811), $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA), and $LiFePO_4$ (LFP). NMC-type cathodes along with NCA and LFP are the predominant EV battery chemistries in Europe and are predicted to remain so until 2030 (Advanced Propulsion Centre, 2021; Wesselkämper et al., 2024). The use of LFP for EVs in the EU has increased in recent years due to its cost and sustainability advantages despite offering lower range than NMC. NCA, NMC811 and LFP are therefore used in the following analysis as representative EV cathodes in the EU. All estimates are based on a pouch cell format which is the most common battery cell format for EVs.

The estimated demanded amount of each chemistry is calculated using Equation (1):

$$M_{cathode}(t) = M_{total} * \%_{split} \qquad 1$$

Table 1
Projected cathode material demand in Europe, measured in kilo-tonne*.

Material	2022	2027	2030
Total cathode demand	174	835	1,274
Mn	198	750	1,200
Co	25	90	115
Ni	78	331	459
Li (LCE)	82	369	537

* Table 1 is based on APC predictions and LCE = lithium carbonate equivalent (Advanced Propulsion Centre, 2021).

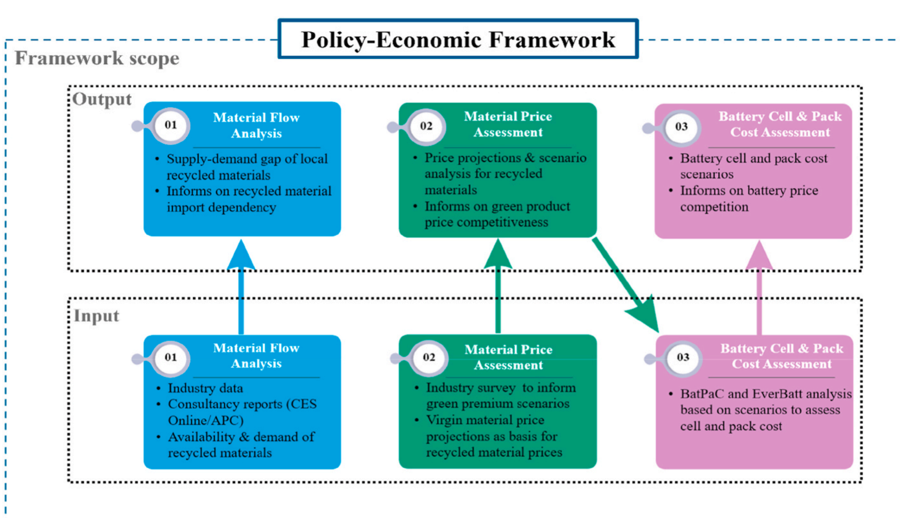

Fig. 1. Policy impact framework as applied to the EU Battery Regulation (Regulation (EU) 2023/1542) as a case study.

where $M_{cathode}$ (in tonnes t) is the estimated demand for a particular cathode chemistry, M_{total} is the predicted total cathode demand in the EU as projected by the APC (1,274,000 t) ((Table 1)), and $\%_{Split}$ represents the share of the cathode chemistry estimated by the APC by 2030 (Supporting Information Table S1). The predicted material demand for Li, Ni, Co and Manganese (Mn) in Table 1 is compared to CES Online predicted demand for these materials and illustrated in Fig. S1. This is done to compared predicted battery materials demands from different sources.

To account for variations in demand projections across the literature, the results obtained from APC were compared with EU demand projections by CES Online for each cathode chemistry by category (*i.e.* portable electronics, heavy and light EV, personal mobility etc.; Tables S2 and S3) (Melin, 2024a).

The potential demand of a recycled metal (*i.e.* Li, Ni, Co) M_{rm} by 2030 was estimated by applying the minimum recycled content for each metal to the calculated overall metal demand (Equation (2)).

$$M_{rm}(t) = (\%_{rm} * \%_{metal,cell}) * M_{projected} \quad 2$$

$\%_{rm}$ is the minimum required amount of the critical metal (16 % Co, 6 % Li and Ni), $\%_{metal,\ cell}$ is the share of the critical metal in a cell of a specific cathode chemistry (Table S2); $M_{projected}$ is the forecasted demand of the virgin battery metals in tonnes for the six main cathode chemistries in a pouch cell format as obtained from reports such as APC and detailed in Table 2. Calculations were conducted for both, CES Online and APC data. The predicted battery chemistry demand in the EU market by 2030 as obtained from CES Online is summarised in Table S3. The data from Table S3 was used in Equation (2) to determine the demand for each recycled strategic and critical metal as mandated by the regulation for each chemistry by 2030. CES Online predicted demand for the following chemistries by 2030: LFP, NCA, NMC111, NMC622, NMC721 and NMC811. The assumed recycling rate and efficiency was 80 % based on the material recovery target for Li (the same is extended for Co and Ni in this study) by 2031 as mandated by the regulation.

To understand whether there will be sufficient recycled material available in 2030 to meet the anticipated demand, M_{rm} (as obtained from Equation (2)) was benchmarked against the amount of available recycled material. Data on the amount of EOL LIBs materials available for recycling in tonnes in Europe was obtained from CES Online and is summarised in Table 3 (Melin, 2024a). Note that the values in Table 3 were multiplied for further analyses by 0.8 to account for an 80 % recycling efficiency based on the targets of the EU Battery Regulation. In addition, EOL LIBs from portable devices and production scrap were included in Table 3. The total amount of recoverable active material from EOL EV batteries and battery production scrap is predicted to be 43,117 t (Melin, 2022). APC and CES Online data were used to estimate the required amount of recycled Li, Ni, and Co by 2030 and the fraction of the demand which could be provided by recycling. Table S4 shows a summary of APC and CES Online predicted demand in 2030 for virgin Li, Ni and Co including the predicted amount of EOL metals available for recycling.

Note that the recycling data used for EOL and scrap batteries available in Europe was accessed from CES Online in June 2024. The data is regularly updated and results using later data from CES Online might therefore vary.

2.1.2. Collection rate

The collection rate and recycling efficiency in the calculations in Section 2.1.a were assumed to be 100 % and 80 %, respectively, and form the here defined Base Case. A scenario analysis was conducted with different collection rates ($\varepsilon_{collect}$) and recycling efficiencies (ε_{recycl}) as detailed in Table 4 to take into account different recovery targets as well as possible improvements in recycling technologies and collection efficiencies (Zhang et al., 2023). The total amount of EOL materials available for recycling was estimated using Equation (3):

$$M_{EOL}(t) = \varepsilon_{recycl} * \varepsilon_{collec} * M_{EOL,CES} \quad 3$$

where M_{EOL} represents the amount of EOL material available to be recycled (in tonnes t), ε_{recycl} is the recycling efficiency, $\varepsilon_{collect}$ is the collection rate, and $M_{EOL,CES}$ is the original amount of EOL critical material available for recycling from CES Online (in tonnes). Three scenarios in addition to the M_{EOL} Base Case are presented as detailed in Table 4.

2.2. Material price assessment

2.2.1. Industry led survey

An industry-led survey was carried out to understand the current battery market situation and to inform the materials price scenarios discussed in this paper. The survey included experts from world leading battery manufacturers, car makers, consultants, recyclers, and independent government bodies. Positions of the contacted experts include analysts and senior consultants, senior engineers, CEOs, and managers. The interviewees were based mainly in the UK but also China and Germany. In total, 19 industry experts were contacted through an online survey and 11 responded. There were questions on the potential price evolution of virgin and recycled material and the implementation of price premiums. The identities of the experts were kept anonymous for this study. All survey questions and answers can be found in the SI Section A.

2.2.2. Material price evolution

The second part of the paper examines the impact of the demand-supply scenarios on materials prices. Tables S5–S7 list the historical prices of virgin Li, Ni, and Co from 2012 to 2024 based on data from Boer et al. (2023), which are based on data from the IMF, US Geographical Survey mineral commodity summaries and World Bureau of metals statistics of lithium carbonate (International Monetary Fund, 2021; Stuermer and Schwerhoff, 2015; U.S. Geological Survey, 2024; World Bureau of Metal Statistics, 2020). Currently, black mass pricing is the most commonly available data for recycled materials, and little data is available for single recycled metals (Allen and Harty, 2023). Therefore, for this study, the price of recycled metals was estimated based on raw materials prices projected in the Net Zero scenario up to 2033 described by Boer et al. (2023). Recycled material prices projected in the Net Zero scenario, which is more aggressive in terms of price

Table 2
Chemistry demand and virgin raw material demand projections for a pouch cell containing the six cathode chemistries assessed in this paper*.

Materials	NMC111	NMC532	NMC622	NMC811	NCA	LFP
Chemistry demand/installed capacity by 2030	8.0 %	6.0 %	9.0 %	41.0 %	5.0 %	25 %
Estimated demand (t)	101,920	76,440	114,660	522,340	63,700	318,500
Li	7,338	5,504	8,256	37,608	4,586	14,014
Co	20,690	660	13,759	32,803	5,669	–
Ni	20,690	277	41,278	240,329	30,385	–
Mn	19,365	17	13,759	28,206	–	–
Aluminium (Al)	–	–	–	–	3,440	–

* Table 2 is based on APC forecast (in tonnes) (Advanced Propulsion Centre, 2021).

Table 3
EOL battery materials available for recycling in Europe (tonnes)*.

Europe	2024	2025	2026	2027	2028	2029	2030
Total	13,829	15,345	17,579	20,529	24,752	30,804	43,117

* Table 3 is edited to show only total values from CES Online data (CES Online, 2024; Melin, 2024a). Note that for further analyses these values were multiplied by 0.8.

Table 4
Assumptions on recycling efficiencies and collection rates for the M_{EOL} Base Case and Supply Cases 1–3.

	Recycling efficiency ε_{recycl}	Collection rate $\varepsilon_{collect}$
M_{EOL} Base Case	80 %	100 %
Supply Case 1	100 %	100 %
Supply Case 2	80 %	80 %
Supply Case 3	80 %	50 %

development, are also compared with the prices based on the less aggressive Stated Policy scenario in Boer et al. (2023). The Net Zero scenario, being the most ambitious with net zero CO_2 emissions by 2050, assumes that the total consumption of Li and Co rises more than 20-fold and 6-fold, respectively. In addition, battery demand reaches 14 TWh by 2050 with EVs representing 86 % of the market share for cars. In contrast, the Stated Policy scenario is based on historical trends. Furthermore, Boer et al. (2023) model critical minerals prices using structural vector autoregressive models for each metal, drawing on a long historical dataset that, for some metals, extends back to 1879. This modelling approach captures aggregate commodity demand shocks (e.g., an unexpected economic expansion that increases demand for all commodities), metal-specific supply shocks (e.g., a strike at a major mine), and metal-specific demand shocks (such as the energy transition). Future price projections are then made based on the International Energy Agency's Stated Policy and Net Zero Emissions scenarios (IEA, 2024).

As a base case, this study assumes that the price of recycled material is equal to the virgin metal price. The recycled metals price for a specific year y in the Base Case scenario, $P_{rm,y,base}$, was obtained following Equation (4):

$$P_{rm,y,base}\left(\frac{\$}{kt}\right) = P_{vm,y} * \%_{v,price} \quad (4)$$

where $P_{vm,y}$ (in \$/kt) refers to the price of the virgin metal in year y as sourced from Boer et al. (2023) and $\%_{v,price}$ to the price percentage of virgin material paid for recycled material (for the Base Case and Scenario 1 this is equal to 1 while for Scenarios 2 and 3 this varies from 0.4 to 1.5). The virgin metal prices of Year 2024 were used as starting point to estimate historical prices for recycled metals and were set at \$10,310/kt for Li, \$18,827/kt for Co, and \$141,080/kt for Ni.

Based on the outputs of the industry-led survey (Section 3.2.a) on the possible impacts of the EU legislation on the recycled and virgin metals prices by 2030, and to account for unpredictable price volatilities, three additional scenarios were developed and assessed. The scenarios vary in the compound annual growth rate (CAGR) of recycled material prices and in the application of a premium on the price of each recycled metal (currently a 4–8 % green premium is seen in Class 1 Ni metal and 3–5 % for Al) (Coyne and Sims, 2024; CRU, 2022; Su, 2024). From 2012 to 2033, recycled material prices are estimated from the projected virgin raw materials prices from Boer et al.'s Net Zero projections (Tables S5–S7) (Boer et al., 2023; The London Metal Exchange, 2024; U.S. Geological Survey, 2024).

The assumptions for the Base Case and the three scenarios are as follows:

- Base Case: Recycled metals prices are estimated to be 100 % of virgin raw material prices, indicative of battery grade quality (Equation (4)).
- Scenario 1: Recycled metal prices reach 100 % of virgin raw material value. This analysis further considers a 6 % price premium from 2030, which reflects the opinion of the industry experts that a potential premium might be introduced as a result of the increased demand for recycled metals due to the legislation.
- Scenario 2: Based on expert inputs from recyclers, it is assumed that a recycler in Europe will get paid 40 % of the London Metal Exchange (LME) price for Ni and Co given that the quality of the recycled material is not battery grade and further processing is required. Due to a lack of data, the same was assumed for Li. Based on this assumption, from 2012 to 2024, the recycled metals prices reach only 40 % of the virgin raw material price. From 2025 onwards, recycled metals prices reach 100 % of virgin raw material value indicative of improved battery grade quality. No premium is imposed.
- Scenario 3: Recycled materials prices reach 150 % of virgin metals prices by 2030 indicative of technological improvements in battery recycling and increased demand. A 6 % premium is applied from 2030 onwards to reflect the impact of the legislations on demand.

The recycled materials prices for Scenarios 1, 2, and 3 from 2024 to 2029 before applying any premium, $P_{rm,y,sc}$, are calculated following Equation (5):

$$P_{rm,y,sc}(\$/kt) = P_{rm,y,base} + P_{rm,y,base} * \%_{CAGR} \quad (5)$$

The recycled materials prices for Scenarios 1 and 3 from 2030 onwards with a premium are calculated following Equation (6):

$$P_{rm,y,sc}(\$/kt) = \left(P_{rm,y,base} + P_{rm,y,base} * \%_{CAGR}\right) + \left(\left(P_{rm,y,base} + P_{rm,y,base} * \%_{CAGR}\right) * \%_{premium}\right) \quad (6)$$

where $\%_{premium}$ refers to the price premium and $\%_{CAGR}$ to the CAGR of the recycled materials price. Table 5 summarises the input values for the Base Case and the three scenarios calculated using Equations (4)–(6). Since the battery recycling industry is currently still in its early stages and, to the best of our knowledge, recycled material is never or barely used in the manufacturing of new batteries to date, no percentage increase nor premium on recycled material prior to 2020 was assumed.

The projected recycled materials prices calculated in Equations (4)–(6) are used as input data for BatPaC and EverBatt (Section 2.3) to assess how these will affect cell and pack costs for three main cathode chemistries: NCA, NMC811, and LFP.

Table 5
Input values for the Base Case (as calculated via Equation (4)) and Scenarios 1–3 (as calculated via Equations (5) and (6)).

	Base Case	Scenario 1	Scenario 2	Scenario 3
$\%_{premium}$	0	2020–2029: 0 2030–2033: 0.06	0	2020–2029: 0 2030–2033: 0.06
$\%_{vm}$	1	1	2012–2024: 0.4 2025–2033: 0.4–1	2012–2024: 1 2025–2033: 1–1.5
$\%_{CAGR}$	0	0	2012–2024: 0 2025–2033: 0.15	2012–2024: 0 2025–2033: 0.05

2.3. Battery cell and pack cost assessment

To understand how the four price scenarios will affect battery cell and pack costs, BatPaC (Argonne National Laboratory, 2024; Nelson et al., 2019) was used to benchmark the costs for cells and packs with 100 % virgin materials against their cost with the minimum recycled content required by the EU Battery Regulation. BatPaC is an Excel-based cost model developed by Argonne National Laboratory which bridges technical design and economic analysis for batteries. It uses a bottom-up cost modelling approach to provide a detailed cost breakdown (for battery cell, module, and pack including manufacturing plant cost) and bill of materials (Gallagher and Nelson, 2014). BatPaC serves as a tool to evaluate costs based on materials, labour, equipment, process steps, overhead and facility expenses. Here, the BatPaC model was customised, where the cost for cathode active materials (CAMs) was adapted to reflect the usage of recycled materials. CAMs serve as key components in a cell, which in turn is considered as the basic electrochemical unit of a battery pack. Therefore, the price uncertainty of raw materials and CAMs would have a direct effect on the cost of cells and consequently on packs. Calculating all three costs (CAM, cell, and pack) was essential to understand the overall economic impact along the battery value chain.

The cost of CAMs by 2030 was first estimated using the 2022/2023 BatPaC cost with a 10 % and 50 % increase and a 50 % and 10 % decrease to reflect potential price fluctuations. For each scenario, we used the composition of a typical pouch cell for a NCA, LFP, and NMC811 cathode (Table S2).

The Battery Regulation requires 6 % for Li and Ni, respectively, and 16 % for Co as minimum recycled content for new cells; the remaining 94 % (for Li and Ni) and 84 % (for Co) are virgin material. The amount of virgin material, M_{vm}, and recycled material, M_{rm}, in kg required for each critical metal in a specific cathode chemistry is determined using Equations (7) and (8):

$$M_{vm}(kg) = M_{cathode} * \%_{cm} * \%_{v,mass} \quad (7)$$

$$M_{rm}(kg) = M_{cathode} * \%_{cm} * \%_{rm} \quad (8)$$

where $M_{cathode}$ (in kg) is the mass of the cathode in a pouch cell, $\%_{cm}$ is the percentage of critical metal for a specific cathode material, $\%_{v,mass}$ is the percentage of virgin material, and $\%_{rm}$ is the percentage of recycled material. Input values for Equations (7) and (8) are summarised in Table S8–S9.

To determine the cost of a specific virgin and recycled metal, C_{vm} and C_{rm} (in \$/kg), respectively, for each cathode chemistry, Equations (9) and (10) are used as follows:

$$C_{vm}\left(\frac{\$}{kg}\right) = M_{vm} * C_{total,vm} \quad (9)$$

$$C_{rm}\left(\frac{\$}{kg}\right) = M_{rm} * C_{total,rm} \quad (10)$$

where M_{vm} (in kg) is the amount of virgin material required (Equation (7)), and M_{rm} (in kg) is the amount of recycled material required (Equation (8)). $C_{total,vm}$ (in \$/kg) is the total cost of active material for a specific chemistry using 100 % virgin material (data from BatPaC, Tables S10–S11). $C_{total,rm}$ (in \$/kg) refers to the total CAM cost using the amount of recycled material set by the EU Battery Regulation. Input price data was used as obtained from the recycled cost scenarios projections in Section 3.2.b for the year 2030.

The total cost, C_{total} (in \$/kg) for the active material for each cathode chemistry and each price scenario was calculated according to Equation (11):

$$C_{total}\left(\frac{\$}{kg}\right) = \sum C_{vm} + \sum C_{rm} + C_{conv} \quad (11)$$

The final battery cell and pack costs were calculated using BatPaC, where C_{total} calculated using Equation (11) was implemented in the 'Dashboard' tab, instead of the original cathode price using 100 % virgin material. A material conversion cost, C_{conv}, to account for the additional processing steps needed to make recycled materials reach battery-grade quality was applied as sourced from EverBatt ($CoSO_4$: \$0.05/$kg_{precursor}$, $NiSO_4$: \$0.05/$kg_{precursor}$, LiOH: \$0.27/$kg_{precursor}$ produced) (Argonne National Laboratory, 2024). The C_{conv} applied here avoid underestimating the manufacturing cost of cathodes made from recycled materials.

The BatPaC dashboard tab is separated into three main sections (chemistry, battery design, and manufacturing cost). Table 6 below lists some generic input parameters (if known, otherwise default parameters are applied) required for obtaining cell and pack costs in BatPaC.

See Appendix Tables A.1 and Table A.2 for detailed information on all values used for BatPaC. In a next step, EverBatt, which is also an Excel-based cost model developed by Argonne National Laboratory to evaluate the cost and environmental impact of LIB recycling, was used. EverBatt serves as a tool to simulate a closed-loop system that covers collection, transportation, cathode powder production, and battery manufacturing with recycled materials (Nguyen-Tien et al., 2022). For each stage, EverBatt estimates requirements for equipment, facilities, labour, raw materials, and utilities (e.g., electricity, fuel, water, waste). In addition, input parameters such as geographical location, battery cathode chemistry, throughput, transportation (distance and cost), and feedstock are required to produce a detailed cost breakdown (including profit) of manufacturing cathodes with recycled material for three recycling processes (pyrometallurgical, hydrometallurgical, and direct recycling). The input parameters for EverBatt are summarised in Table 7.

More detailed information on BatPaC and EverBatt and their usage can be found on the Argonne National Laboratory website (Argonne National Laboratory, 2024; Nelson et al., 2019).

3. Results

The policy-economic framework introduced in this paper includes three steps (material flow analysis, material price assessment, and battery cost analysis) to assess the impacts of the EU Battery Regulation on the recycling market. The results of each step as well as the outcome of the industry survey are presented in this section.

3.1. Material flow analysis: availability of recycled material vs demand forecast

To understand whether the EU is ready to meet its own legislation with regards to the minimum recycled content target, a supply-demand analysis in the EU market was conducted. In 2030, the amount of required recycled material to fulfil the EU Battery Regulation amounts to 14,062 t for Li, 68,122 t for Ni, and 35,881 t for Co (based on CES Online data in Fig. S1) (CES Online, 2024). To account for other sources of recycled materials besides EV batteries, recycled material from portable electronics and battery manufacturing scrap was also included (Table S12). The combined amount of recycled Li, Ni, and Co coming from EV and manufacturing scrap is estimated at 29,211 t in 2030 (Melin, 2024b). Adding portable electronics increases the amount of

Table 6
BatPaC input parameters.

Parameters	Details
Positive electrode with a graphite (G) chemistry	NCA-G, LFP-G or NMC811-G
Vehicle Type	EV
Mass or Cost Sensitive Pack Design	Cost
Positive Electrode cost	CAM cost 2023: \$35.50/kg
Negative electrode cost	Anode active material cost 2023: \$9/kg

Table 7
EverBatt input parameters.

Parameters	Details
Battery cathode chemistry	NCA, LFP or NMC811
Geographic location	EU
Throughput	500 GWh/yr
Transportation (distance)	1000 miles from preprocessor to material recovery
Feedstock-type	End of life pack, module, cell, black mass and rejected cells

material available for recycling in 2030 by 36 %. The material flow analysis results are shown in Fig. 2 comparing recycled material demand against supply by 2030 for Li, Ni, and Co.

Results show that recycling might supply the required amount of recycled Li with a predicted surplus of 12 %, but might not be sufficient to meet the demand for recycled Ni and Co. To consider varying predictions across literature, Fig. S1 shows projections of materials demand and materials availability from two different sources - APC and CES Online (Advanced Propulsion Centre, 2021; CES Online, 2024; Melin, 2024b).

The regulation sets collection targets at 51 % by 2028 and 61 % by 2031 for batteries used for light means of transport. Compared to the M_{EOL} Base Case with 80 % recycling efficiency and 100 collection rate, assuming a 100 % collection rate and 80 % recycling efficiency (Supply Case 1) leads to a 20 % increase of the availability of recycled material. In Supply Case 2, with 80 % collection rate and 80 % recycling efficiency, the available amount of recycled metals decreases by 60 % for Ni and Co. In the case of only 50 % collection rate and 80 % recycling efficiency of EOL LIBs by 2030 (Supply Case 3), the available amount of recycled metals decreases by 36 % for both Ni and Co (Fig. S2).

3.2. Material price assessment

3.2.1. Industry-led survey

An industry-led survey was carried out to obtain valuable insights into the current recycling market and the future impact of the legislation on the market from the perspective of automotive OEMs, battery manufacturers, recyclers and consultants. The survey outcomes were then used to inform the here developed price development scenarios. The questions and answers of the survey are detailed in the Appendix Section A and are summarised in Fig. 3.

The outcomes of the survey can be summarised as follows:

a) Half of the survey respondents voted that the legislation would lead to an increase in virgin battery material prices before 2030.
b) More than half of the experts agreed on the price of virgin materials to decrease after 2030. A probable argument for this might be that the expected increase in recycled materials demand would lead to a decrease in demand for virgin material and consequently to a decrease in their price.
c) Automotive experts expect a negligible price change of recycled materials prior to the legislation being fully implemented; afterwards an increase in the price of recycled metals is expected due to the increase in demand.
d) The majority of industry experts expects a price premium on recycled material prices before the legislation comes into force. The premium is seen as a natural response to an increase in demand in recycled materials as the legislation comes into force. However, only few experts believe that the market would return to normal without the need of regulatory guidance.
e) Battery manufacturing, recycling and automotive OEM experts agreed that the surging demand of recycled metals might increase the price of recycled materials above the price of their corresponding virgin materials even without an imposed premium. Consultants, on the other hand, expect recycled material prices to increase from their original market price but not to reach virgin material prices, even after 2030.
f) At the moment, recycling is more expensive in the EU than in Asia (Lander et al., 2021). When asked about the possibility of Asia providing recycled materials to the EU (a loophole in the Battery Regulation), 20 % of the experts agreed on the possibility of international players penetrating the market and 10 % of which agreed on this being a barrier to entry for new EU recyclers. However, most experts disagreed on the forementioned scenarios and found this as an opportunity for international recyclers to collaborate with EU recyclers and to set up facilities in Europe. This could be positive for the EU as it would allow for knowledge exchange and training opportunities.

3.2.2. Price developments of recycled materials under the EU Battery Regulation

Here, price projections of recycled material were developed under four scenarios, which were informed by the above presented industry-led survey. The price developments of recycled Li, Ni, and Co for the four scenarios are calculated from the virgin material prices from Boer et al. (2023) as described in Section 2. Fig. 4 shows the projected and estimated price evolution of both recycled and virgin materials for the four scenarios by 2033. The same analysis was carried out for the Stated

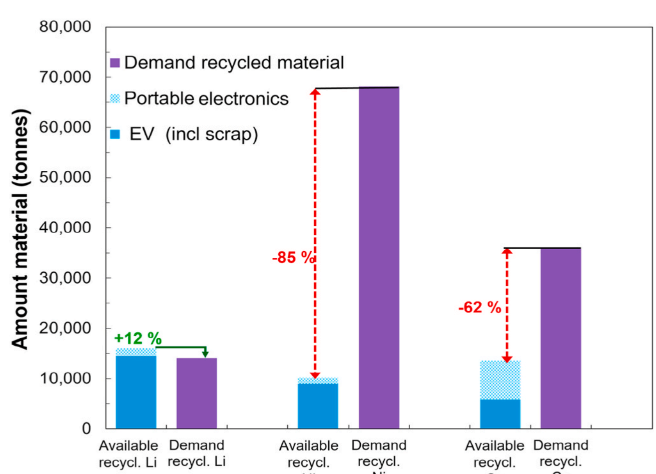

Fig. 2. Demand of recycled Li, Ni, and Co (in tonnes) versus the amount of available recycled material, including EOL EV batteries, and portable electronics (Melin, 2024b).

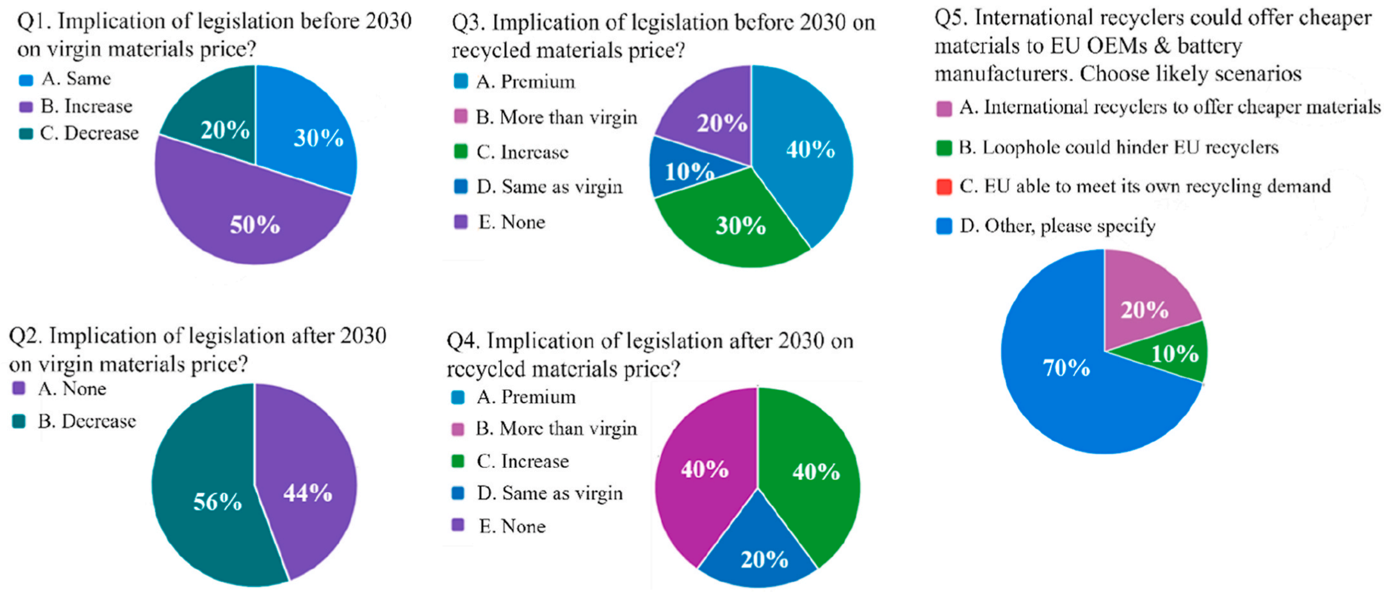

Fig. 3. Results of the industry-led survey on the potential impact of the EU Battery Regulation on material price developments and battery market.

Policy scenario (Fig. S4).

In terms of virgin metal prices, in the Net Zero scenario as described by Boer et al. (2023), Co prices increase and reach a maximum by 2029/2030 of 234,703 $/t before experiencing a decline. Historical virgin prices and the prices of the Base Case scenario of all three metals are the same since it is assumed that recycled material prices will be 100 % of virgin material prices. The historical prices for virgin materials were omitted for better visualisation but can be found in Fig. S3. In Scenarios 1 and 3 a crossing point is achieved between the prices of recycled metals and virgin metals from 2025 to 2028 at $11,688/t and

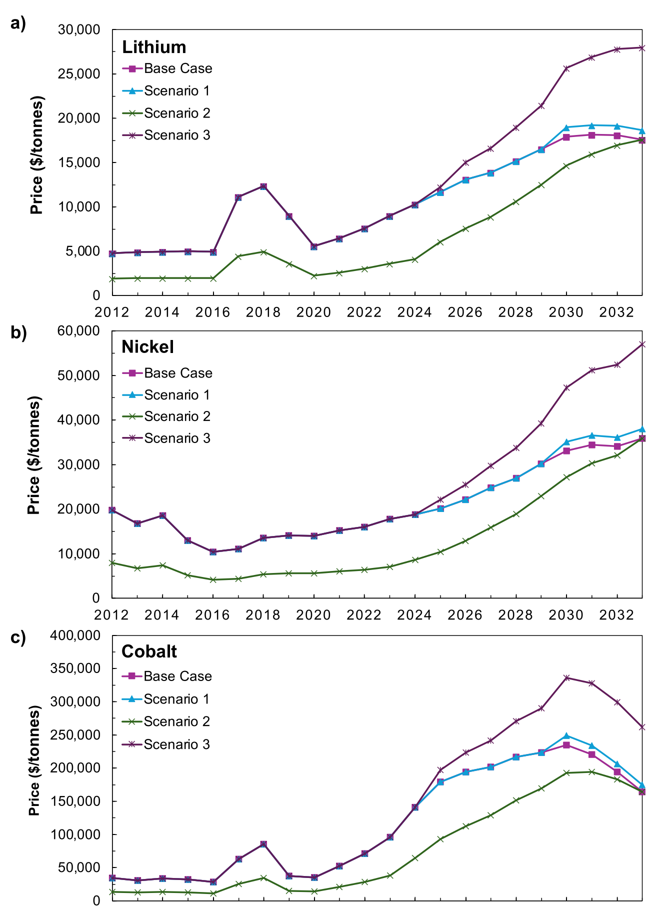

Fig. 4. Recycling materials price scenarios in $/tonnes for a) Li, b) Ni, and c) Co for the years 2012–2033 based on the Net Zero scenario.

$18,997/t for Li, at $20,150/t and $33,741/t for Ni, and at $179,160/t and $270,940,076/t for Co, respectively. This indicates the possibility of recycled material becoming indeed more expensive than virgin material. In Scenario 2, this crossing point is observed in 2033 for all three critical metals.

It is important to note that for Scenario 2, no premium was added, and the price increase is merely the result of the CAGR of recycled materials price. Therefore, regardless of an imposed premium of 6 %, using the Net Zero scenario as described by Boer et al. (2023), the prices of recycled metals could exceed virgin metals from 2033.

A cross-over point is first observed by 2024 for Scenario 3, and by 2028 and 2033 for Scenarios 1 and 2, respectively. Virgin metal prices, in particular Co, in the Net Zero scenario peak around 2030. This is due to the assumptions made by the authors in the Net Zero scenario of a steep rise in demand and an initial price boom causing a supply reaction, which in turn reduces market tightness after 2030 (Boer et al., 2023).

3.3. Battery cell and pack cost assessment

According to Step 3 in the policy-economic framework (Fig. 1), the impact of the price evolutions of the recycled materials (Fig. 4) on the prices of battery cells and packs was assessed using BatPaC. The costs for CAM, cells, and packs with the minimum recycled content of Li, Ni, and Co, were compared to materials containing 100 % virgin material for NMC811, NCA, and LFP chemistries for the years 2023 and 2030 (Fig. 5). Results are summarised in Appendix A in Tables A.1 – A.6.

Fig. 5 shows the projections of CAM for NCA, LFP and NMC 811 chemistries with a 10 % and 50 % increase (Fig. 5a) and a 10 % and 50 % decrease (Fig. 5b) for the Net Zero case. The projections for the Stated Policy case are illustrated in Fig. S5.

For a **10 % increase** in CAM virgin materials prices the results can be summarised as follows:

- For an NCA chemistry: A price increase of 5 % is observed between the Base Case ($43/kg) and Scenario 3 ($45/kg). A price increase of 28 % is observed between 2023 cost ($35.5/kg) and Scenario 3 ($45.4/kg). Finally, a price increase of 21 % is observed between 2023 cost ($35.5/kg) and the Base Case ($43.1/kg).
- For an NMC811 chemistry: A price increase of 5 % is observed for the Base Case ($41/kg) and for Scenario 3 ($43/kg). A price increase of 24 % is observed between 2023 cost ($34.5/kg) and Scenario 3 ($42.9/kg). Finally, a price increase of 19 % is observed between 2023 cost ($34.5/kg) and the Base Case ($41/kg).
- For an LFP chemistry: A 3 % price decrease is observed for the Base Case ($13/kg) and for Scenario 3 ($12.7/kg). A price increase of 11 % is observed between 2023 cost ($11.5/kg) and Scenario 3 ($12.7/kg). Finally, a price increase of 13 % is observed between 2023 cost ($11.5/kg) and the Base Case ($13/kg).

For a **10 % decrease** in CAM virgin materials prices the results can be summarised as follows:

- For an NCA chemistry: A price increase of 6 % is observed between the Base Case ($36.5/kg) and Scenario 3 ($38.8/kg). A price increase

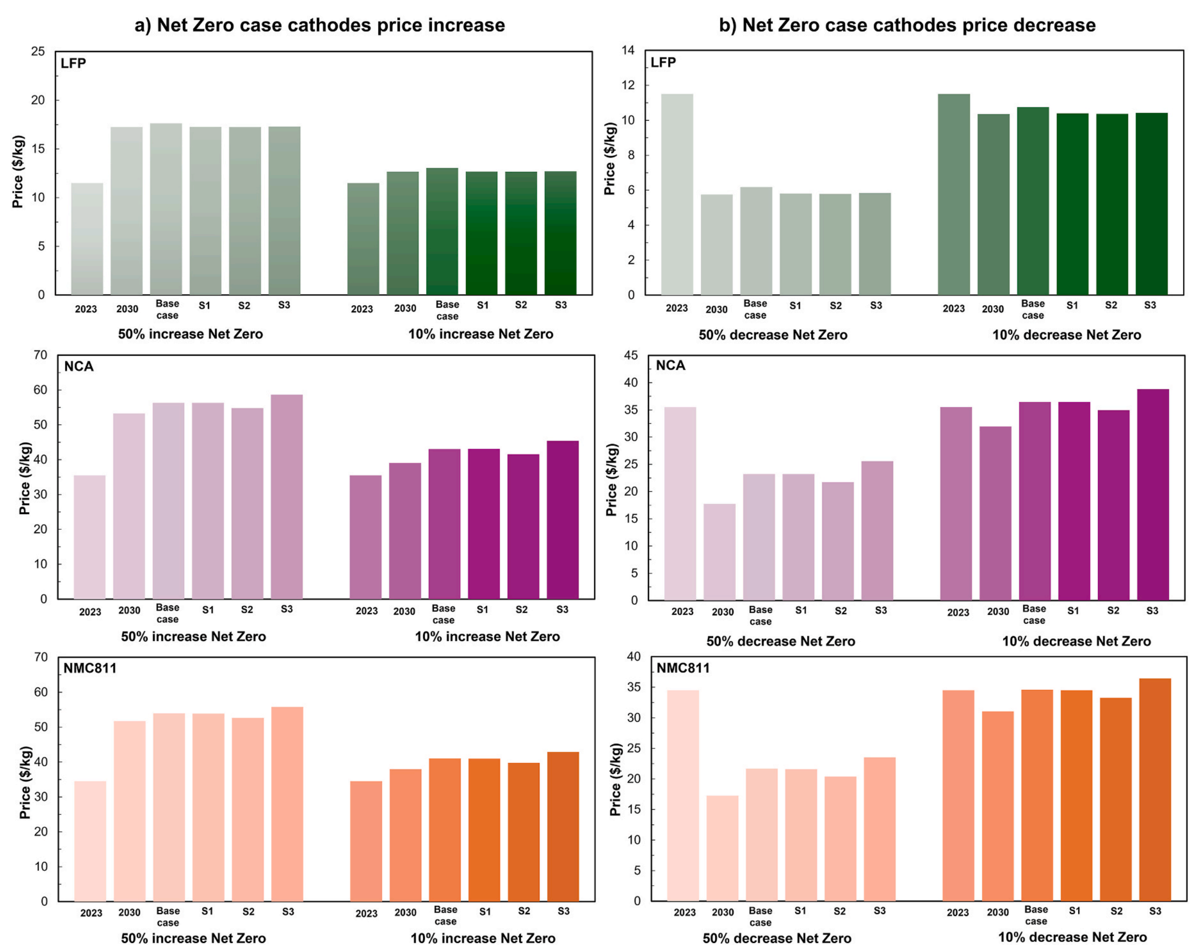

Fig. 5. BatPaC CAM cost with a) 10 % and 50 % price increase on virgin material prices by 2030 and b) 10 % and 50 % price decrease on virgin material prices by 2030 (Argonne National Laboratory, 2024; Boer et al., 2023; Nelson et al., 2019). Note that prices for 2023 and 2030 are based on CAM with 100 % virgin material; Base Case and all scenarios have a mix of virgin and recycled materials. S1-S3 represents Scenarios 1 to 3. The results are summarised in Tables A.1 –A.6.

of 9 % is observed between 2023 cost ($35.5/kg) and Scenario 3 ($38.8/kg). Finally, a price increase of 3 % is observed between 2023 cost ($35.5/kg) and the Base Case ($36.5/kg).
- For an NMC811 chemistry: A price increase of 5 % is observed for the Base Case ($34.6/kg) and for Scenario 3 ($36.4/kg). A price increase of 6 % is observed between 2023 cost ($34.5/kg) and Scenario 3 ($36.4/kg). Finally, a negligible price change is observed between 2023 cost ($34.5/kg) and the Base Case ($34.6/kg).
- For an LFP chemistry: A 3 % price decrease is observed for the Base Case ($10.8/kg) and for Scenario 3 ($10.4/kg). A price decrease of 9 % is observed between 2023 cost ($11.5/kg) and Scenario 3 ($10.4/kg). Finally, a price decrease of 6 % is observed between 2023 cost ($11.5/kg) and the Base Case ($10.8/kg).

For a **50 % increase** in CAM virgin material prices the results can be summarised as follows:

- For an NCA chemistry: A price increase of 4 % is observed between the Base Case ($56.3/kg) and Scenario 3 ($58.7/kg). A price increase of 65 % is observed between 2023 cost ($35.5/kg) and Scenario 3 ($58.7/kg). Finally, a price increase of 59 % is observed between 2023 cost ($35.5/kg) and the Base Case ($56.3/kg).
- For an NMC811 chemistry: A price increase of 3 % is observed for the Base Case ($53.9/kg) and for Scenario 3 ($55.8/kg). A price increase of 62 % is observed between 2023 cost ($34.5/kg) and Scenario 3 ($55.8/kg). Finally, a price increase of 56 % is observed between 2023 cost ($34.5/kg) and the Base Case ($53.9/kg).
- For an LFP chemistry: A 2 % price decrease is observed for the Base Case ($17.6/kg) and for Scenario 3 ($17.2/kg). A price increase of 50 % is observed between 2023 cost ($11.5/kg) and Scenario 3 ($17.2/kg). Finally, a price increase of 53 % is observed between 2023 cost ($11.5/kg) and the Base Case ($17.6/kg).

For a **50 % decrease** in CAM virgin material prices the results can be summarised as follows:

- For an NCA chemistry: A price increase of 10 % is observed between the Base Case ($23.2/kg) and Scenario 3 ($25.6/kg). A price decrease of 28 % is observed between 2023 cost ($35.5/kg) and Scenario 3 ($25.6/kg). Finally, a price decrease of 35 % is observed between 2023 cost ($35.5/kg) and the Base Case ($23.2/kg).
- For an NMC811 chemistry: A price increase of 9 % is observed for the Base Case ($21.7/kg) and for Scenario 3 ($23.5/kg). A price decrease of 32 % is observed between 2023 cost ($34.5/kg) and Scenario 3 ($23.5/kg). Finally, a price decrease of 37 % is observed between 2023 cost ($34.5/kg) and the Base Case ($21.7/kg).
- For an LFP chemistry: A 5 % price decrease is observed for the Base Case ($6.2/kg) and for Scenario 3 ($5.8/kg). A price decrease of 49 % is observed between 2023 cost ($11.5/kg) and Scenario 3 ($5.8/kg). Finally, a price decrease of 46 % is observed between 2023 cost ($11.5/kg) and the Base Case ($6.2/kg).

Fig. 6 shows the BatPaC analysis results of cost differences between NCA, LFP and NMC811 cells and packs with 100 % virgin materials against those containing the mandated minimum recycled content for the three scenarios. The results indicate that the cost of a battery cell and pack (considering the case of a 10 % increase in CAM cost) will increase for the Base Case, Scenarios 1 and 3 for NCA and NMC811 as follows:

For the cell cost:

- For the Base Case: Analysis shows a cost increase of 12 % and 10 % between 2023 prices and the Base Case for NCA ($112/kWh and $125/kWh) and NMC811 ($106/kWh and $116/kWh), respectively. Furthermore, comparing the Base Case with 2030 prices gives a 6 % and a 4 % increase for NCA ($118/kWh and $125/kWh) and NMC811($112/kWh and $117/kWh), respectively.
- For Scenario 1: A 12 % and 10 % increase is observed between prices in 2023 and Scenario 1 for NCA ($112/kWh and $125/kWh) and NMC811 ($106/kWh and $116/kWh), respectively. A cost increase of 6 % and 4 % is observed when comparing the Scenario 1 with 2030 prices for NCA ($118/kWh and $125/kWh) and NMC811 ($112/kWh and $116/kWh), respectively.
- For Scenario 2: A 9 % and 8 % increase is observed between prices in 2023 and Scenario 2 for NCA ($112/kWh and $123/kWh) and NMC811 ($106/kWh and $114/kWh), respectively. A cost increase of 4 % and 3 % is observed when comparing the Scenario 2 with 2030 prices for NCA ($118/kWh and $123/kWh) and NMC811 ($112/kWh and $114/kWh), respectively.
- For Scenario 3: A 15 % and 13 % increase is observed between 2023 prices and Scenario 3 for NCA ($112/kWh and $129/kWh) and NMC811 ($106/kWh and $120/kWh), respectively. Furthermore, 9 % and 7 % increase is observed between 2030 prices and Scenario 3 for NCA ($118/kWh and $129/kWh) and NMC811 ($112/kWh and $120/kWh), respectively.

For the Pack cost:

- For the Base Case: Analysis shows a cost increase of 10 % and 8 % between 2023 prices and the Base Case for NCA ($133/kWh and $146/kWh) and NMC811 ($127/kWh and $137/kWh), respectively. Furthermore, comparing the Base Case with 2030 prices gives a 5 % and a 4 % increase for NCA ($139/kWh and $146/kWh) and NMC811($132/kWh and $137/kWh), respectively.
- For Scenario 1: A 10 % and 18 % increase is observed between prices in 2023 and Scenario 1 for NCA ($133/kWh and $146/kWh) and NMC811 ($127/kWh and $137/kWh), respectively. Furthermore, analysis shows a cost increase of 5 % and 4 % when comparing the Base Case with 2030 prices for NCA ($139/kWh and $146/kWh) and NMC811 ($132/kWh and $137/kWh), respectively.
- For Scenario 2: An 8 % and 7 % increase is observed between prices in 2023 and Scenario 2 for NCA ($133/kWh and $143/kWh) and NMC811 ($127/kWh and $135/kWh), respectively. A cost increase of 3 % and 2 % is observed when comparing the Scenario 2 with 2030 prices for NCA ($139/kWh and $143/kWh) and NMC811 ($132/kWh and $135/kWh), respectively.
- For Scenario 3: A 13 % and 11 % increase is observed between 2023 prices and Scenario 3 for NCA ($133/kWh and $150/kWh) and NMC811 ($127/kWh and $140/kWh), respectively. Furthermore, 8 % and 6 % increase is observed between 2030 prices and Scenario 3 for NCA ($139/kWh and $150/kWh) and NMC811 ($132/kWh and $140/kWh), respectively.

In all four scenarios, there is less than a 4 % increase observed for LFP. This is due to the fact that iron and phosphorous are not required to be recycled and therefore remain constant in our analysis; here, the price changes only stem from Li. However, only 4 % of Li is contained in an LFP pouch cell and the impact of Li price developments is thus negligible for the CAM, cell and pack costs.

Fig. S6 shows cell and pack costs applying a +50 % price shock in CAM cost as an extreme case to better reflect the large uncertainty in critical mineral prices. A 15 % increase in cell and pack costs is observed between 2023 prices and Scenario 3 for LFP and a 36 % and 33 % increase in cell costs and a 30 % and 27 % increase in pack costs for NCA and NMC811, respectively.

Similar analysis was carried out to benchmark cell prices in the Net Zero scenario against the Stated Policy scenario (Fig. S7, Table A.9). For NMC811 and NCA, the Stated Policy scenario results in at least 6 % lower cell cost in Scenario 2 compared to the Net Zero scenario with $110.12/kWh and $116.85/kWh, respectively.

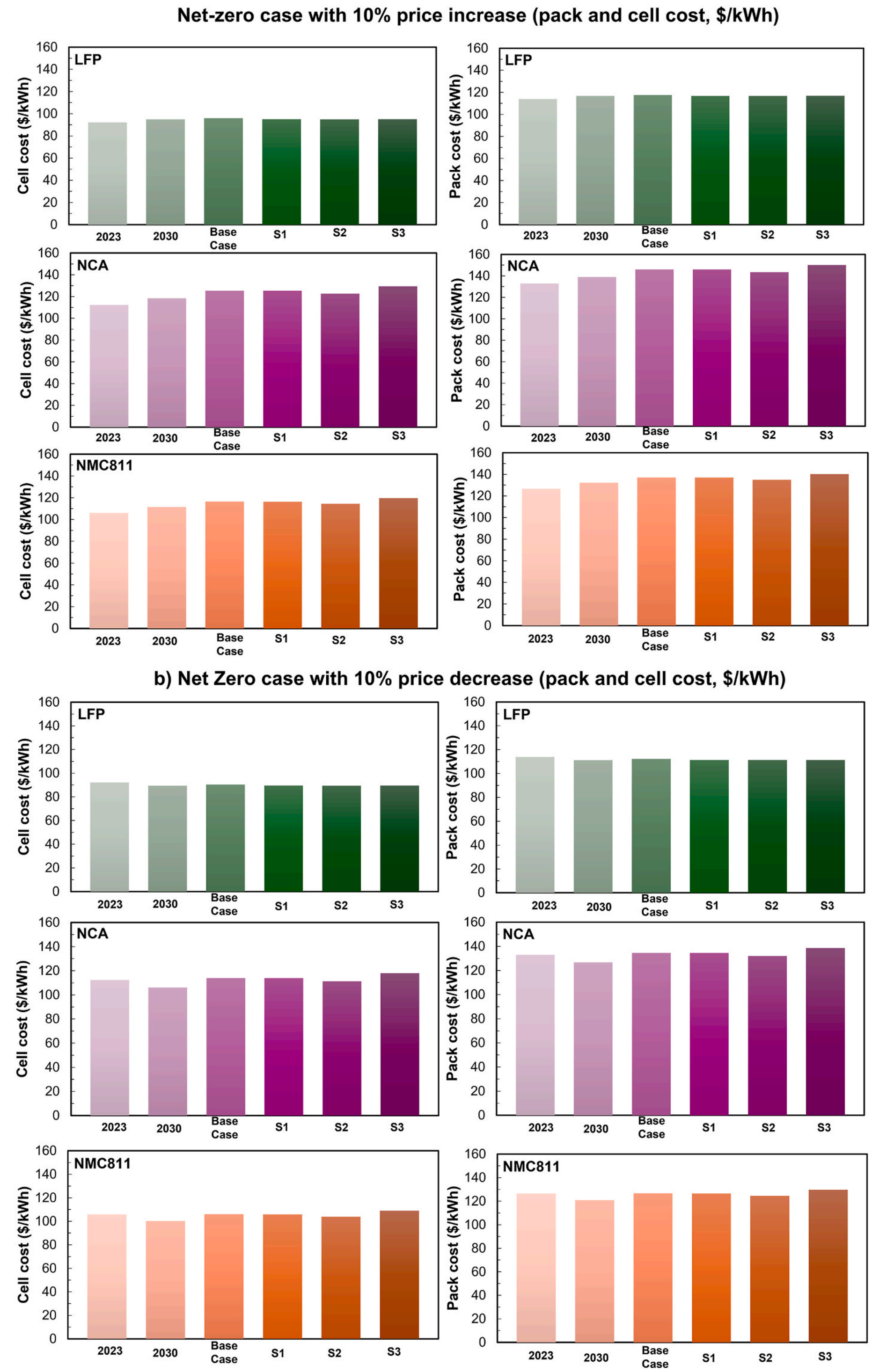

Fig. 6. a) Price scenarios for cell and pack cost calculated with BatPaC, assuming a 10 % increase by 2030 in virgin cathode materials prices (Argonne National Laboratory, 2024; Boer et al., 2023; Nelson et al., 2019). b) Price scenarios for cell and pack cost calculated with BatPaC, assuming a 10 % decrease by 2030 in virgin cathode materials prices (Argonne National Laboratory, 2024; Boer et al., 2023; Nelson et al., 2019). Note that prices for 2023 and 2030 are based on cathodes with 100 % virgin materials; Base Case and all scenarios have a mix of virgin and recycled materials. S1-S3 represents Scenarios 1 to 3. The results are summarised in Tables A.3–A.8.

4. Discussion

The material flow analysis shows recycling might supply the required amount of recycled Li but is unlikely to be sufficient to meet the demand for Ni and Co. This result matches Ginster et al. (2021), which demonstrated that even with a 100 % recycling efficiency, the recycled content targets may be overly ambitious. Thus, to meet the demand, the EU will need to increase local refining output, cathode production (an important but missing element in Europe's quest for a closed-loop battery ecosystem), maximise recycling, and secure sustainable imports (Daw, 2025; Dixit et al., 2024; Melin, 2024a; Rizos and Urban, 2024; Slupek, 2024). Note that the rate of increased battery demand is moving ahead of EOL battery supply for recycling as the average lifespan of a battery is estimated between 8 and 10 years with reports suggesting an even longer lifespan further increasing the demand-supply gap (Nguyen-Tien et al., 2025). Consequently, end customers such as battery and automotive OEMs might have to pay a premium on the price of recycled materials leading to higher recycled metal prices and thus increased CAM, cell and pack costs as shown above.

The green premium currently observed in metals such as Class 1 Ni and aluminium recycled with green energy could be a good indicator of how the recycling market could evolve with the EU Battery Regulation. The price premium in fact could be attractive to EU recyclers to increase their profits. However, the opposite could be true where a high price premium could be an entry barrier to the recycling market for small and new companies as OEMs would go to suppliers with lower prices. Fan et al. (2025) assessed the influence of a green premium in China and found battery EV market penetration to be highly affected by premiums (Fan et al., 2025). To minimise their impact, government subsidies, financial incentives and technological advancement will be crucial (Fan et al., 2025). Therefore, focusing on policy support and investment would strengthen the market and increase EV adoption (Fan et al., 2025; Gu et al., 2017).

An additional point in the EU Battery Regulation needs to be considered. In its current form, it does not specify the source of recycled material thus international recyclers could penetrate the EU market with potentially cheaper materials (Arcibal and Xue, 2024; Melin et al., 2021). This, in turn, could hinder the successful growth of smaller EU recycling companies as more OEMs will look to these suppliers to cover their recycled metal demands (Gulley et al., 2019). It would further need to be assessed how increasing cell prices as a result of the EU Battery Regulation will impact the market uptake of local EVs as customers might choose lower-cost Asian brands.

As discussed above, a potential threat to the EU battery market stems from an increase in recycled materials prices. Several solutions could be envisaged to avoid this:

a) The vertical integration of recycling into the battery manufacturing process allows for access to internally recycled material reducing vulnerability to price fluctuations and other external market impacts and enabling a more stable supply and price for recycled material.
b) Diversifying the battery portfolio via a stronger shift towards LFP and sodium-ion batteries (SIBs): Helbig et al. (2018) have demonstrated that LFP had a lower supply risk compared to other battery chemistries and is not subject to geopolitical tensions and socio-economic concerns as in the case of Co in the Democratic Republic of Congo (Cao et al., 2024; Helbig et al., 2018). This could lead to a possible higher adoption of LFP or SIBs after the legislation is imposed.
c) The EU legislation would need to reflect the current reality of the market. For instance, Ku et al. (2024) encourages policy makers to perform retrospective studies of the battery market to assess the effectiveness of policies across the industry. Here, revisiting lessons learnt from the rare earths' crisis may be useful. These lessons could be applied to the current critical battery materials scenario unfolding in Europe and the interactions between the Chinese industrial policy on materials, the US Inflation Reduction Act, and the EU Critical Raw Material Act (Ku et al., 2024).

Compared to the US or China, the EU Battery Regulation is one of the most extensive and detailed regulations to date. However, China's robust regulatory framework, which includes extended producer responsibility and higher materials recovery targets, the involvement of its well-established battery OEMs in recycling activities, as well as local incentives, have facilitated a successful move towards a circular economy (Wang et al., 2022). Moreover, China's early investment in EV deployment and recycling, in addition to its access to battery materials in Africa and Latin America through trade agreements, loans, and investments, have provided China with a competitive advantage and positioned the country as a leader in the battery manufacturing and recycling sector (Jetin, 2023). The EU and US, on the other hand, have lagged in terms of their involvement in the EV transition. To reduce their materials dependencies, they have established and strengthened their Net Zero policies (i.e. the US Inflation Reduction Act (IRA), the EU Battery Regulation, and the Green Deal). The US IRA's main purpose is to reduce import dependency, establish a strong recycling industry and attract foreign investment (Jetin, 2023). Like the EU, the main challenge for the US is to secure a reliable supply of virgin and recycled materials whilst putting measures in place to minimise the loss of strategic and critical materials through EV exports (i.e. OEMs would have ownership of the EV batteries) (Wu and Moerenhout, 2024). Furthermore, it will need a strong nation-wide policy (with individual state's involvement) promoting a gradual increase in recycled content in new EVs and increasing mutual trade agreements with resource-rich nations (Wu and Moerenhout, 2024). China's dominance on battery critical minerals and its geopolitical tensions with the US will force EU OEMs to re-strategize to remain in the battery race (Jetin, 2023).

5. Conclusion

In summary, this study proposes a novel policy-economic assessment framework including a material flow analysis and a resource economic approach that allows researchers to evaluate the multifaceted implications of new regulations for the battery market. This framework is applied to the recent EU Battery Regulation to understand its impact on the availability and prices of recycled critical metals by 2030. The study was supported by an industry-led survey, which informed the development of four price scenarios. Finally, the study presented a cell and pack cost analysis of batteries containing the mandated minimum recycled content conducted with BatPaC and EverBatt.

The material flow analysis demonstrates that recycling can meet recycled Li demand with a surplus of 12 %; however recycled Ni and Co demand could exceed supply by 2030 by 85 % and 62 % respectively. Furthermore, the Industry-led survey indicates 40 % of participants expect a premium on recycled strategic battery metals before the Regulation is in force.

For cell costs, an overall price increase was observed for NCA and NMC811 by 2030. The cell costs for NCA between 2023 prices and the Base Case rise by 12 % ($112/kWh and $125/kWh) and by 10 % for NMC811 ($106/kWh and $116/kWh), respectively. Comparing NCA cell cost between 2023 and Scenario 3 (the most pessimist scenario with a 6 % imposed premium on recycled material prices), there might be a price increase of even up to 15 % ($112/kWh and $129/kWh). For the battery pack, analyses reveal a cost increase of 10 % and 8 % between 2023 prices and the Base Case for NCA ($133/kWh and $146/kWh) and NMC811 ($127/kWh and $137/kWh), respectively. The comparison between the Base Case (no premium) with 2030 prices shows a 5 % and a 4 % increase for NCA ($139/kWh and $146/kWh) and NMC811($132/kWh and $137/kWh), respectively.

While this study focuses on the EU battery landscape, it has global applications beyond the EU. In the future, it would be of interest to assess the price development and demand of these critical materials in different geographical locations such as Asia and the US. For instance, South Korea has announced a soon-to-come legislation that will mandate minimum recycled content for critical minerals. Adopting the here-presented policy-economic framework to South Korea would provide valuable insights to understanding the impact of such policies and benchmark how the market may evolve in this region compared to the EU. Such comparison would provide a holistic view of how international policies and legislations could impact the battery sector as the global battery supply chain is becoming increasingly complex, intertwined, and interdependent.

6. Limitation of the study

Acquiring historical prices for recycled critical and strategic battery materials has been a limitation to the study and assumptions were made based on virgin raw materials and LME prices. The Li conversion cost to reach battery-grade materials quality presents a second limitation to the study due to the lack of data and assumptions were made based on the Ni and Co conversion cost, which were considered reasonable at this stage.

CRediT authorship contribution statement

Malene Fumany: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Viet Nguyen-Tien:** Writing – review & editing. **Nanxi Li:** Data curation. **Robert J.R. Elliott:** Writing – review & editing, Validation. **Laura Lander:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2025.105787.

11. Appendix A.

Table A.1
Parameters used into BatPaC for cell and pack costs for 10 % change in price for CAM (with virgin materials)*.

Net Zero case - 10 % increase												
Parameters	Base Case	S1	S2	S3	Base Case	S1	S2	S3	Base Case	S1	S2	S3
Positive electrode	NCA	NCA	NCA	NCA	NMC811	NMC811	NMC811	NMC811	LFP	LFP	LFP	LFP
Negative electrode	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite
Vehicle Type	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV
Mass or Cost Sensitive Pack Design	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost
Positive Electrode cost, $/kg	43.1	43.1	41.6	45.4	41.0	41.0	39.7	42.9	13.0	12.7	12.7	12.7
Negative electrode cost, $/kg	9	9	9	9	9	9	9	9	9	9	9	9
Net Zero case - 10 % decrease												
Parameters	Base Case	S1	S2	S3	Base Case	S1	S2	S3	Base Case	S1	S2	S3
Positive electrode	NCA	NCA	NCA	NCA	NMC811	NMC811	NMC811	NMC811	LFP	LFP	LFP	LFP
Negative electrode	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite
Vehicle Type	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV
Mass or Cost Sensitive Pack Design	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost
Positive Electrode cost, $/kg	36.5	36.5	34.9	38.8	34.6	34.5	33.3	36.4	10.8	10.4	10.4	10.4
Negative electrode cost, $/kg	9	9	9	9	9	9	9	9	9	9	9	9

* Parameters were derived from the Base Case and the three price scenarios for CAM containing the mandated minimum recycled materials content.

Table A. 2
Parameters used into BatPaC for cell and pack costs for 50 % change in price for CAM (with virgin materials)*.

Net Zero case - 50 % increase												
Parameters	Base Case	S1	S2	S3	Base Case	S1	S2	S3	Base Case	S1	S2	S3
Positive electrode	NCA	NCA	NCA	NCA	NMC811	NMC811	NMC811	NMC811	LFP	LFP	LFP	LFP
Negative electrode	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite
Vehicle Type	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV
Mass or Cost Sensitive Pack Design	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost
Positive Electrode cost, $/kg	56.3	56.3	54.8	58.6	53.9	53.9	52.6	55.8	17.6	17.3	17.2	17.3

(continued on next page)

Table A. 2 (*continued*)

Net Zero case - 50 % increase												
Parameters	Base Case	S1	S2	S3	Base Case	S1	S2	S3	Base Case	S1	S2	S3
Negative electrode cost, $/kg	9	9	9	9	9	9	9	9	9	9	9	9
Net Zero case - 50 % decrease												
Parameters	Base Case	S1	S2	S3	Base Case	S1	S2	S3	Base Case	S1	S2	S3
Positive electrode	NCA	NCA	NCA	NCA	NMC811	NMC811	NMC811	NMC811	LFP	LFP	LFP	LFP
Negative electrode	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite
Vehicle Type	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV	EV
Mass or Cost Sensitive Pack Design	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost	Cost
Positive Electrode cost, $/kg	23.2	23.2	21.7	25.6	21.7	21.6	20.4	23.5	6.2	5.8	5.8	5.8
Negative electrode cost, $/kg	9	9	9	9	9	9	9	9	9	9	9	9

* Parameters consist of Base Case and the three price scenarios for CAM containing mandated minimum recycled materials.

Table A. 3
Costs for cathode cells with 100 % virgin material and predicted cost for cathodes with recycled material as calculated using BatPaC*.

Cathode	LFP	NCA	NMC811
2022/2023 Prices	11.50	35.50	34.50
2030 (10 % increase)	12.65	39.05	37.95
Base Case	13.04	43.07	41.03
Scenario 1	12.68	43.08	40.97
Scenario 2	12.66	41.56	39.73
Scenario 3	12.71	45.42	42.88

* Here, a 10 % increase of the BatPaC cathode cost was assumed (in $/kg cathode) (Nelson et al., 2019).

Table A. 4
Costs for cathode cells with 100 % virgin material and predicted cost for cathodes with recycled material as calculated using BatPaC*.

Cathode	LFP	NCA	NMC811
2022/2023 Prices	11.50	35.50	34.50
2030 (10 % decrease)	10.35	31.95	31.05
Base Case	10.75	36.45	34.57
Scenario 1	10.39	36.46	34.51
Scenario 2	10.37	34.95	33.27
Scenario 3	10.42	38.80	36.43

* Here, a 10 % decrease of the BatPaC cathode cost was assumed (in $/kg cathode) (Nelson et al., 2019).

Table A. 5
Cell cost scenarios using BatPaC based on Boer et al. (2023)'s Net Zero case and assuming a 10 % increase of the virgin cathode material price by 2030 (in $/kWh).

Scenarios	LFP	NCA	NMC811
2023 prices 100 % virgin	92	112	106
2030 prices 100 %virgin	95	118	112
Base Case	96	125	117
Scenario 1	95	125	116
Scenario 2	95	123	114
Scenario 3	95	129	120

Table A. 6
Cell cost scenarios using BatPaC based on Boer et al.(2023)'s Net Zero case and assuming a 10 % decrease of the virgin cathode material price by 2030 (in $/kWh).

Scenarios	LFP	NCA	NMC811
2023/2022 prices 100 % virgin	92	112	106
2030 prices 100 %virgin	89	106	100
Base Case	90	114	106
Scenario 1	90	114	106
Scenario 2	90	111	104
Scenario 3	90	118	109

Table A. 7
Pack cost scenarios using BatPaC based on Boer et al. (2023)'s Net Zero scenario and assuming a 10 % increase of the virgin cathode material price by 2030 (in $/kWh).

Scenarios	LFP	NCA	NMC811
2023/2022 prices 100 % virgin	114	133	127
2030 prices 100 %virgin	117	139	132
Base Case	118	146	137
Scenario 1	117	146	137
Scenario 2	117	143	135
Scenario 3	117	150	140

Table A. 8
Pack cost scenarios using BatPaC based on Boer et al. (2023)'s Net Zero scenario and assuming a 10 % decrease of the virgin cathode material price by 2030 (in $/kWh).

Scenarios	LFP	NCA	NMC811
2023/2022 prices 100 % virgin	114	133	127
2030 prices 100 %virgin	111	127	121
Base Case	112	135	127
Scenario 1	111	135	127
Scenario 2	111	132	125
Scenario 3	111	139	130

Table A. 9
Cell cost comparison between Net Zero and Stated Policy scenario for Scenario 2 (in $/kWh).

	Net Zero Scenario	Stated Policy scenario	2023 prices 100 % virgin
LFP	95.01	94.88	92.21
NCA	125.34	116.85	112.25
NMC811	116.41	110.12	105.93

Data availability

All open-access data used in this analysis can be made available upon request. Data obtained from CES Online is restricted by membership and cannot be shared. Survey participants have been guaranteed anonymity, and their identities will not be disclosed.

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