Optimising the geospatial configuration of a future lithium ion battery recycling industry in the transition to electric vehicles and a circular economy

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DOI:
10.1016/j.apenergy.2022.119230

Applied Energy 321 (2022) 119230

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimising the geospatial configuration of a future lithium ion battery recycling industry in the transition to electric vehicles and a circular economy ☆

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HIGHLIGHTS

- Annual EV LiB recycling demand in the UK is projected to grow dramatically and reach 12.7 GWh by 2040, sufficient to feed 60% of a 20GWh battery plant in 2040.
- Financial incentives, robust EV commitment and strict EOL LiB enforcement, are required to support the nascent recycling industry.
- Scaling up a geospatially-optimised central recycling plant is the most cost-effective option, while the domestic market can host up to three pyrometallurgical recyclers or seven hydrometallurgical recyclers.
- Closed-loop recycling is estimated to substantially reduce cost, save resources and cut emissions of EV battery manufacture.

ARTICLE INFO

Keywords:
Lithium-ion batteries
Electric vehicles
Circular economy
Recycle
Life cycle assessment
Supply chain
Material flow analysis
Transitions
Transition management

ABSTRACT

Rapid electrification of the transport system will generate substantial volumes of Lithium-ion-battery (LiB) waste as batteries reach their end-of-life. Much attention focuses on the recycling processes, neglecting a broader systemic view that considers the concentration of the costs and impacts associated with logistics and transportation. This paper provides an economic, environmental and geospatial analysis of a future LiB recycling industry in the UK. Hitherto, state-of-the-art assessment methods have evaluated life cycle impacts and costs but have not considered the geographical layer of the problem. This paper develops a GSC derived supply chain model for the UK electric vehicle and end-of-life vehicle battery industry. Considering both pyrometallurgical and hydrometallurgical recycling technologies, the optimisation process takes into account anticipated EV volumes, and, based on anticipated near-term technological evolution of LiBs, the evolution of the mix of battery cathodes in production, and presents a number of scenarios to show where LiB recycling facilities should ideally be geographically located. An economic and environmental assessment based on a customised EverBatt model is provided.

1. Introduction

As the world rapidly scales-up its transition to electric mobility [1], attention shifts to considering the end-of-life (EoL) of lithium-ion batteries (LiBs) that power electric vehicles (EVs) to address some critical concerns. The motivation behind the transition to electric vehicles, is one of a system wide transformation to cleaner automobility. Whilst there is a broader boundary that encompasses the socio-technical regime of mobility and the shift to electric vehicles, a tighter boundary could be

☆ GABREAL: An Economic, Environmental and Geospatial Analysis of Recycling Electric-vehicle Lithium-ion Batteries.

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https://doi.org/10.1016/j.apenergy.2022.119230
Received 30 June 2021; Received in revised form 20 March 2022; Accepted 30 April 2022
Available online 30 May 2022

Abbreviations

g	gram
GBP	British pound sterling
GWh	Gigawatt hours (10^9 Wh)
kg	Kilogram(s)
km	kilometre
kt	thousand tonne (s) (10^6 kg)
l	litre
MJ	Megajoule
USD	United States Dollar

Acronyms

ABTO	Approved Battery Treatment Operator
ATF	Authorised Waste Treatment Facility
BEV	Battery Electric Vehicle
CO2	Carbon dioxide
EEA	Economic and Environmental Assessment
ELV	End-of-life Vehicle
EOL	End of life
EV	Electric vehicle
GABREAL	Geospatial Assessment of Battery Recycling Economics, Environment and Location
GDP	Gross Domestic Product
GHG	Green-house Gas
GSC	Geospatial Supply Chain
GVW	Gross Vehicle Weight
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LCO	Lithium cobalt oxide
LDV	Light-duty vehicle
LFP	Lithium iron phosphate
LGV	Light-good vehicle
LiB	Lithium-ion battery
LMO	Lithium manganese oxide
MFA	Material Flow Analysis
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide
NOx	nitrogen oxides
PHEV	Plug-in Hybrid Electric Vehicle
PM10	Particulate Matter of 10 μm / Microns in diameter or smaller
SOx	Sulfur oxides
T&D	Transmission and Distribution
ULEV	Ultra-low emission vehicles

drawn around the industry that deals with vehicles at the end of life. This paper has been written to inform elements of that transition, illustrated in Fig. 1, and encompasses recommendations for some elements of the emerging new socio-technical regime which sits at a nexus of concerns about energy transition, materials security, sustainability and the circular economy. Whilst the focus of this paper is not on the nature of the transition, or about transitions theory per-se its recommendations can be considered as forming a contribution to the transition management of this domain. Transitions management scholar have advocated for scholars to consider how to influence ongoing transitions in more sustainable directions [2].

First, how does an economy deal with the spent lithium-ion batteries

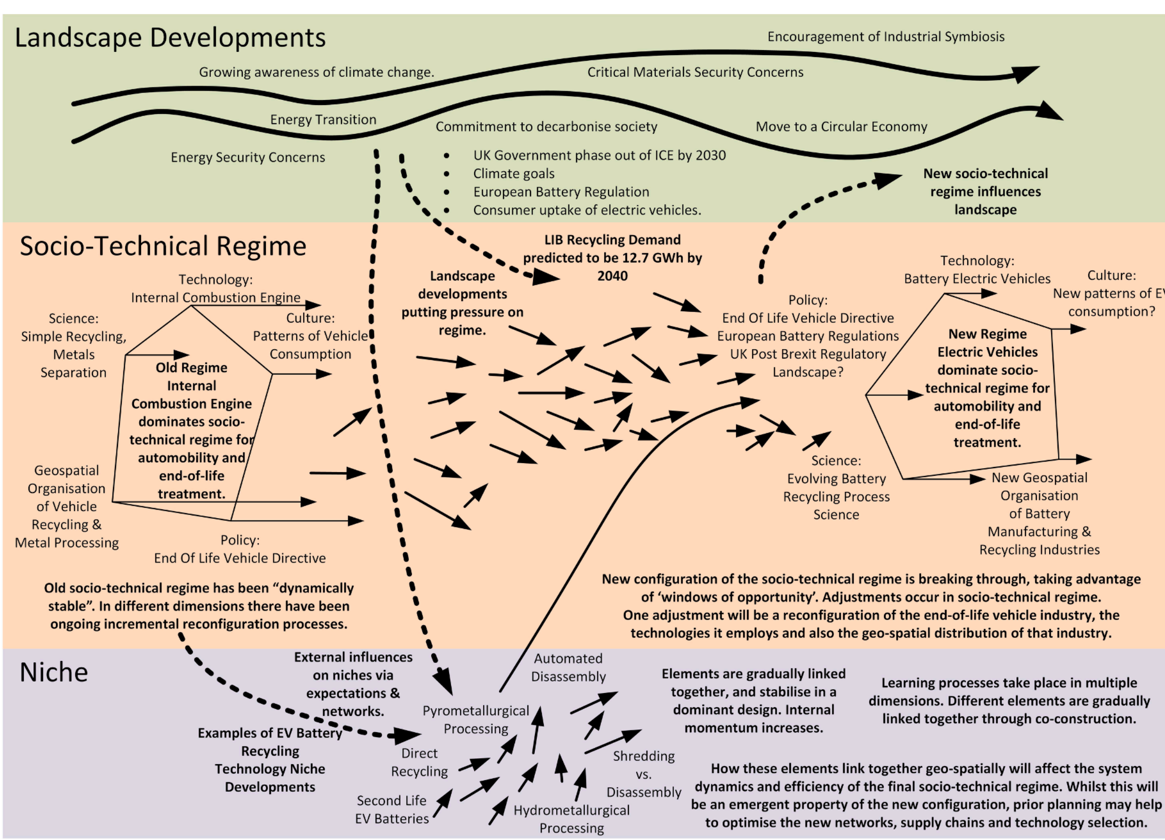

Fig. 1. The transition to a circular economy of electric vehicles, framed through the multi-level perspective. Reworked after Geels [3].

(LiBs) when they no longer meet the required level of performance to be used in EVs. As illustrated in [4], the sale of over one million EVs in 2017 will result in around 250 thousand tonnes (kt) and half a million m^3 of unprocessed pack waste. LiB waste if disposed to land in an unmanaged manner could leak toxic substances to water supplies [5] and risk explosion [6]. Secondly, the predicted increase in demand raises questions about the future availability of the raw materials that are considered critical for the production of EVs and LiBs [7] such as cobalt, lithium and graphite. Coronavirus pandemic-induced supply disruptions in refined materials from China, Japan and South Korea [8] and more recently in raw lithium from Argentina and Chile [9] highlight the vulnerability of the supply chain and the importance of material security to EV manufacture. These two problems are closely related because many countries with the largest potential demand for EVs are those countries with limited supply of the critical raw materials but are also, paradoxically where governments and stakeholders have expressed strong ambitions to develop a global leading EV industry.

One possible solution is to create a "circular economy" for LiBs that has the potential to address both problems simultaneously [10,11]. For example, a number of retired batteries, such as relatively new ones from crashed cars, could be refurbished and reused in other EVs. Batteries no longer fit for use in EVs may still find a useful second life in less demanding applications such as stationary energy storage. However, in all cases, at some point, recycling provides an opportunity to supply recycled materials for the manufacture of new EV batteries. To this end, closed-loop recycling has the potential to transform retired LiBs from an environmental burden into a strategic resource [12]. Indeed the Nobel laureate Akira Yoshino claims that recycling is crucial to meet future raw material demand driven by the rise of EVs [13]. A range of strategies will be employed in a future circular-economy of electric vehicle batteries. The strategies implicit in the analysis of this paper fit Morseletto's framework in the range of R3-R9 strategies [14], with the bulk of the analysis focused on R8 Recycling[14], and implied through the nature of the Pyrometallurgical Recycling Processes which consumes some battery materials in the recycling process, R9, Recovery[14].

While the feasibility of LiB recycling has been proven in certain contexts, there remain a number of important barriers to the widespread adoption of recycling technologies including in more developed economies. One constraint is that existing EV batteries have not been designed with recycling in mind so there is considerable scope to improve the efficiency and versatility of the recycling process to cost-effectively handle different types of LiBs, including those using low amounts of cobalt [15]. As the recycling process is capital-intensive, economies of scale issues mean that investment is sensitive to recycling demand, which is, however, uncertain because of many factors including, but not limited to, market size, EV penetration rates, LiB lifespans in their first life serving EVs and subsequent cascades of reuse and repurposes, the enforceability of the bans to landfill LiBs, and the competitiveness of the business. The logistics associated with processing spent batteries for recycling is also a concern due to hazards related to the thermal instability of LiBs [16,17] and as such, establishing localised recycling facilities is advantageous [18]. For many of the issues mentioned above, policies and regulations can play a role in reducing business risks and optimising the supply chain for any new recycling industry.

This paper introduces a self-consistent, transparent, and updated quantitative assessment framework that combines a Material Flow Analysis (MFA), a Geospatial Supply Chain (GSC) model and an Economic and Environmental Assessment (EEA) using the UK as a case study. As such, it integrates numerous techno-economic factors to assess the economic and environmental (where applicable) cost and benefit of LiB recycling along different stages of development, including (1) an establishment of a central recycling scheme in the infancy of the capital-intensive industry, (2) a competitive structure when the industry scales up, and (3) the integration of a mature recycling industry with the full supply chain of the automotive sector to form a closed loop. The model is dynamic and forward-looking to cover the crucial period of 2030–2040 to support policymaking. For exposition purposes, the framework used in this paper is labelled GABREAL (Geospatial Assessment of Battery Recycling Economics, Environment and Location).

This study is at the frontier of a rich literature strand to investigate the economic and environmental impact of EVs. Most recent studies highlight the urgent need for leading EV markets such as China [19], US [20-22], and EU [23-25]. to plan for the proper treatment of the anticipated volumes of waste from spent LiBs. In response, there has been a rapid increase in research on how to treat LiBs after their retirement from EVs [26]. The environmental impact of recycling however, was not well settled, perhaps due to a variation in the context, energy mix, cathode chemistry, recycling configuration and system boundary. Some claim that the environmental benefit of hydrometallurgical and pyrometallurgical recycling is insignificant or negligible [27-29] while others highlight a wide range of benefits, including resource conservation [30,31], energy saving [32], toxic air pollutant emission reduction [33], and GHG emission reduction [34,35]. In terms of economic impact, researchers have considered different aspects of recycling viability such as material prices [36], scale and chemical composition [37], logistics [33,38], project cashflow and utility rates [39], government subsidy [40], technological choices [15], and the relationship between LiB recycling and EV recycling [41].

The technology underpinning the LiB recycling sector is still under active development. As a result, using contemporary data and advanced modelling is important to understand how a new industry will perform. Early studies have used the Excel-based EverBatt model developed by Argonne National Laboratory [42] to model the LiB recycling industry for different regions and has most recently been used to assess the viability of closed-loop recycling in China [43]. In this paper it is argued that the insights that can be gained from using process-based static models, such as EverBatt, can be improved considerably if the results from the standard model are incorporated into a broader dynamic modelling process that takes into account the underlying socioeconomic, institutional, regulatory, and technical drivers of recycling demand and, crucially, the spatial aspect of the planning problem.

The UK provides an ideal country to apply the GABREAL framework. Its automotive sector is strategically important but faces fierce global competition and potential damage from post-Brexit tariff regimes on final and intermediate goods. It is widely thought that a country can only be competitive in the EV sector if it is able to secure ready access to batteries which is assumed to mean having batteries manufactured locally and at scale (which has its own important employment implications) [44]. It was with some relief therefore when Britishvolt (a start-up company) announced that the UK's first large-scale GigaFactory would be built in Wales although batteries would not be produced until 2023 and even then the investment was dependent on government financial support [45]. Later, it was announced that the manufacturing facility would be moved to the North East of England. Sourcing the raw materials for EV batteries (primarily. lithium, cobalt, and nickel) from ethical and sustainable sources in a nation without significant natural resources will be an ongoing challenge [46,47]; potentially amplified following the UK's departure from the EU. Fig. 2 presents a model of the circular economy associated with EV LiBs and how recycling can play an important role in the electrification of the transport sector.

An important dimension when it comes to justifying a LiB recycling sector is how waste batteries are regulated. Currently, LiBs are regulated by the Waste Batteries and Accumulators Regulations 2009 which stipulates that batteries cannot be sent to landfill. As there is currently no well-established recycling facility in the UK , it means that the only legal route to handle most of spent LiBs is to stockpile them somewhere or to export them (the nearest recycling facility is in Belgium). Strategically, in a post-Brexit world, a local recycling plant not only provides a means to deal with the waste materials but also provides a valuable source of raw materials for domestic battery producers. However, while politically and strategically it might appear obvious that the UK should

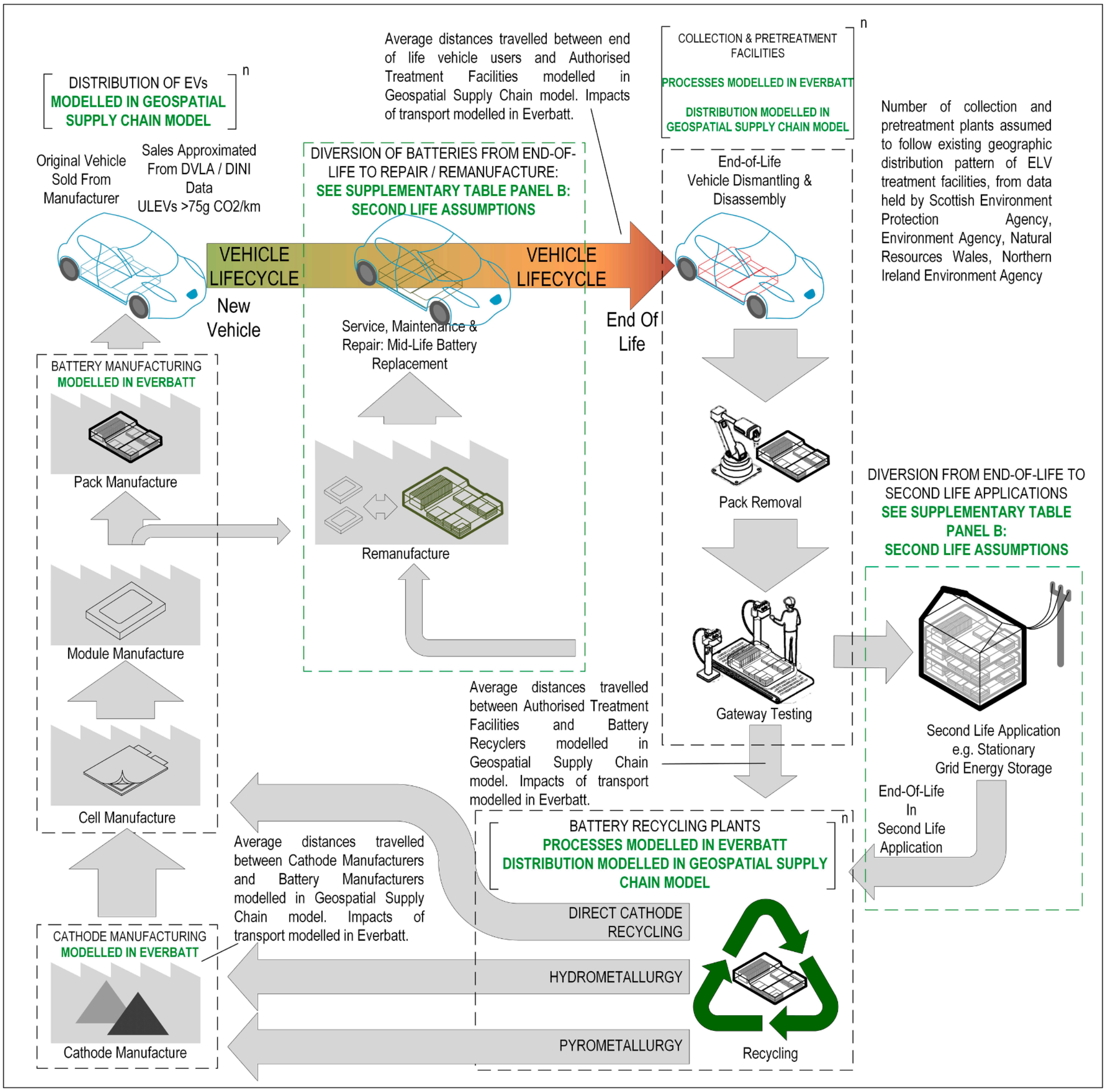

Fig. 2. Modelling the Circular Economy of Electric Vehicle LiBs.

prioritise the development of LiB recycling facilities it is important to consider the underlying economics. As Nissan recently warned, any new industry should not be scaled up too early, at least not before there is a clear and sustainable source of retired EV batteries [48]. So while there are risks around the possibility of insufficient capacity, the converse risk is a "tragedy of the commons" type scenario, where, given a finite stock of EoL LiBs being supplied to the market, multiple independent recyclers seeking first-mover advantage end up creating excessive capacity, for which there is insufficient waste to enable any of the plants to be profitable in the short to medium term.

2. Materials and methods

This study is interdisciplinary in nature and uses a wide range of data as detailed in Supplementary Table 1 (see above-mentioned references for further information). The data are inputted into three sequential modules: Material Flow Analysis (MFA), Geospatial Supply Chain (GSC) and Economic and Environmental Assessment (EEA) that together to form GABREAL (Geospatial Assessment of Battery Recycling Economics, Environment and Location). Each module is discussed in turn.

2.1. Material flow analysis

The MFA forecasts the demand for lithium-ion battery recycling by cathode chemistry at the regional level. Although there could be a mismatch between the lifespan of EVs and LiBs, the MFA follows the previous literature, for example [21] and simplifies the analysis by only considering LiBs from new EVs which are by far the most important in terms of volume. The calculation is given by:

$$R_{icT} = \sum_{t=2010}^{T} \left\{ S_{it} \times E_{it} \times B_t \times C_{ct} \times \sum^{r} \sum_{t_1 \geq 0}^{t+t_1+t_2(r,t_1)=T} [P(r|D(t,t+t_1)) \times P(D(t,t+t_1))] \right\} \quad (1)$$

In Equation (1), recycling demand (R_{icT}) is measured in terms of total energy (kWh), for cathode chemistry c, in region i, and year $T(2025 \leq T \leq 2040)$ and is estimated as the sum of the battery capacity of that chemistry equipped in EVs that were registered in each year t (2010 $\leq t \leq T$) and are projected to enter the recycling channel in year T. Batteries starting their useful life in year t have various outcomes. After serving t_1 years in an EVs a battery follows one of four routes (denoted by subscription r): (1) recycling; (2) reuse; (3) repurpose; or (4) other (such as research) before ending up recycling (see Section 2.1.4 for details). Each route could extend battery life by t_2 years ($t_2 \geq 0$), with no life extension if batteries go directly to recycling after serving in an EV. As such, the demand for recycling depends on a number of variables including:

- New LDV sales proxied by registration number at the regional level (S_{it})
- The regional EV penetration rate (E_{it})
- The average EV battery capacity (B_t)
- The penetration rate of chemistry j in new EV sales (C_{ct})
- The discard probability of batteries serving t_1 year in EVs conditional on the technology in registration year $t(P(D(t, t+t_1)))$
- The probability of batteries to entering each route r conditional on registration in year t and the discard in year $t + t_1$ $(P(r|D(t, t+t_1)))$
- The average extension time in route r of the second life, which is assumed to depend on service time in EVs $(t_2(r, t_1))$.

Historical data or estimates for 2010–2019 and projections for 2020–2040 are used. Vehicle-related data are disaggregated at the regional level while battery specific variables are assumed to be homogenous across the country and depend on the available technology in registration year t. The assumptions and methodology used for the projections for each component of this function are described below.

2.1.1. New LDV sales

This study only considers light-duty vehicles (LDV), which includes cars and light goods vehicles (LGVs). This vehicle type constitutes the most important segment of the vehicle fleet and is at the centre of vehicle electrification policies in the UK. As a first step, vehicle sales are projected for 12 regions across the UK using the same subscriptions as equation (1) and given by:

$$s_{it} = \beta_0 + \beta_1 y_{it} + \beta_2 p_t + \mu_i + \psi_i t + \varepsilon_{it} \tag{2}$$

- s_{it}: The annual number of LDV registrations per head at the regional level (in logs).
- y_{it}: Annual deflated Gross Domestic Product (GDP) per head at the regional level (in logs) as a proxy for real income level with an expected positive impact on the dependent variable.
- p_t: An index for fuel price incorporated with fuel efficiency (in logs) with an expected negative impact on the dependent variable.
- μ_i: Regional fixed effects to capture regional unobserved specific effects.
- $\psi_i t$: A regional time trend to capture monotonic time varying factors that are specific to each region.
- ε_{it}: an idiosyncratic error term.

The model is calibrated using data from official sources such as the Office for National Statistics (ONS), Driver and Vehicle Licencing Agency (DVLA), Department of Transport (DfT) for the period 2010–2018. Supplementary Table 3 shows that the coefficients are statistically significant and have the expected signs. The baseline model (model 3) explains 94% of variation in the dependent variable as captured by the adjusted R^2. To forecast LDV registration at the regional level, the model is combined with the latest projections for regional economic growth (these predictions have been adjusted for the impact of the COVID-19 pandemic), population, and fuel prices (from official sources). The forecasts are presented in Supplementary Fig. 1.

2.1.2. EV penetration rates

EV registrations are calibrated for the UK using official statistics and include battery electric, plug-in hybrid electric, and range extended electric cars, taxis and LGVs. This annual series is then disaggregated by region using the simplifying assumption that each vehicle type has the same regional share as that officially recorded for ULEVs (defined as vehicles that emit less than 75 g of carbon dioxide (CO2) from the tailpipe for every kilometer travelled). Given that the share of EVs in total ULEV registrations is gradually approaching 100% (as ULEV registrations increases over time), this is arguably a fair approximation. Historical regional EV penetration rates are estimated as the ratio of EV registrations to LDV registrations.

Forecasting future EV penetration rates is challenging as the rates are driven by a variety of factors that are difficult to anticipate such as growth in incomes, consumer tastes, policy incentives (being turned on and off), and the speed of technological progress [49]. The existing literature presents a wide range of projections for the EV uptake rate (for example see [50] for a synthesis of forecasts). Different versions of the same technical model to forecast EV adoption, for example [51,52] could produce a different range of projections with the more recent models that include new policy commitments, technical advances and changes in customer behaviour, being more optimistic.

In this study of the UK, the policy commitments used to project the future of the EV market is similar to the approach followed by [53,54]. Most recently, prime minister Boris Johnson announced a new policy target to outlaw the selling of all polluting cars and vans including petrol, diesel and hybrid vehicles by 2035 [55], this was later brought forward to 2030. However, hybrid cars will remain on sale until 2035, which may include relatively mild hybrids. The commitment is ambitious and aims to deliver zero emissions from road transport by 2050 [56]. A committee of the Commons even called for a more ambitious target of only zero emission cars and vans being allowed to be sold in 2032 [48]. The current opposition Labour party also proposed to introduce a policy to ban ICEVs from 2030 [57]. External pressure to deliver on zero emission transport commitments include similar policies that are expected to bring forward the date by which no ICEVs can be sold by 2025 in Norway and 2030 in Denmark, Iceland, Ireland, Isreal, Netherlands and Slovenia [1].

In the base case, after 2019 the forecast assumes regional EV penetration rates will grow at a compound rate of 33.29% per annum until it reaches 100%. Because, as of 2019, regions have adopted EVs at different rates, this approach allows LDV sales in regions other than North East and Wales to become fully electrified earlier than 2035. This is illustrated in Supplementary Fig. 2. London, together with West Midlands, are predicted to lead the way and to have stopped buying ICEVs and hybrid cars and vans by around 2030. Although highly ambitious this target is consistent with the vision set out by London Mayor [58]. In another example, LDV sales in Scotland are projected to be full electrified by 2032 which is close to the target announcement by Scottish government [59].

2.1.3. Battery mix

With a relatively high power density, low weight, long life [60] and high charge–discharge efficiency [61], LiBs are currently the preferred technology for EVs. The cathode chemistry of a battery is what determines how a LiB behaves [62]. Lithium cobalt oxide (LCO) has a high-performance rating and is widely used in electronic devices but has relatively low stability and its high cobalt content makes LCO batteries uncompetitive for EV applications. Reliable and inexpensive lithium manganese oxide (LMO) was used in the first EVs such as the Nissan Leaf but become less attractive as new cathodes with higher cell durability emerged [62]. Lithium iron phosphate (LFP), with low energy density but low cost, is used predominantly in China [63] or for heavy-duty EVs such as trucks and buses [64]. High energy density and high power capability makes lithium nickel cobalt aluminium oxide (NCA) the chemistry of choice for the high performing and relatively expensive Tesla range of vehicles [7,65]. Other automakers prefer lithium nickel manganese cobalt oxide (NMC), which has a lower energy density but has a longer cycle life [16]. NMC has several variants depending on the ratio of nickel, cobalt, and manganese on a molecular fraction basis. Their overall commercial notation is NMCabc corresponding to chemical representation $LiNixMnyCozO_2$, where $x + y + z = 1$ and $x = a/(a + b + c)$, $y = b/(a + b + c)$ and $z = c/(a + b + c)$ [12].

Understanding the chemical mix of retired LiBs is important when it comes to assessing the economic viability of co-mingled recycling in the context of this research as values of recovered materials vary between different types of battery. In this study it is assumed that the composition of new LiBs depends on the technology available in the year of the EV registration and rely on analysis from a recent study for the EU [23]. Accordingly, the penetration rates of LiB in EVs are assumed to be 80% in 2010 and then to linearly increase to 100% by 2015. The share of LiBs that are NMC variants (NMC111, NMC532, NMC622 and NMC811) and NCA are presented in a table in [23] for every five years between 2010 and 2030. However, they do not sum to 100% except in 2030, which mean that the chemistries of many LiBs are not specified. After 2020, the NMC chemistry is expected to evolve so that the cobalt content is reduced and NMC111 is gradually replaced by NMCs with more nickel such as NMC532, NMC622, or NMC811.

In the analysis input data for every year between 2010 and 2030 is linearly interpolated. With reference to additional information from [1,66] it is assumed that a portion of the unspecified LiBs (other than NMCs and NCA) are LMO and it is also assumed that its percentage in LiBs decreases from 20% (2010) to 15% in 2015, 5% in 2020 before being phased out from 2025. LMO is a predecessor of NMC and NCA and is still used as a blend with other chemistries. LFP is not included because it is little used in the UK, especially when only cars and vans are modelled and not buses. The remainder of the unspecified LiBs are considered as either NCA or NMCs using their reported ratios. After 2030 other assumptions are added. First, it is assumed that the penetration rate of current LiBs in EVs will gradually decrease to 70% between 2030 and 2040 due to the acceleration of next-generation batteries that are not included in the analysis for recycling yet. For example, solid-state batteries are expected to outpace LiBs thanks to their smaller size, lower cost, faster charging and longer life [67]. Sodium-ion batteries are also being considered, although they do not outperform LiBs yet but are attractive because sodium is more abundant and cheaper than lithium [68]. Battery design such as Li-air and Li-sulphur have higher theoretic energy densities and lower theoretical costs but the technology is not considered to be robust enough to replace LiBs in a far future (i.e. after 2030) [1]. Among current LiBs, we assume that the trend to decrease the cobalt content of NMC remains, with NMC111 assumed to be phased out by 2035 so that the LiB mix by 2040 includes 50% NMC811, 25% NMC622, 10% NMC532 and 15% NCA. The assumptions underpinning the cathode chemistry mix are captured in Supplementary Fig. 3.

In addition, the average capacity of LiBs, as illustrated in Supplementary Fig. 4, is based on the European battery capacity of PHEVs and BEVs estimated in [1] and projected in [69] and a split between PHEVs and BEVs in EV registrations, which is calculated from DVLA data and Ricardo's Medium xEV Scenario for Europe [50].

2.1.4. First life, second life and recycling rates

As the world is at an early stage in the electrification of the transport system, knowledge of the lifespan of different LiBs in EV applications is still in its infancy with current evidence reporting a wide range that stretches from 5 to 20 years [70]. Previous studies use distributions to characterise life span as this approach allows a variation between users with different use and charging patterns [20].

To derive a discard function for LiBs from the first life (being in an EV) this study uses a two-parameter Weibull distribution similar to one that was recently used for the US [21]. Accordingly, the shape parameter that describes the contrariness of the pattern is assumed to be time-invariant and fixed at 3.5 while the scale parameter is set close to the expected average EV lifespan, which is assumed to increase over time due to technical progress (see Panel A of in Supplementary Table 4). One modification used in this paper is to assume that all EVs bought before 2020 are similar to those purchased between 2010 and 2015 and have a common average life span of 8 years (which best matches the evidence from the UK [25]).

For simplicity, it is assumed that once the UK has established its own recycling facilities, then the capacity will be sufficient to meet the demand from domestic EVs. This means that there are no exports or imports of used LiBs in the base case (otherwise they cancel each other out). LiBs used as a source of power in EVs are classified as industrial batteries and the Waste Battery and Accumulator Regulations 2009 outlaws the disposal of them through landfill or incineration [71,72]. It is assumed that regulations will be strictly enforced, and all domestic LiBs at their EoL will ultimately reach the recycling channel. However, the potential for a battery to have a second life means that recycling could be delayed.

For modelling purposes, the second life assumptions are based on a recent study for Europe [73] and presented in Panel B of Supplementary Table 4. Accordingly, the fate of a retired LiB is determined by its residual capacity and the overall state-of-health. Four pathways are considered: (1) immediate recycling at discard year; (2) reuse in other EVs after refurbishment; (3) repurpose for other application such as stationary energy storage; and (4) other purposes such as research. Battery age, when removed from EVs are categorised into four groups (up to 10 years, 11–15 years, 16–20 years and 21 years and more) and determines the probability that a battery is assigned to each fate and the duration of the second life application if applicable. Older batteries are less likely to go through a second life before recycling and any second life, if available, will tend to be shorter and less demanding in terms of residual capacity.

2.2. Geospatial supply chain model

To deliver the GSC model, it was necessary to collate a wide range of GIS data. Local Administrative Units Level 1 were used by [74] to determine regional boundaries of the UK. The road network is merged from the Strati dataset [75] for UK roads and OSNI Open Data – 50 k Transport Lines [76] for Northern Ireland roads. To enhance the computational speed while maintaining the network's overall connectivity, only A and B class roads were included (dual carriages and primary roads). Road networks separated by the sea are connected by ferry routes and the shapefiles were obtained from OpenStreetMap. In addition, shapefiles were created for various facilities using the address lists provided by the authorities. More specifically, ATF locations are merged from national lists [77-80]. A list of ABTOs for industrial and automotive batteries was obtained from [81].

For modelling purposes, the current network of Authorised Waste Treatment Facilities (ATFs) are used. ATFs are legally designated to handle End of Life Vehicles (ELVs) and can be used as a proxy for future demand for LiB recycling. A competing channel is the collection of retired LiBs through car dealerships [33] if producers are legally bound to take back industrial batteries if they supply a new one to a customer [82]. Assuming that batteries are processed through ATFs better suits the assumptions underpinning the MFA, which focuses on retired LiBs from ELVs rather than battery replacement. In addition, it is assumed that recycling demand as forecasted by the MFA is distributed equally between ATFs in a same region but vary across regions. Using the current ATF network to model the future, means that any changes over time to the network are assumed to be approximated by the current spatial distribution between regions.

Although proximity to current demand points is set as a target in the model optimisation, candidate locations for future recycling facilities should ideally satisfy a number of conditions such as a good access to logistics corridors for bulk transportation, a skilled pool of labour [83] and facilities that are able to meet the duty of care and hazardous waste regulation requirements when processing industrial waste. It can be argued that these considerations are similar to the factors that are taken into account when Approved Battery Treatment Operators (ABTOs), which are licensed to treat or recycle portable, industrial or automotive batteries, decide where to locate. Hence, current ABTOs locations are used as proxies for the hypothesised candidates for future LiB recycling plants. Ultimately the locations chosen from the analysis should not be interpreted as an exact set of coordinates but as proxy for the surrounding area (such as a local authority or region) that is most likely to be able to host a recycling plant and share some characteristics with existing ABTOs.

The optimisation procedure assumes that retired LiBs will be sent to the nearest recycling plant, which are selected to minimise the cost and hazard associated with the transportation of LiBs as measured by km-tonne travelled [33]. GIS data for the GSC analysis are gathered or georeferenced from official sources [74-76,78-81].

2.3. Economic and environmental assessment

The economic and environmental assessment is based on a customised version of the current EverBatt model [42] which, in turn, built on BatPaC model [84] and GREET model [85]. The EverBatt model is a versatile, process-based model that is able to simultaneously assesses the cost and environmental impact of LiB recycling. It can be used in combination with other activities to form a closed loop, so that it includes battery collection and transportation, cathode powder production, and battery manufacturing with recycled materials. For each of these activities, EverBatt details the process and then computes (some) requirements from machinery, buildings, operating labour, raw materials, utilities (such as electricity, fuel, water and waste disposal) and then calculates factor costs using a transparent and customisable library of unit costs and environmental impacts. The factor costs are then used to model capital requirements and production costs based on a cost structure for a general-purpose chemical plant [86]. Economies of scale in this study are modelled through a non-linear relationship between plant capacity and purchased machinery cost, which allows a larger facility to achieve a more efficient investment capital, and a more competitive production cost [42]. Meanwhile, revenue is derived from the calculation of the quantity of recovered materials and commodity prices that are assumed to depend on the larger global market.

A contribution of this paper is to introduce a number of modifications to the publicly available EverBatt model. First, this study is the first to provide parameters that are specific to the UK (and Europe in general). At the current time, the four geographic variants included in the standard EverBatt model are California, a US national average, China, and South Korea. Second, the NMC532 battery chemistry is added to six cathodes that are already available in the standard EverBatt model (LCO, LFP, NMC111, NMC622, NMC811 and NCA). Third, the hydro plant modelling used in the base case of this paper is an upgrade of the existing Everbatt hydro plant modelling system (which recycles batteries via mechanical separation followed by hydrometallurgical processing but does not recover lithium). More specifically, the hydro modelling in this paper expands the default process by adding a series of evaporation, centrifugation, and precipitation steps to allow for lithium recovery as a crude lithium carbonate from the solvent extraction effluent with the assumption that the recovered lithium carbonate is worth a half the value of virgin materials. A sensitivity analysis uses the EverBatt default hydrometallurgical recycling set up. Pyro plants in this study are the same as those included in the default pyro plant option in EverBatt which is in fact, a pyro and hydro hybrid process that recycles batteries via smelting followed by hydrometallurgical processing (e.g., leaching, solvent extraction, precipitation, etc.). Direct physical recycling is not considered in this study as the technology is still in a very early stage and less likely to be commercially operational soon.

The set of parameters for UK as a new geo-variant for the EverBatt model are derived as follows. Building costs were computed from US costs, adjusted by a factor of 0.7607, which is the ratio between the average building cost of a high tech factory/laboratory between the UK and the US derived from [87]. Direct labour costs were computed from US costs, adjusted by a factor of 0.73 according to relative hourly compensation costs in manufacturing reported by an industrial source [88]. Electricity and Gas costs were from the IEA [89]. Water and wastewater discharge costs were calculated as an average of ten regions for a medium-size business that consumes 1,500 m3/month [90]. Landfill costs were calculated from [91]. Whenever data for several years was available, data for 2017 or the nearest year was used. The hazardous materials transportation cost, assumed to be transported by heavy-duty truck, was estimated from a recent reliable industrial source. Non-hazardous materials transportation costs were calculated based on [92]. A medium-duty truck is assumed to be 7.5 tonnes GVW with an annual mileage of 40,000 while a heavy-duty truck is assumed to be 26 tonnes GVW with an annual mileage of 60,000. Equipment costs are adjusted by a factor of 90% (which is the average of the US (100%) and Korea (80%)). The default values for materials are kept the same as the US and South Korean model as they are consider global commodities [42]. The exchange rate used to convert USD to GBP is 0.74. Unit conversion was performed to align UK units with those used in the standard EverBatt model. Costs are rounded up to the same number of digits as the other EverBatt geo-scenarios.

In our analysis, the assumptions on cost structure of the model are adhered to but excludes a profit of 5% on the total investment capital. The EverBatt default assumption that plant capacities are set at the nearest thousand tonnes of 1.5 times annual throughput and plants operate 20 h per day for 320 days per year is also adopted in this paper. Geographical variation in the environmental impact is only modelled via energy mix differences. More specifically, the energy mix forecast is used for the UK in the Two Degree Scenarios [93] and a T&D loss of 8% is assumed (which is similar to the level reported in [94]).

The economic impact of recycling is evaluated in two alternative setups. First, an open-loop assessment quantifies the costs and benefits of recycling as an independent business and as such the viability of the business is judged based on the differences between revenues and costs. Open-loop recycling includes two processes: (1) collecting and transporting spent batteries from collection sites to the recyclers; and (2) the recycling of collected batteries. The cost of these processes is calculated separately for each plant and as such in competitive recycling scenarios, a small plant serving remote customers faces higher costs than a large central plant. Following the literature, the transportation cost between end-users and collection sites is negligible and hence ignored [33]. The weighted average distance between collection sites and each recycler, as optimised in the GSC model, are inputted to calculate the transportation cost using a UK-specific heavy-duty rate with hazardous materials transportation requirements. Non-negative profits (the difference between revenues and the cost of collection, transportation, and recycling) are required for the industry to be financially sustainable. In reality, the economic benefits can be shared between participants along a supply chain which include the recycling plants and logistics agencies but it could also be used to buy EoL LiBs from their owners, or to reduce material costs for battery manufacturers.

Second, a closed-loop assessment is examined where open-loop recycling is a component of an extended process whereby recovered materials are used to produce new batteries. The economic performance of recycling is assessed by comparing the cost of battery manufacturing from recycled materials against battery manufacturing using virgin materials. To capture the environmental impact, closed-loop recycling is benchmarked against the manufacturing of LiBs from virgin materials across four environmental impact categories including energy use, water consumption, air pollutant emissions, and greenhouse gas (GHG) emissions based on output attributes from the GREET LCA model. As the assessment is for the future, the energy mix used is a forecast for the UK using Two Degree Scenarios [93] while assuming a transmission and distribution (T&D) losses of 8% (which is similar to the contemporary level reported in [94]). A caveat is that the raw materials that are assumed to be imported into the UK for the whole process have a similar environmental impact based on the technology modelled in GREET. Since not all materials recovered from recycling are useful for battery manufacturing, how to assign the environmental impact of recycling for battery manufacturing from recycled materials is controversial. To be cautious, this paper adopts a conservative allocation method that assigns all environmental impacts to recovered cathode materials or their precursors such as cobalt and nickel compounds in pyrometallurgical recycling.

3. Results and discussions

3.1. Recycling demand projection

Our MFA considers a wide range of factors that drive EV adoption such as rising incomes (updated in this paper to include the impact of Covid-19), fuel prices, regional heterogeneities, and policy commitments (such as the 2035 mandate to eliminate the sales of petrol, diesel and hybrid cars and vans). Combined with a range of plausible technical assumptions such as changes in the chemical composition of LiBs, increases in battery lifespan and capacity, and the possibility of a number of different second life applications, Fig. 3 illustrates the projections for cathode chemistry composition (top panel) and demand for recycling services across different UK regions (bottom panel).

Demand for recycling is projected to rise rapidly from 0.75 GWh in 2030 to about 2.9 GWh and 12.7 GWh in 2035 and 2040, respectively. In the last year of the analysis, six of the twelve regions have a recycling demand greater than 1 GWh. For example, it is projected that by 2040, the South East (the leading region) will need to recycle batteries with a combined original capacity of about 3 GWh.

Crucial to the viability of a LiB recycling industry is the amount of material that could potentially be recovered from these EoL batteries (and the price of the recycled material on the world market). Predictions are that volumes are likely to be significant and could be fed directly into the local GigaFactory system (predicted to be about six factories by 2040 with an average capacity of 20 GWh) [44]. The main EV battery types that are expected to enter the recycling channel between 2030 and 2040 are NCA and different NMC variants with cobalt-intensive batteries such as NMC111 gradually being replaced by batteries with lower cobalt content such as NMC811.

3.2. Optimal facility placement

The infancy of UK LiB recycling facility in 2020 provides an opportunity for policymakers to plan ahead and construct a network of facilities taking into account not just the best interests of the economy but also to address environmental and safety concerns [4,5,17]. The serious risk of battery fires and the costs associated with the transportation of retired LiBs means that geography matters and that the proximity of a recycling plant to the source of retired batteries (modelled as collection points in the global supply chain analysis) becomes the most decisive factor when it comes to modelling the location of future recycling facilities [83]. In practice, it may be expedient for EVs to be decommissioned on-site where the batteries will be processed, with the remainder of the vehicle either dealt with by co-located facilities or transported elsewhere. In contrast, proximity to the demand for the recycled materials (e.g. from GigaFactories) is less important as the recovered materials themselves are far less hazardous and can be traded easily on the global market. Once pack casings, modules casings etc. are removed, there is a significant mass reduction in the output of recycled material. Therefore, the optimal plant location is far more sensitive to the source of waste batteries, than the destination of the customer for the recycled materials.

The GSC analysis provides a number of alternative organisational structures for a possible new recycling network that minimises the long-hauling of spent LiBs from supply centres (such as garages or specialist collection points) to recyclers, subject to recycling plants providing sufficient capacity to meet domestic recycling demand at any given point in time. Optimising the logistics of such an industry, and minimising the overheads of LiB recycling, is especially important during the early stages of a new industry before the benefits from economies of scale can be realised.

Hence, after obtaining regionally disaggregated forecasts on LiB recycling demand from the MFA, the GSC analysis provides a set of optimised recycling facility locations for a range of market structures and including all existing battery collection points. These include a large central recycling plant (a single recycler) to more competitive structures with two, three of seven recycling plants. The model provides snapshots at three key years 2030, 2035 and 2040. The main change over this period is that the total market size of EVs increases dramatically. The other difference is a small change in the regional composition of demand.

Fig. 4 shows the results of the GSC analysis for the 2040 snapshot. The results from each snapshot are similar. For a single-plant solution, the results suggest that there should be a large single plant located in the West Midlands. The selection is intuitive, as it is the weighted centre of recycling demand for the UK. If the GSC analysis is set to optimise a two-plant solution, then the results suggest that there should be two roughly equal sized plants, one located in the West Midlands and the second in London. If more plants are needed, Fig. 4 also shows a 3-plant and 7-plant solution that places them in a sequential order after the West Midlands and London as: Yorkshire and The Humber, Scotland, Wales, East of England and then the South East.

3.3. Open-loop recycling assessment

The economic assessment in this paper is based on a customised EverBatt model [42] that has been carefully calibrated for the UK. A large number of factors determine how many, and what scale of recycling plants are required. Central to private investors' decision-making processes is expected profits, which in turn depends on the expected market size, technological readiness, and government support (political and financial). The role of government is important in shaping the market and creating a favourable business environment. Possible government involvement can be direct, through financial incentives such as subsidies or tax relief, or indirect, through strong support for electrification of the transport system and the creation and strict enforcement of LiB recycling rules.

Geo-economic factors, as modelled in the GSC analysis, also play a decisive role. The more entrants into the market that then must share the limited supply of batteries (at least in the short term), the lower the scale that each recycler would need to operate at and the higher the costs. In the early stages of an industry, especially one that is capital intensive, the more entrants there are, the longer it will take for each individual plant, and hence the overall industry, to reach a breakeven point. However, the benefit of a multi-plant solution is that greater geographical coverage reduces transport costs (and risks of moving hazardous materials long distances). A multi-plant solution also makes the sector less vulnerable to the shutdown of a single plant with a single technology. Finally, there may also be pro-competitive gains from multiple entrants, with only the strongest, most productive, and most innovative surviving.

Our economic assessment begins with an examination of an open-loop recycling system with one recycling plant (which is the market structure that is most suited to the establishment of a new capital-intensive industry). The results are presented in Fig. 5 To meet domestic demand for recycling by 2030, the left-hand panel of Fig. 5 shows that the UK needs to build a plant with the annual capacity to process 5 kt of battery cells which needs to be scaled up to 22 kt by 2035 and 92 kt by 2040.

Two technologies are modelled: 'Pyro' (smelting followed by hydrometallurgical processing) and 'Hydro' (mechanical separation followed by hydrometallurgical processing, including lithium carbonate recovery). As shown in the right-hand panels of Fig. 5, expected revenue for the Pyro recycling route is measured in £2017 per kg/cells prices and

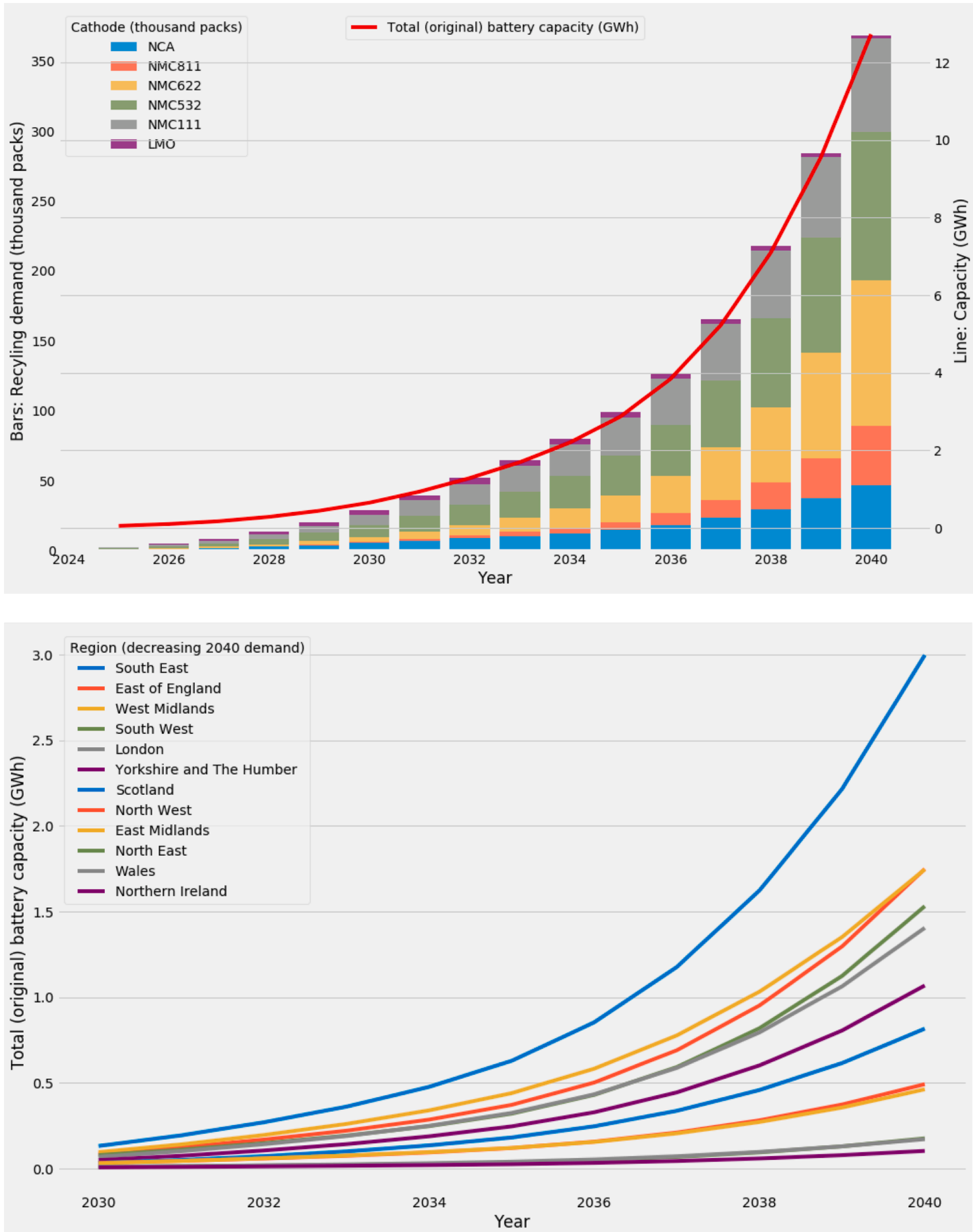

Fig. 3. EV LiB recycling demand by battery cathode (top) and by region (bottom).

is projected to gradually increase from 2.97 (2030) to 3.21 (2037) before falling back to 3.19 (2040). The U-shape is mainly driven by variation in the cobalt content in EoL LiBs. Expected revenue from the Hydro route follows the same pattern and is expected to vary from 3.60 (2030), to 3.81 (2037) before falling a little to 3.77 (2040). In an additional analysis, Supplementary Table 2 shows the expected recovery from the Pyro route is 17.99 kt useful materials, including cobalt, copper, and nickel which, when combined, will be worth 195.11 million (in £2017 prices) in 2040. Hydro recycling, which can recover additional materials including lithium carbonate, manganese, aluminium, and graphite, would reclaim a mass of 44.2 kt materials worth 230.84 million (in £2017 prices) in 2040. These valuations are roughly twenty times those projected for 2030.

Overall profitability comes from the exponential increase in demand for recycling which means that the cost curve falls away sharply from 2030 to 2040. For Pyro recycling, the fall is from 4.92 to 1.64 (£2017/kg cell), and for Hydro recycling, it falls from 4.15 to 1.72 (£2017/kg cell). Of these costs, those related to transportation are around 0.45–0.56 (£2017/kg cell), which is only a modest contribution to total costs. As such, benefits from economies of scale soon offset transportation cost savings from additional recyclers coming on stream between 2030 and 2040. Accordingly, central recycling is the most efficient scenario. However, it remains crucial to optimise the facility location decision because of the need to reduce hazards related to the thermal instability of LiBs. The analysis suggests that easing transport-related regulations related to the safe movement of used LiBs (which would compromise on safety) would do little to alter the cost structure of the industry during its initial stages of development.

In terms of economic viability, the GABREAL framework estimates that, without any government intervention, a newly built plant that captures all of the domestic recycling market will be profitable by 2031 for Hydro recycling and 2033 for Pyro recycling, with profits increasing from then on. To ensure that a recycling plant is in operation before 2031 (to ensure LiBs are not stockpiled or exported), government incentives will be needed. Such policies reduce the risks for would-be investors, who would then be more likely to absorb initial losses to

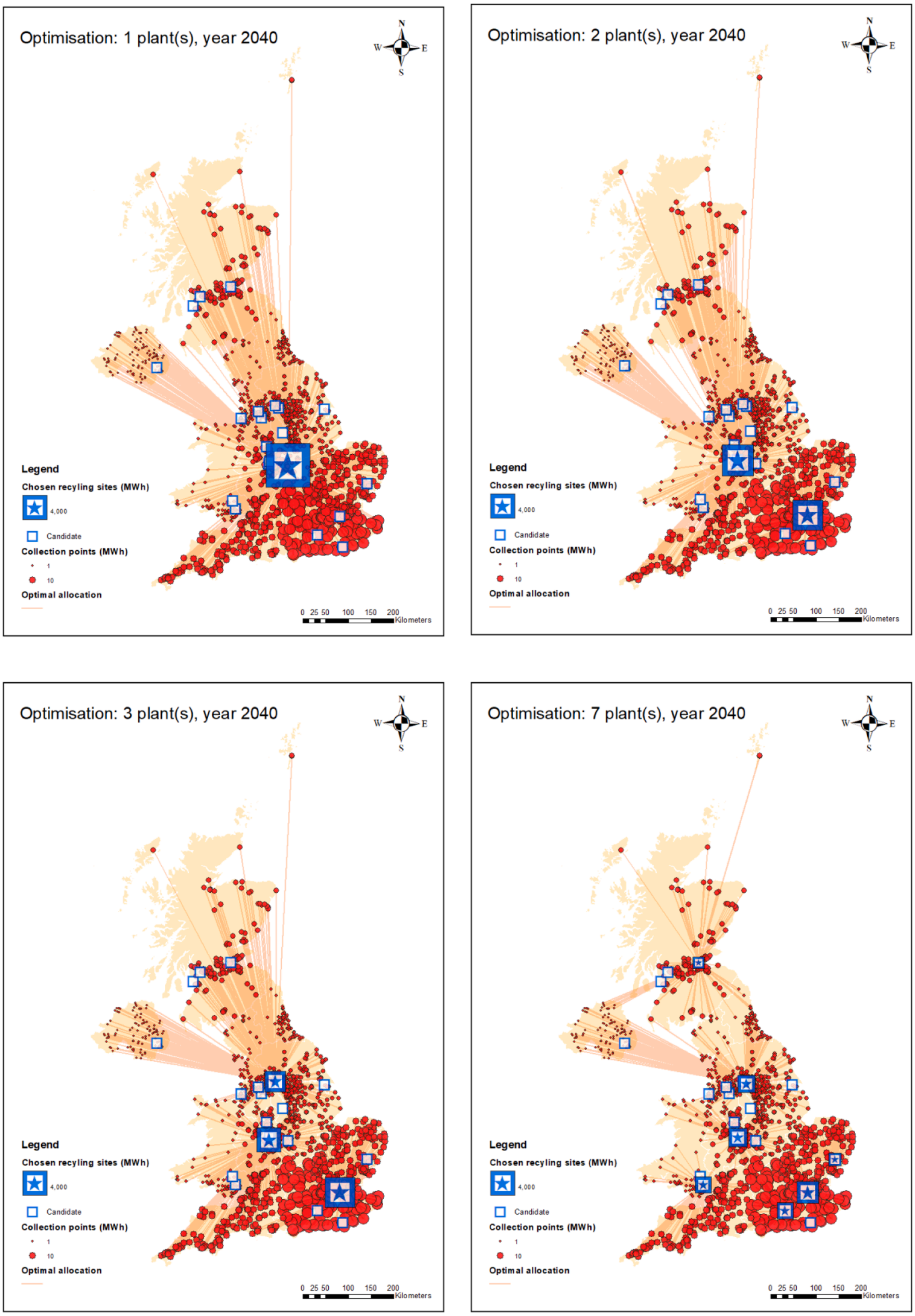

Fig. 4. Optimal UK LiB recycling facility placement (2040).

gain a first-mover advantage. The estimated profit for a single, centrally located recycling plant in 2040 even without government support is estimated to be 94.6 million (in £2017 prices) for Pyro and 125.3 million (in £2017 prices) for Hydro. Such profits may eventually attract more than one player to the market.

To investigate the possibility of multiple recyclers the cost curve of the industry in response to different number of recyclers is analysed. It is assumed that each plant has its own local advantage and serves customers that are closer to it than any other competitor plants and that they are all situated at an optimal location suggested in a previous GSC model. The capacity of each plant is determined by the recycling demand that they serve. A larger plant in the proximity of a large demand center faces lower costs. However, it is assumed that recyclers charge similar prices for recovered materials as determined by global market prices and a larger plant enjoys a larger markup. The equilibrium is defined as the scenario that allows for the largest number of competitors

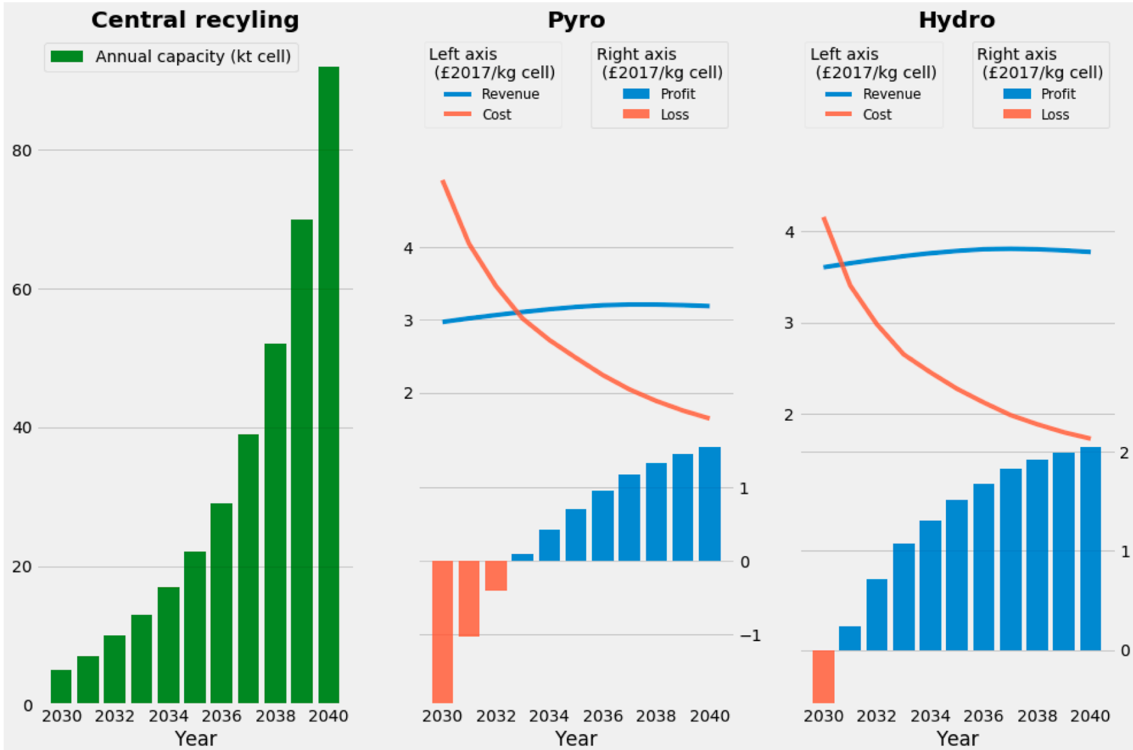

Fig. 5. Economic assessment for central open-loop recycling.

with no recycler making a loss. As can be seen from Fig. 6, by 2035, domestic demand cannot feed more than one pyrometallurgical recycler but could host two hydrometallurgical recyclers. By 2040, the market is sufficient for three or seven recyclers corresponding to pyro and hydro processes, respectively. Combined with the GSC model, this information allows a sketch of the optimal trajectory for the recycling industry with vision to 2040 to be made.

If pyrometallurgical technology is chosen, the first plant should be built in the West Midlands before 2033 followed by two further plants in London and Yorkshire and The Humber before 2040. Their total capacity in 2040 would be 28 kt, 44 kt, and 21 kt cells, respectively and they would share a total annual profit of 62 million (in £2017 prices). For hydrometallurgical recycling, the first plant should be built in the West Midlands before 2031, followed by a second plant in London before 2035 then five others before 2040. Their capacity split in 2040 is shown to be 25kt (London), 16 kt (West Midlands), 15 kt (Yorkshire and The Humber), 13 kt (South East), 12 kt (Wales), 8 kt (East of England) and 7 kt (Scotland) and their combined profit would be about 72 million (in £2017 prices). There is no speculation in the paper as to the exact year for plant construction, but the time points are noted when the market is likely to be mature enough to ensure profitability for all players. It is possible that a plant may enter the market earlier as a pilot plant or is willing to accept losses in the first few years of the project [39], and government incentives could also encourage earlier participation [40]. The capacity that is estimated in 2040 should also be thought of dynamically as plants may start small and then gradually ramp up capacity to meet demand.

3.4. Closed-loop recycling assessment

A closed-loop recycling solution is modelled where a viable recycling sector also supports LiB manufacturing and it is shown that coordination between manufacture and recycling could make the broader EV sector more cost-effective, efficient, and environmentally responsible. When integrated into a larger supply chain to form a closed-loop, LiB recycling appears to promise considerable economic and environmental benefits.

The exercise is based on a hypothetical manufacturer that has a throughput of 100 kt of NMC811 cells per year in 2040, which is consistent with an UK EV manufacturing sector that produces around 1.6 million EVs per year [44] and low-cobalt high-performance cathodes like NMC811 being significantly more important. In addition, it is assumed that there is a central recycling facility based in the West Midlands (which is the outcome from the optimisation process in the GSC analysis) with a (weighted) average distance to demand points of around 170 km and a capacity of 92kt/year. In this case such a plant is able to process the 2040 predictions of the national supply of batteries from the MFA. A hypothetical battery plant is assumed to be located 200 km away from the preferred location of the recycling plant (to match the location of the first Gigafactory announced in the UK [45][1]). A hypothetical cathode producer is assumed to be located somewhere in the middle (100 km from either the recycling facility or the battery producer to form a closed-loop system (no imports or exports). Recycling, cathode production and battery manufacture are assumed to use a decarbonised energy mix as projected in the Two Degree Scenarios [93]. The benchmark for the analysis is the manufacture of NMC811 cells from 100% virgin materials in 2040. The estimated cost is 20.0 (£2017 per kg cell prices) and consumes 177.8 MJ of energy and 78 L of water. From a cradle-to-gate perspective, the process is responsible for a range of air pollutants, 18.8 g nitrogen oxides (NOx), 270.1 g sulphur oxides (SOx), 6.6 g particulate matter 10 μm or less in diameter (PM10), 10.8 kg CO2 equivalent greenhouse gases (GHGs).

Fig. 7 shows that, depending on the technology, the manufacture of NMC811 cells from 100% recycled materials could help reduce 17.8–20.4% of the cost, 1.8–6.1 % of energy use, 15.0–19.6% of water use, 13.1–13.3% NOx emissions, 22.4–26.5% SOx emissions, 30.1–32.7% PM10 emissions, and 15.3–16.7% of GHGs emissions.

[1] Since this initial announcement of building a Gigafactory in South Wales, it has been announced that the location of Britishvolt's venture has since changed to Blyth, in the North East.

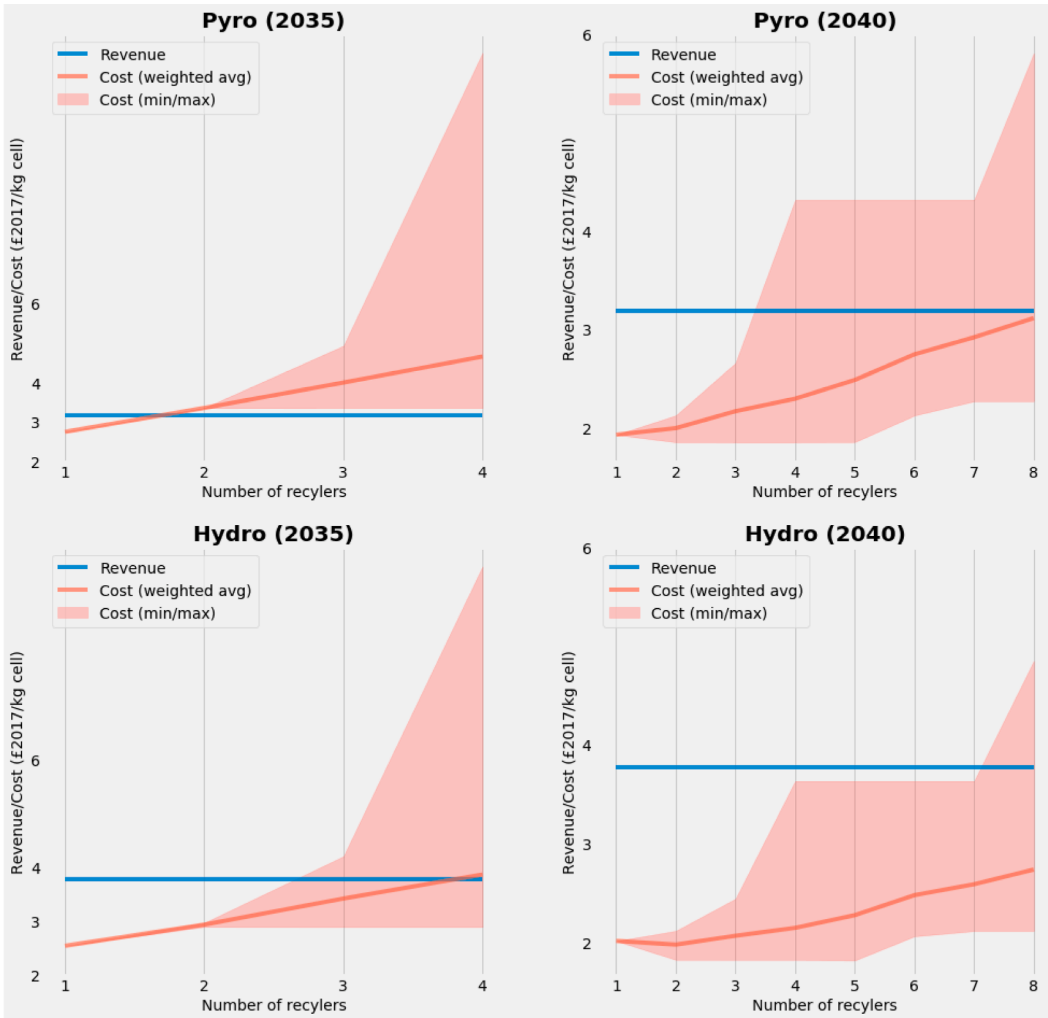

Fig. 6. Economic assessment for open-loop recycling with multiple recyclers.

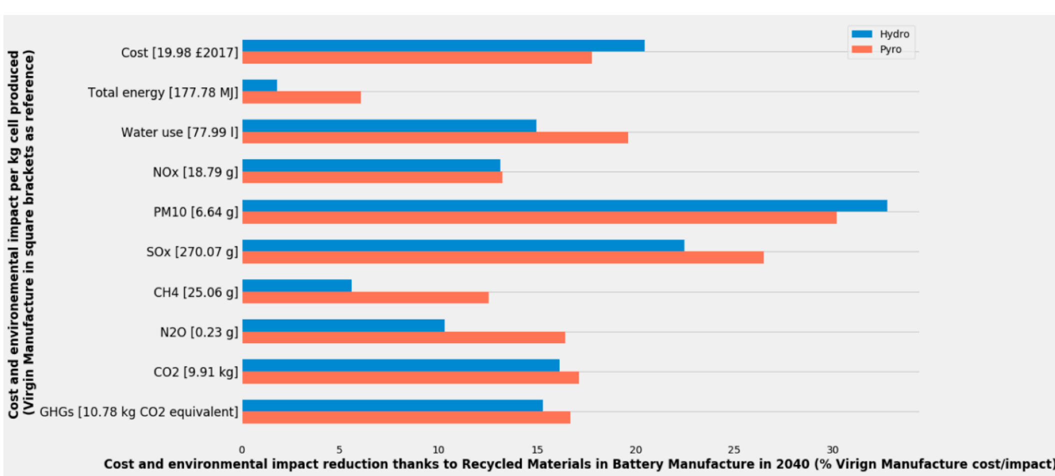

Fig. 7. Economic and environmental assessment for closed-loop recycling in 2040.

Hydro recycling reduces costs even more and emits less PM10, whereas Pyro recycling saves more energy and water and emits fewer air pollutants. The pyrometallurgical process consumes some of the battery constituents to facilitate the separation of materials, but this in turn results in a reduction in the energy demands of the plant, albeit it results in less materials recovery. The Everbatt model within the GABREAL model accounts for CO_2 emissions from the consumption of graphite, carbon black, binder electrolyte and plastics in the course of the process. Gas treatment is provided to the pyrometallurgical processes in order to clean up the output, including fluoride emissions from the decomposition of the electrolyte.

3.5. Sensitivity analysis

To understand how uncertainties in the economic dynamics, the political environment, market volatility and technical progress affect our projections, a number of sensitivity checks are undertaken for central open-loop recycling using the Hydro approach (Fig. 8) as 12 different factors used to model our baseline scenario are changed. Other sensitivity checks are available upon request. For each factor except the inclusion of lithium recycling, two scenarios are analysed (high and low), for example, by increasing and decreasing the baseline estimated/projected values by 50% or by some other plausible unit. Fig. 7 illustrates the notable changes in the results in response to each factor change.

Panel A of Fig. 8 highlights the importance of second life in the infancy of recycling. Suppose the availability of a reliable second life does not develop as quickly as expected. In that case, the demand for recycling will become more urgent, and the nascent industry will scale-up earlier. An increase in the probability of a retired battery entering the recycling channel after serving in an EV without any second life application would make the industry profitable three years earlier. A decrease or an increase in the average life span of a battery by two years due to the possibility of a second life would push the breakeven point two years earlier or later, respectively. Meanwhile, a change in the initial lifespan of a LiB by the same amount adjusts the breakeven point by just one year. Turning to raw material prices, a fluctuation by 50% in the price of cobalt would change the breakeven point by one to two years while only in a low nickel price scenario (a decrease by 50%) would the breakeven point be pushed back (to 2032).

Note: The vertical axes list the factors, their units, and their values in the base case (in square brackets). [est, fc] indicates that the baseline value varies across time, region or batteries and the result sensitivity to both (historically) estimated and forecasted values of the factors is analysed. [fc] indicates that the baseline value is various and the result sensitivity to forecasted values only while keeping historical (estimated) values unchanged is analysed. For almost every factor (except for the inclusion of lithium recycling), two scenarios (high and low) are analysed. Small text next to each horizontal bar shows how these scenarios are defined. ± x% bl means that the baseline value is increased/

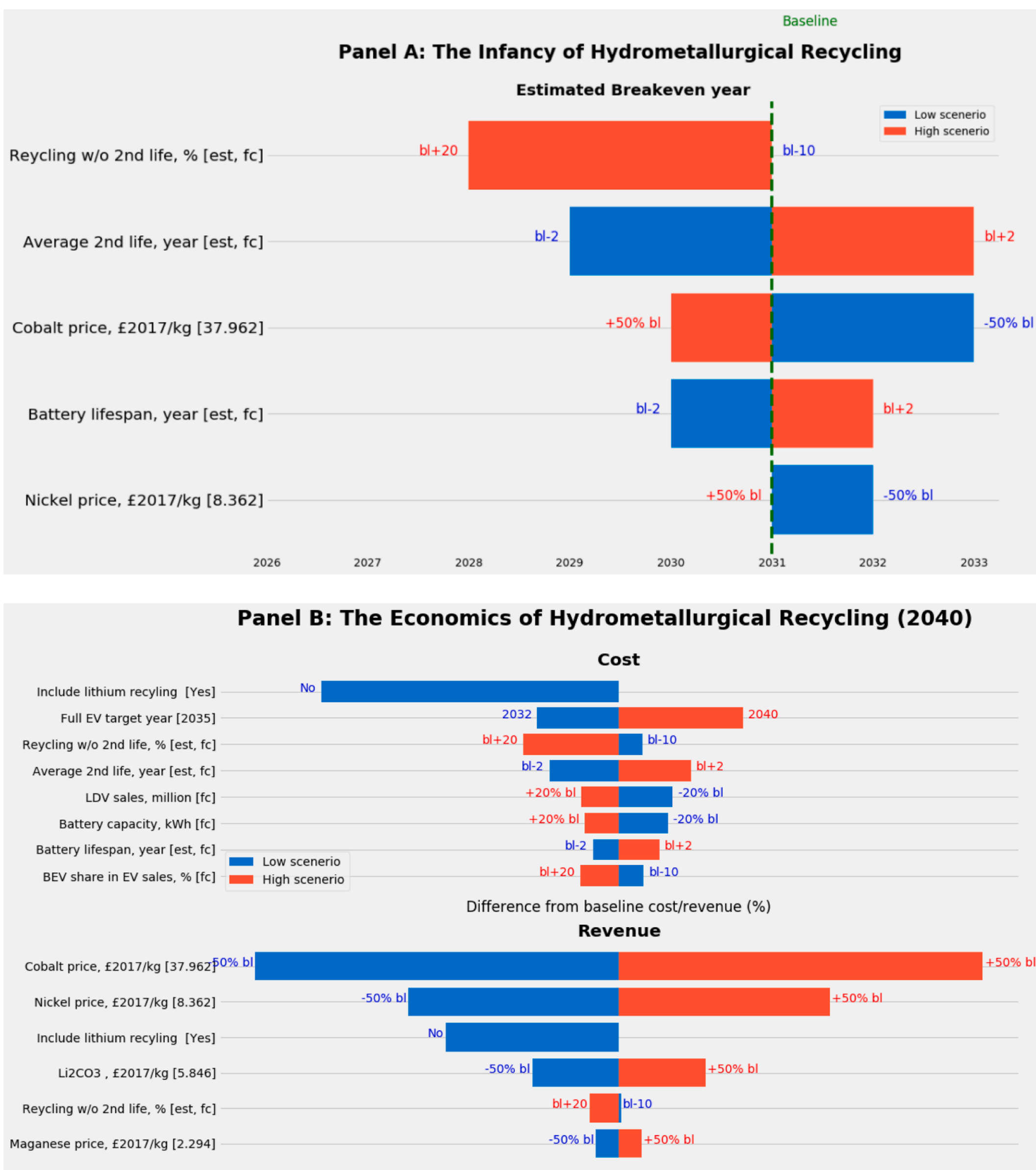

Fig. 8. Sensitivity Analysis for Hydrometallurgical Recycling (2040).

decreased by x%. bl $\pm$ x means the baseline value is increased/decreased by $\times$ units.

Panel B shows that the exclusion of lithium carbonate recovery would decrease the recycling cost in 2040 by 17% and revenue by 9.9%. As the revenue is larger, this factor, however, has a small impact on overall profitability. The progress of new LDV electrification is the second most prominent factor that affects the recycling demand and cost (per kg cell) by 2040. If full electrification is achieved by 2032, earlier than the current 2035 mandate, the cost will decrease by 4.4%. If it is delayed by 2040, the cost will increase by 7.1%. Other factors that could significantly drive recycling cost in 2040 include second life application progress, annual LDV sales, battery characteristics (capacity and life-span), and the share of BEVs in EVs. Revenue is expected to be mainly driven by the prices of mined commodities. A variation by 50% of baseline prices of cobalt, nickel, lithium carbonate and manganese will lead to variations in 2040 recycling revenues by 20.9%, 12.1%, 5.0% and 1.3%, respectively.

4. Conclusions

The UK currently trails other nations in LiB manufacturing and recycling capacity. However, this provides a unique opportunity at a critical inflexion point to provide substantial evidence that may help both industry and government to make critical decisions about strategic planning and the spatial distribution of a recycling industry with informed techno-economic analysis.

To some extent, the idealised scenarios presented here, are more aligned to a 'theoretical dream' of a circular economy[95] within the constraints of what can be adequately modelled, however, there is every potential for the lessons derived from this analysis to be translated into an 'implementable reality'[95], given the early stage of the UK's LiB recycling industry's development.

Since the initiation of this work, and after the experimental work have been conducted, there have been a number of industrial developments and announcements of new facilities, which appear to validate the findings of this work, during the process that the paper was under review, there have been announcements by Veolia, that they hope to establish a recycling facility for LIBs at Minworth in the West Midlands[2] that will be operational by Q3 2022. This resonates with our hypothesis that the Midlands is the best place to build the UK's first recycling plant. Furthermore, Britishvolt have announced a partnership with Glencore, who plan to build a recycling plant in Northfleet, Kent, that will be a source of raw materials for the Gigafactory in Blyth. Again, this strongly resonates with our proposals around the citing of a second recycling plant as volumes grow[3] as shown in Fig. 4. One development is that given both facilities will be located on the East Coast of the UK, there is the potential for goods movements by boat. This has not been modelled as this contemporary development evolved after the analytical work for this paper had been completed.

In the context of the more recent appetite for state intervention and industrial support [96], it is important for policy makers to anticipate the timing of the new industry and attempt to organise its development, based on a clear understanding of the system dynamics and geospatial considerations for this new industry, that takes into account economics, as well as environmental and security of supply concerns. This paper advances the literature on the economic and environmental impact of EVs by introducing a quantitative framework (GABREAL) that considers the business challenges faced by a future recycling industry. In isolation, but augmented with UK specific data, the GABREAL framework provides information on the temporal dimension of when waste volumes will reach the point where a plant will breakeven and also provides information on where the new a plant(s) should be located.

A word of caution when interpreting the results. This study does not consider future recycling technologies, which could offer better materials recovery. One benefit of the GABREAL modelling framework is that there is scope to explore a range of alternatives, including direct recycling and biological processing methods, as well as the potential for automation in sorting and dissembling batteries. However, until these concepts are proven at scale, no data is available. Instead, this paper focuses on the existing state-of-the-art pyrometallurgical and hydrometallurgical processes which are already commonly in use. Given that a great proportion of the impacts that occur at the end-of-life are in transportation and logistics, our supply chain model offers a novel evolution of existing strategic planning techniques.

5. Further research

Since the analytical work was conducted for this publication, we have witnessed proposals to build a number of recycling plants, that align well with the models best fit locations for the first two recycling plants. The model presumes a topology where batteries are removed from End-Of-Life vehicles at "spokes" that correspond with ATFs and then the battery recycling takes place at a centralised hub. In North America, the hub and spoke business model involves shredding batteries and separating out black mass at spoke locations and then sending black mass to be processed for material recovery at the hub location. This aligns with the commercial models that many manufacturers are pursuing. However, as the industry develops, it is uncertain whether that model will prove durable. For example, a high degree of capital investment in automated pack removal may lead to the greater centralisation and consolidation of battery pack removal facilities. As plans for the UK battery industry become clearer, it will be possible to use the GABREAL model to interrogate the evolving industry configuration. Furthermore, presently, the topology envisaged is focused around the valorisation of end-of-life battery packs when they become available. A greater degree of vertical integration of the industry (as we see in China) may lead to co-location or short-loop recycling processes for QR-fail cells from manufacturing and/or the production of cathode materials nearer to site. This additional complexity has not been modelled, however, there is scope to within the model.

CRediT authorship contribution statement

Viet Nguyen-Tien: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Qiang Dai:** Methodology, Software, Validation, Writing – review & editing. **Gavin D.J. Harper:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Paul A. Anderson:** Writing – review & editing, Supervision, Funding acquisition. **Robert J.R. Elliott:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Funding

The authors would like to thank the Faraday Institution for funding through the ReLiB Project, (grant numbers FIRG005 and FIRG006) and for support from the ReCell Center, at Argonne National Laboratory, funded by the US Department of Energy.

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.

[2] https://www.mrw.co.uk/news/veolia-to-open-battery-recycling-plant-13–01-2022/.

[3] https://www.ft.com/content/18c42872-aad9-4a95-a5c4-9e8f93077240.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2022.119230.

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