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Review

# Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition

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ABSTRACT

Industrial advances and academic enquiry into the transition towards electrified mobility has been arguably preoccupied with the earlier phases of technological development, while less consideration has been given to the end-of-life phase. One example of this is the current technical and economic difficulties surrounding Battery Electric Vehicle (BEV) recycling; and specifically, their high voltage lithium-ion batteries. In this study of the automotive sector, we adopt a longer-term perspective to better understand the overall transition towards "zero-emissions" road transport by empirically and theoretically contributing to the strategic management of lithium-ion powered, vehicle electrification. Through the careful exploration of BEV end-of-life, this paper forecasts a dynamic end-of-life stockpile of lithium-ion batteries, using the UK as a case study. By establishing the 'dynamic stockpile' as the central problématique, this paper then describes various technical challenges, business model implications and policy debates around reuse, recycling and disposal that countries will have to contend with as first generation BEVs begin to enter technological obsolescence. While innovation and technological progress are desirable, industry, governments and society must remain aware – and prepared – for the significant economic and environmental costs and opportunities associated with not only the diffusion, but also the waste generated by new technologies.

## 1. Introduction

The accelerated introduction of new electric vehicles (EVs) by automakers is an observable trend that has been welcomed due to improved environmental performance [1,2] comprising zero emissions in use and lower net carbon emissions per kilometre [3]. However, this research is solely concerned with plug-in Battery Electric Vehicles (BEVs) in the UK, sometimes called all-electric or pure-electric vehicles. This paper does not account for Plug-in Hybrid Electric Vehicles or PHEVs, which combine a conventional internal combustion engine with some form of electric propulsion.[1]

Net carbon emissions from BEVs depend upon the source of electricity generation, where system boundaries and energy carriers are clearly defined [3,5]. Over the last few years, average BEV range has increased, battery durability has improved, and costs per kWh of charge capacity has fallen. Combined with regulatory pressures, favourable market incentives, and consumers' dramatic pivot away from diesels[2] in the wake of the Volkswagen emissions testing scandal [6], the stage seems set for increased displacement of traditional internal combustion engine (ICE) passenger cars. This is further reinforced by the UK government's recent announcement of its intent to bring forward the ban on petrol and diesel cars to 2035 [7].

However, less consideration has been given to the environmental and economic implications for society as increasing numbers of BEVs reach their end of life, and in particular, the reuse and recycling [8,9] of rechargeable, high-voltage lithium-ion batteries (LIBs). Generally, BEV batteries are composed of cells, modules and a pack. Battery cells are the basic units of a BEV lithium-ion battery, where a fixed number (or cluster) of cells makes up a module, and a cluster of modules makes up a pack, which is the final shape of the core battery system [10].

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[1] PHEVs on the UK market mostly use nickel metal hydride [NiMH] batteries, and to a lesser extent Lithium-ion batteries (LIBs), but some market analysts expect LIB use in PHEVs to overtake NiMH batteries by 2030 [4]

[2] SMMT data shows a 17% decrease in new diesel vehicle registrations in 2017, 30% in 2018, and a further 21.8% decrease in 2019.

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There is a growing appreciation of the environmental and economic benefits of recycling LIBs, notably in those countries where the uptake of BEVs is distinctively high [11]. China, for example, launched a trial in 17 cities in 2018 with the expectation that 170,000 tonnes of LIB waste would be processed [12]. However, recycling automotive LIBs poses unique challenges and opportunities compared with more traditional lead-acid batteries, as is expanded upon in later sections. By more carefully exploring LIBs' end-of-life, this paper aims to answer the following research questions:

- **RQ1**: What will the UK's estimated 'dynamic stockpile' of obsolete (i.e. end-of-life) lithium-ion battery packs (OLIBs) be by 2025?
- **RQ2**: What are the environmental, economic and policy challenges of such an accumulation?

This paper proceeds in the following fashion: First, the neglected theme of product retirement or disposal is discussed in Section 2. While theories of new product adoption and the penetration of such technologies are long-established, theories related to product disposal (or retention) are less well developed. Section 3 outlines this paper's empirical research methods and how we used them to derive our forecasts (results). It should be noted that in this paper, we define OLIBs or Obsolete (end-of-life) LIBS as the share of battery packs in UK BEVs that have either been retired from road use, or whose electric battery warranty has expired. Later in this paper (Section 5.4.) we also discuss the dilemma of out-of-warranty BEV batteries still in use. Accounting for such an accumulation is important because accelerating sales and consistent growth of the UK BEV segment means that there is an urgent need to prepare for the environmental, economic, and regulatory challenges of responsibly storing, recycling and disposing of OLIBs.

Thereafter, we present our forecasts of the rate of OLIB stockpiling in the UK in Section 4. The penultimate Section 5 discusses the implications – based on our findings in conjunction with relevant literature – for academics, regulators and those in the End-of-Life Vehicle (ELV) industry to consider. A short conclusion (Section 6) highlights some immediate considerations and areas for further research.

## 2. Product retirement in sociotechnical literature

Technological forecasting in general tends to relate to the introduction of new products and services, or expectations on output, Gross Domestic Product (GDP), and other socio-economic variables. The intention of such research is largely to forecast how quickly an individual technology might permeate a given market [13], and the focus on consumer acceptance of new products has a tradition that goes back to the Rogers model [14,15]. However, little attention is given to various aspects of product retirement. We can distinguish at least two 'modes' of product retirement. The normal mode is when, with a mature technology (albeit with an expected rate of product improvement) and established market, there is a stable rate of product retirement related to the passage of time or a decline in functionality. The second is an 'accelerated' mode of retirement that can occur in at least two settings. First, when a mature technology in an established market suffers an increase in retirement due to the emergence of superior competing technology. Second, where an emergent technology progresses rapidly through generational improvements in cost and performance, rendering early versions more rapidly redundant. The broad aim of the paper is to frame the accelerated retirement process of OLIBs in sociotechnical terms.

Regarding BEVs, considerable research has gone into forecasting the rate of market penetration. A particular focus has been to identify and seek to remedy barriers to market penetration for these vehicles [2]. In other words, the predominant research focus in this domain has been on understanding the acceptance of BEVs, and hence the extent to which traditional ICE cars will be displaced [16].

Research grounded in sociotechnical transitions theory is essentially concerned with understanding how innovations permeate at a system level, thereby creating new sociotechnical systems [13]. The End-of-Life Vehicle (ELV) recycling structure can be understood as an existing, if neglected, part of the current automobility sociotechnical regime. The contention here is that the widespread uptake of BEVs will have differential impacts across the automobility sociotechnical system and require the creation of an End-of-Life Electric Vehicle (ELEV) recycling structure. Trading of raw materials, goods and ultimately waste is making use of a worldwide network of producers, manufactures and recyclers. Put alternatively, the restructuring of the ELEV recycling industry is likely to be a necessary condition for the establishment of electro-mobility sociotechnical systems across the world, thereby resonating with the wider concept of the circular economy. The caveat here of course is that the systems of reuse and recycling that are adopted will have to win in competition against less sophisticated methods of disposal [17].

While there is considerable science, technology, engineering, and mathematics (STEM) research (over 200 papers and 100 patents) aimed at solving spent LIB recycling [18], sociotechnical research stops short of investigating the eventual end-of-use phase of this technology. The neglect of this issue with respect to cars is different to the attention accorded other consumer items. There is a growing body of research into the recycling of clothing and textiles, and small electronic items under the Waste Electrical and Electronic Equipment (WEEE) Directive for example [19]. There is an understanding that reverse logistics and take-back systems will become more significant in the future as the concept of the circular economy becomes manifest [17,20].

In the following section we review the prevailing car processing system for End-of-Life Vehicles (ELVs), as well as automotive lead-acid battery and consumer electronics (CE) LIB end-of-life. In this, we explain how the system works for prevailing cars with internal combustion engines (ICEs) as well as other types of batteries as a context to understanding why in some key respects the system will not work in the same way with end-of-life automotive LIBs.

### 2.1. Car dismantling, scrapping and recycling in the uk

The academic neglect of car recycling might be attributable to several factors. The sector is strongly regulated, and scrapped cars – known as End-of-Life Vehicles (ELVs) – are subject to planning and operational controls. Directive 2000/53/EC sets out quantified targets for reuse, recycling and recovery of ELVs and components. The vehicle dismantling and shredding industry is also subject to a range of EU and national regulatory controls regarding equipment, facilities, processes, and the collation of data, with clear targets for recycling. In the UK there is an established and viable economic structure for recycling based on the three-tiered system of dismantlers (Authorised Treatment Facilities or ATFs), shredders, and smelters. The structure has been in place a long time, with little by way of exciting technological change. There is a distinctly 'unglamorous' image associated with the post-use recycling of vehicles. Finally, there is a paucity of data across the sector.

The owner of a car who no longer wishes to keep it has essentially three legal options: sell the car to another party; declare the car to be off road (in the UK, a Statutory Off Road Notification or 'SORN' declaration); or scrap the car themselves or through a third party such as a charity e.g. Giveacar (giveacar.co.uk) via an ATF. Historically, the long-run trend has been for the rate of car scrapping to be lower than the rate of new car sales by approximately 50% in the UK,[3] resulting in the steady expansion of the overall stock of cars in circulation, also known as the parc.

The rate of car scrappage is related to the size of the parc, the rate of new car sales, and economic or other factors, such as deliberate

[3] Calculated by cross referencing SMMT new registration data with EUROSTAT vehicle scrappage data 2010-2015

government intervention to increase the rate at which old cars are removed from the parc (typically to stimulate new car sales). Examples of this are scrappage schemes in Germany and UK as a response to the 2008 global financial crisis [21,22]. Otherwise, normal mode car scrappage is influenced by technical and economic considerations primarily. A car loses value over time, and this depreciation rate varies but is typically 50–60% over 36 months [23]. A car deteriorates in functional and aesthetic condition. In addition, new cars brought to the market embody new technologies, materials, features and performance that render the older cars comparatively less attractive. Car scrappage events are typically triggered at the annual Ministry of Transport tests or simply 'MOT',[4] when the required repair and maintenance costs are seen to exceed the economic value of the car to the owner.

Cars become available for recycling through one of three basic routes. First, the car is so damaged in a collision or other event that it is beyond safe and / or economic repair, and so must be scrapped. Insurance write-offs occur when an assessor deems the damage to a vehicle to be beyond economic repair, but sometimes these vehicles can return to the market. Second, the car is of such an age and condition that the cost of keeping the vehicle outweighs the value of the vehicle. The rationality of this calculation varies. For example, the owner of a car of low value, who spends resources in keeping that vehicle on the road, may still deem the maintenance costs as lower than the cost of replacement with a (younger or better condition) vehicle. Moreover, there may be emotional attachment to a vehicle that transcends economic logic. Third, the car may be (illegally) abandoned resulting in collection by a Local Authority. According to Morley [24], Freedom of Information requests to over 400 UK councils revealed the number of cars being reported as abandoned had risen nearly threefold from 40,876 in 2012 to 147,616 in 2016.

The EU [25] and other regional sources [26] state that in the EU, typically 6 to 7 million cars are scrapped each year in compliance with the ELV directive. However, about 3 to 4 million additional vehicles are classed as 'vehicles of unknown whereabouts'. These are vehicles that are deregistered but without a Certificate of Destruction (CoD) issued, and no documentation regarding export out of the EU. Further, EU reports [25] discuss at length the difficulties of obtaining good quality data for the region, though the UK appears to have stronger records than many countries. Despeisse et al. [27] estimated that as much as 30% of ELVs generated in the UK were being illegally exported as used vehicles to Eastern Europe and African countries.

### 2.2. Lead-acid battery end-of-life

Previous research has sought to examine the recycling of automotive lead-acid (Pb-acid) batteries [28] as a template for automotive LIB recycling, and there have been several insights gained. Approximately 90% of automotive Pb-acid batteries are recycled today, compared to 5% of OLIBs [29,30]. In the United States (U.S.), Pb-acid battery recycling rates saw significant fluctuation due to changes in the market price of lead [31]. When lead prices were low – in conjunction with stringent environmental regulations – end of life Pb-acid batteries were either exported or dumped [32].

Pb-acid battery handling, transport and disposal has long been stringently regulated in the U.S. and other markets because of their well-known toxicity, with recycling being promoted at both state and federal levels [32]. However, in the late 1980s, States began to ban the dumping of Pb-acid batteries in landfills and additionally required that they be recycled. In the wake of these policies, rates of recycling significantly increased, resulting today's near 100% recycling rate [33].

In addition to increased government regulations, there are several other factors that have contributed to the success of Pb-acid battery recycling. For instance, these batteries share one common chemical composition, and recycled lead is known for its high quality [28]. The business model is further supported by well-established collection centres and recovery technologies, which makes Pb-acid battery recycling relatively simple and cost-effective [30].

### 2.3. Consumer electronics LIB end-of-life

Unlike the Pb-acid battery, LIB recycling has proven to be expensive (even at scale) and profitability remains limited, despite some recyclers' claims. It is estimated that 95% of all[5] LIBs are landfilled (globally) rather than recycled upon reaching end-of-life. Consumer electronics (CE) accounts for 50% of the LIB global market and 39% of the cobalt used in all LIBs [34]. Consumer electronics recycling research[6] in North America in 2016 shows [30] that cell/mobile phones make up about 68% of CE *units* sold, but represent only 20% of the CE battery *mass* sold, and have an approximate recycling rate of 15%[7] . Laptops make up 20% of CE *units* sold but represent 73% of the battery *mass* sold, with a much higher recycling rate of about 40%. Laptop LIBs are the heaviest and hence have the highest rate of battery mass recycling, while cell/mobile phones are the most used, but least recycled and hence their lower share of battery mass recycled. Overall, the average recycling rate for CE in North America stands at approximately 33% of *battery mass* sold, and as a result the majority of LIBs are landfilled [30,33].

In the EU, prior to the implementation of new regulations in 2008, the return rate for CE was estimated to be between 3% and 7% [33]. Despite 5% being often quoted as the recycle rate for LIBs in the EU [36], present-day LIB recycling statics for the EU remain obscure, as LIB data is mixed in with 'other' unspecified batteries [34].

### 2.4. Automotive LIB end-of-life

There is an assumed displacement effect, whereby BEVs substitute existing ICE vehicle sales. Eventually, if BEV sales constitute the dominant share of new cars sold, so the proportion of ICE vehicles in use will decline towards zero. Thus, BEVs sold into the new car market will be used and will eventually reach the end of their useful lives. As an ELEV, the constituent technologies and materials of BEVs (e.g. OLIBs) may not necessarily mirror the retirement patterns of ICE vehicle components (e.g. Pb-acid batteries). Today's industrial LIB knowledgebase mostly originated from firms in CE markets that established robust supply chains and accumulated significant experience long before the emergence of modern battery-electric vehicles (circa 2010). This knowledge was transferred across to the automotive industry and applied to the production of traction duty LIBs [33].

Automotive LIB lifespan can be measured in either cycle life or calendar life. Cycle life is the number of charge-discharge cycles a lithium-ion battery can endure before falling below a specific performance threshold. Calendar life on the other hand is the amount of time a battery can be stored, with minimal charging-discharging, before its capacity is similarly diminished [4]. A battery is usually considered to have reached its end-of-life when its maximum capacity is 80% of its original fully charged state [37,38]. While LIB lifespan is highly uncertain [39] for a variety reasons including the technology still being in its infancy, most research places average LIB calendar life between 8 and 10 years [40–45], subject to favourable conditions. Factors that can reduce LIB lifespan includes overcharging, rapid discharge, frequent charging and high operating temperatures [4,46].

There also exist safety concerns regarding the safe disposal of OLIBs

[4] The MOT is an annual test of a vehicle's safety, roadworthiness and exhaust emissions. This is a requirement in the UK for most vehicles over three years old.

[5] Portable consumer electronics + automotive LIBs combined

[6] Only cell phones, laptops and tablets were considered in the category of 'consumer electronics' in the research cited, with all other devices ignored.

[7] Compared to a global average recycling rate of 10% [35]

that include the release of hazardous chemicals under landfill conditions and fire risks [30,47–49]. OLIBs can spontaneously ignite or even explode, also known as thermal runaway [50], where the ignition of one cell, leads to a rise in heat that spontaneously ignites its neighbors. Once combustion has started, it is extremely difficult to stop. Of equal concern is emerging research that confirms the presence of toxic fluoride gas emissions – specifically, the notoriously lethal hydrogen fluoride (HF) – from lithium-ion battery fires [51]! All of this suggests that the post-use treatment of OLIBs will be expensive compared to the 12-volt lead-acid batteries found in traditional ICE vehicles. Alternatively, the OLIB packs and associated power components are likely to have a relatively high absolute content of valuable metals e.g. cobalt, copper, magnesium or lithium, the recovery of which via recycling may be an attractive option [52,53].

### *2.5. 'The shape of retirement': theoretical underpinnings of technological obsolescence in relation to OLIBs*

This section is primarily concerned with accelerated retirement linked to the concept of technological obsolescence. Technological obsolesce has been the subject of many studies, but its dynamics are still not very well understood (Amankwah-Amoah, 2017), specifically in the context of accelerated retirement. Technological obsolescence occurs when the functionality of a piece of technology is inferior, relative to other available technologies, in its ability to address current and future problems or tasks [54]. Technological obsolescence is characterized as a problem that will only 'get worse' as time progresses, with studies showing that approximately 3% of all global electronic components become obsolete each month [55] or 30–50 million tons each year [56].

A more nuanced description of technological obsolescence, is that it is a 'mismatch between the life cycles of products, and the technologies they incorporate' [57], where fundamental interdependencies ultimately result in varying degrees of technological obsolescence [54], including accelerated retirement. Simply put, within a given technological product, there exists life cycles within life cycles, where the function of that product partially depends on the functionality of its components. Products with multiple components become obsolete over time in multiple stages, and the inability to obtain and replace parts only accelerates this process [58,59].

The inability to procure and replace parts – or component obsolescence – is said to be at the root of technological obsolesce at any product level [58]. For example, large internet routers and military systems have projected lifespans of two decades, but the electronic components that support their functionality have around two years' lifespan [60,61]. When product developers upgrade their technologies and discontinue older technological components, this causes life-cycle mismatch. This lack of backward or forward compatibility between old and new components within the product package often leads to systemic obsolescence [62]. Thus, BEVs and their corresponding LIBs' lifecycles become mismatched due to high replacement costs of OLIBs or damage due to automotive collisions [4], and hence complete systemic obsolesce and accelerated retirement ensues. Compounding this vulnerability, is the fact that there is presently no market for non-Original Equipment Manufacturer (OEM[8]) compatible batteries, making the entire automotive LIB supply chain exclusively dependant upon OEM support.

## 3. Research methods

Transport studies have often followed the epistemological practice of using quantitative methods with a positivist world view [63,64], which has at times been characterized as archaic [65,66]. Alternatively, others have argued that qualitative approaches are increasingly contributing to fuller understandings of transport practices and policies [67–70]. Hence, there continues to be an appeal for more critical (qualitative) analysis in transport studies, to compliment the already well-established technical (quantitative) scholarship [71]. This research combines these two approaches by forecasting our unit of interest – end-of-life lithium-ion batteries – using statistics and discusses these results within the context of an end-of-life document review of the automotive industry.

### *3.1. Forecasting new car registrations in the UK from 2019 - 2025*

First, we collected publicly available historical data from the UK Driver and Vehicle Licencing Agency (DVLA) and Society of Motor Manufacturers and Traders (SMMT) databases for all new car registrations from 2011 – 2018. We chose to collect registration data from 2011 because that is when the UK launched its 'plug-in car grant' [72]. We then forecast total new car registration figures in the UK between 2019 and 2025 using a quadratic trend projection ($y_t = \beta_0 + \beta_1 t^2 + \beta_2 t$) (see Fig. 1; Table A. 1. in Appendix A).

It has been long established in academic literature that the fitness of competing forecast models can be tested using two specific information criteria – the Akaike Information Criterion (AIC) and Schwarz Information Criterion (SIC) [73,74]. When selecting between models, the one with the smallest value of the criterion is recommended for selection. In practice, when both criteria are applied, they often lead to the selection of the same model.

Table 1 below shows the AIC and SIC criteria for the linear, quadratic and exponential trend models applied to total new car registrations (data graphed in Figure A. 1. in Appendix A). Both AIC and SIC select the quadratic model. In a relatively mature and stable market in which total change is largely incremental, this model gives a reasonable and illustrative expectation forecast without recourse to more complex approaches such as stock adjustment modelling.

It is important to note here that the process of the UK leaving the EU (or 'Brexit') has been a source of significant uncertainty within the automotive industry, and for this reason we chose to conservatively project new car registrations. Another factor influencing our forecast has been the slowing new car market in the UK, which has seen five consecutive years of reduced growth, with the last two (2017, 2018) actually resulting in negative growth (contraction) (see Fig. 2), despite continued growth in the BEV segment (see Fig. 3) [75]. We are confident that our forecast is reasonable, given that it aligns with estimations made by other industry analysts [76,77].

### *3.2. Document and thematic analysis*

The latter portion of this Review involves discussing our empirical results within the context of documents published by the automotive sector, official European Commission and UK government documents, academic journals and press articles. While press articles are not widely used for academic support, this secondary source of data proved invaluable in tracking the rapidly shifting landscape of the automotive industry. Our document analysis provided the large-scale material context of how OEMs develop and integrate LIBs into the automotive value chain [78], and the challenges of sustainably transitioning these technologies beyond their primary function. The use of secondary data from various sources has the added benefit of contributing to the triangulation of information as well as capturing relevant themes from the perspectives of automakers, regulators and other industry stakeholders. By analysing these documents, it then becomes possible to establish linkages between collections of different sets of knowledge within the industry [79], and render an account structured around central themes that have emerged [80].

[8] Within the automotive industry, automakers are typically referred to as OEMs

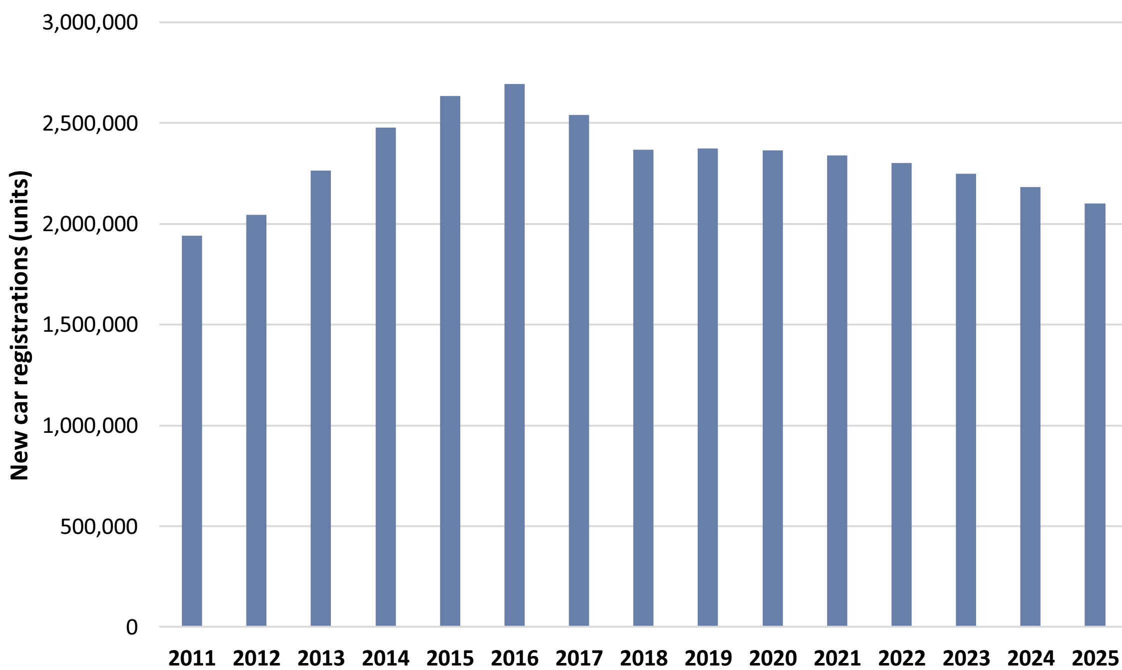


**Fig. 1.** Historical and forecast of new car registrations in the UK: 2011 – 2025.

**Table 1**
AIC and SIC criteria for the linear, quadratic and exponential trend models for total new car registrations 2011–2018.

| Trend models | Akaike Information Criterion (AIC) | Schwarz Information Criterion (SIC) |
|---|---|---|
| Linear Trend | 27.25 | 27.29 |
| Quadratic Trend | 26.95 | 27.02 |
| Exponential Trend | 32.22 | 32.24 |

### *3.4. Defining Obsolete (end-of-life) Lithium-Ion Batteries' (OLIBs)*

As previously mentioned above, we define Obsolete Lithium-Ion Batteries (OLIBs) as the share of lithium-ion battery packs in UK BEVs that have either been prematurely retired from road use via insurance write-off (Type 1) or whose high voltage electric battery manufacturer's warranty has expired (Type 2). Our research shows that 8 years is the average period that automakers will cover high voltage lithium-ion batteries under warranty based on 2019 OEM policy data we collected

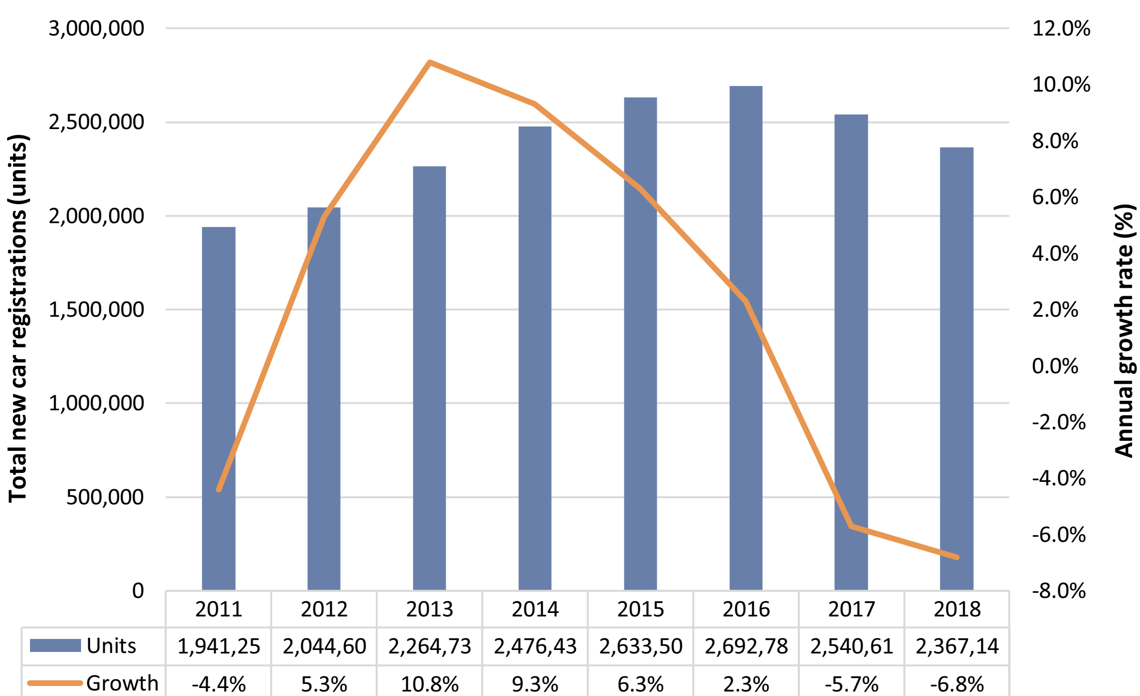


**Fig. 2.** Total new car registrations and annual growth (%) in the UK. Generated using SMMT data.

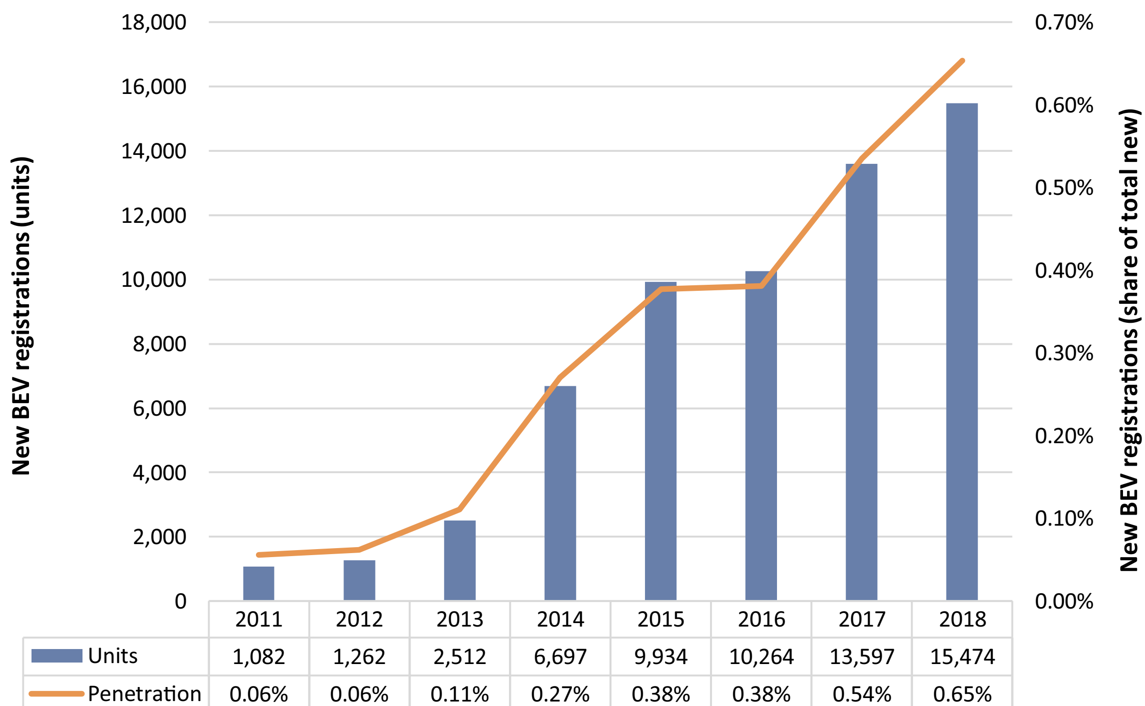


**Fig. 3.** New BEV registrations and share (%) of new car registrations by year in the UK. Generated using SMMT data.

**Table 2**
Vehicle manufacturer warranty comparison of high-voltage LIBS in UK BEVs. All data collected from manufacturers' websites in January 2019.

| Make and Model | Lithium-ion Battery warranty[a] | Battery capacity loss / degradation[b] |
|---|---|---|
| BMW i3 | 8 yr / 100k miles | 70% |
| Chevrolet Bolt EV | 8 yr / 100k miles | (2017, 60%, 2018 not covered) |
| Fiat 500e | 8 yr / 100k miles | Not covered |
| Ford Focus Electric | 8 yr / 100k miles | Not covered |
| Kia Soul EV | 10 yr / 100k miles | 70% |
| Mitsubishi i-MiEV | 8 yr / 100k miles | Not covered |
| Nissan Leaf (24 kW) | 5 yr / 60k miles | 9 / 12 bars (approx. 70%) |
| Nissan Leaf (30 kW) | 8 yr / 100k miles | 9 / 12 bars (approx. 70%) |
| Nissan Leaf (40 kW) | 8 yr / 100k miles | 9 / 12 bars (approx. 70%) |
| Tesla Model S and X (60 kW) | 8 yr / 12k miles | Not covered |
| Tesla Model S and X | 8 yr / Unlimited | Not covered |
| Tesla Model 3 (medium range) | 8 yr / 100k miles | 70% |
| Tesla Model 3 (long range) | 8 yr / 120k miles | 70% |
| Volkswagen e-Golf | 8 yr / 99.3k miles | 70% |
| Jaguar I-PACE | 8 yr / 100k miles | 70% |

[a] Each provides coverage until either the year, or total mileage figure is reached - whichever comes first.

[b] This covers repairs needed to return battery capacity to the indicated% of original battery capacity (if applicable). Usually the battery components are repaired or replaced, and the original battery pack is returned to the vehicle. In some cases, however, the battery pack is replaced with either a new or re-manufactured Lithium-Ion Battery.

(see Table 2 below). Thus, 2019 OEM policies seem to be in line with average LIB calendar life expectations found in the literature (See Section 2.4.).

In this study, we assume that the annual rate of attrition (insurance write-offs) for vehicles in the UK is approximately 1.2% based on previous industry estimates [81]. This rate remains much the same today, according to a more recent insurance group study [82] that showed 380,000 annual insurance write-offs within the parc of 32 million vehicles. While high-voltage batteries present unique challenges to automotive safety, over a decade of crash test reports indicate that BEVs are just as robust as traditional internal combustion engine (ICE) vehicles [83] in collisions. For this reason, we have applied the same 1.2% rate of insurance write-offs to the population of BEVs, assuming that they are no more likely to be written-off in road incidents.[9]

Therefore, in order to estimate the dynamic OLIB stockpile, we combined insurance write-off BEV estimates (Type 1 OLIBs) with out of warranty LIB estimates (Type 2 OLIBs). The reason being is that in both circumstances, OEMs no longer manage these batteries' 'primary use' functionality. We argue that this dynamic OLIB stockpile is a useful indicator of BEV component obsolescence, as these batteries are now technically only eligible for end-of-life processing (reuse, recycling or disposal).

It must be noted that the 1.2% rate of attrition used *only* represents insurance write-offs, which is just one of the three means by which a vehicle enters end-of-life. Voluntary scrappage, and illegal abandonment are omitted from this rate of attrition for two reasons. First, the data is simply not available at the desired level of granularity, i.e. there are no data on the volume of BEVs voluntarily scrapped or illegally abandoned in the UK by year of registration. Secondly, vehicles that are voluntarily scrapped or illegally abandoned are likely to be much older in age. Insurance write-offs, however, are unaffected by age, and thus are applicable across all cohorts of BEVs annually for our calculation purposes. A final segment of the OLIB population that could not be accounted for are battery packs that have been repaired or replaced under warranty due damage or defect, and similarly, battery packs replaced or repaired by owners during the warranty period, but whose

[9] It must be noted here that during our research we interviewed a senior manager at Thatcham Research, the UK's only Euro NCAP accredited crash testing centre, and he challenged the findings that BEVs perform the same in accidents as ICE vehicles for two reasons. First, BEVs carry relatively more mass into collisions and thus can sustain more structural damage and secondly, a growing trend in 'non-repairable' batteries fitted with pyrotechnic fuses that discharge during impact often results in a total insurance write-off. An insurance claims specialist from Admiral Insurance that we interviewed had similar concerns about "constructive total loss" of these vehicles in anything other than a "low velocity impact" due to the cost of LIB repairs / replacement.

repair or replacement costs were not covered by the manufacturer.

## 4. Results: forecasting the dynamic stockpile of OLIBs in the UK: 2011 - 2025

Using our forecast of total new car registrations from 2019 - 2025, we calculated the UK's dynamic OLIB stockpile along three possible trajectories based on low (4%), medium (8%) and high (24%) rates of BEV market penetration (see Table A. 2. in Appendix A). The rates of BEV market penetration used, reflect the most common forecasts made by various investment banks and business intelligence firms regarding the BEV market share of new vehicles in 2025. We used the lowest (4%) and highest (24%) BEV penetration forecasts for 2025 directly from these secondary sources [84–86]. Our medium forecast (8%) however, was calculated using the average of all other forecasts which fell in between the highest and lowest predictions (see Table A. 3. in Appendix A).

As stated earlier, these estimates have been specifically disaggregated to reflect BEV rates of penetration *only*, and do not include Plug-in Hybrid Electric Vehicles or any other Alternative Fuel Vehicles (AFVs). We use 2025 as our forecast 'cut off' year due to the common industry belief that 2025 will be an inflection point for BEV market penetration [87]. This is the point where growth in the BEV segment ceases to rely on government incentives and regulations, and is instead driven by BEV purchase price and Total Cost of Ownership (TCO) as it reaches parity with ICE vehicles [88].

We applied the 1.2% annual attrition (insurance write off) rate to each cohort of newly registered BEVs in the UK from 2011 to 2025 to estimate the number of BEVs that exit the market prematurely (Type 1 OLIBs) and are added to the dynamic OLIB stockpile. This 1.2% annual rate of attrition is applied for the first seven years of each BEV cohort, and on the 8th year, the remainder of the cohort is added to the stockpile as their high-voltage battery packs are now out of warranty (Type 2 OLIBs). Hence while a 10-year-old BEV may still be on the road in the UK, we consider its battery pack to be in an 'end-of-life state', and thus part of our dynamic OLIB stockpile.

The main concern that emerges from our forecast above (Fig. 5.) is the possibility that by 2025, the UK's dynamic stockpile could exceed 100,000 redundant battery packs, or 42,000 t of lithium-ion battery waste, for which – as we will discuss below - there is there is no readily available sustainable solution.

## 5. Discussion of results and implications for industry and policymakers

Projecting new car registrations in the UK between 2019 and 2025 is quite challenging, given the ongoing uncertainty around Brexit and the UK's unknown trading status afterwards, primarily with the EU. We do project however, that new car registrations will settle at just above two million in 2025, assuming less-than-ideal trading conditions, down from 2.3 million at the end of 2018. This would put new registrations at levels similar to what they were at the beginning of the 2008 global financial crisis. From the predicted volume of BEVs, we derive penetration rates based on assumptions of 4%, 8% and 24% penetration (share of new car registrations) in 2025. These figures serve as insight into the size of not only the BEV market, but more relevant to this paper, the size of the eventual LIB end-of-life unit population.

Using our 3-scenario penetration rates (see Fig. 4), we estimated the corresponding dynamic stockpile of OLIBs in the UK, which is the main output of this paper, and objective of **RQ1**. The significance of the dynamic stockpile estimations in Fig. 5 lies in its shape, which tells us that each year after 2018, entire cohorts of lithium-ion batteries will enter an 'end-of-life state'. This OLIB stockpile will also exponentially increase in size each consecutive year, if annual sales of BEVs in the UK continue to increase.

What then, are the environmental, economic and political challenges of an increasing dynamic stockpile of OLIBs in the UK (**RQ2**)?

If society is to take a circular approach to the adoption of electrified propulsion, then we must consider battery materials reuse or remanufacturing, recycling, and safe disposal in order to achieve maximum sustainability benefits across the entirety of a BEV's life cycle.

In the context of our research, reuse of an OLIB in a second application – or second-life – refers to when an OLIB is no longer fit for traction (its original purpose in a BEV), and is used as a stationary power storage system for example. The reuse of OLIB cells or modules could also be part of a remanufacturing process, or a complete battery pack may be reused as replacement in a BEV, having passed appropriate functionality checks. Remanufacturing refers to an OLIB being rebuilt to the specification of a new OEM LIB, and in this context could include some battery module replacement and/or software upgrades [44]. Second life or remanufacturing simply defers the point at which the battery pack must be disposed of – though the longevity of the battery is unknown and could possibly be longer than the original automotive application.

The eventual safe disposal of OLIBs is equally important as there are several environmental health and safety concerns regarding the impact of this battery waste. Organic electrolytes in OLIBs are considered to be the main toxicity and flammability risks, because in storage or landfill conditions, OLIBs may explode or catch fire, and if the electrolyte is exposed to water, hydrogen fluoride formation may eventuate [30]. Additionally, cobalt or reactive lithium salt concentrations in the surface and underground water may rise above general environment levels in locations where OLIBs are disposed [18]. OLIBs in landfills can also introduce heavy metals such as copper and nickel, as well as carbonaceous materials (graphite and carbon black) into the environment [4].

### 5.1. OLIB recycling

While recycling is environmentally preferable to mining, it still needs to be carried out responsibly. For example, e-waste is informally recycled (with low recovery rates) in many parts of the world under hazardous working conditions, and as noted above, the environment is exposed to dangerous toxins, heavy metals and acid fumes that can result in severe illness and wider ecological damage [48].

Beyond that, it should be understood that the recyclability of the OLIB waste stream will vary with the battery chemistry and form factor (cell or module physical configuration) [4]. Therefore, the first, and most pressing concern is the recognition that as of 2019 there is no efficient or indeed sustainable method of recycling heterogeneous OLIB feedstock, and thus, there is an urgent need for more powerful, industrialized methods of recovering materials from OLIBs. Each BEV-specific OLIB is different, and thus the dynamic OLIB stockpile will collectively possess a wide variety of proprietary chemical compositions [89] and physical characteristics. Some batteries are developed for power, some for energy density, and others for longevity, which in turn makes OLIB recycling much more complicated and expensive, compared to generic 12 V Pb-acid battery recycling [90].

Although there are various ways of recycling OLIBs, the two main methods of processing within the EU are pyrometallurgy and hydrometallurgy. Pyrometallurgy (or smelting) uses high temperatures to recover cobalt, nickel, copper and iron from OLIBs and spent Nickel–Metal Hydride (NiMH) batteries. Unfortunately, the manganese, aluminium and lithium contained in the slag (that is eventually landfilled) cannot be recovered and are generally lost during this process. Hydrometallurgy (or acid leaching + chemical precipitation) involves mechanical pre-treatment and the use of chemicals to separate and recover metals and using this process can also recover lithium. It is quite common to combine these two processes, pyrometallurgy *then* hydrometallurgy, however a purely hydrometallurgical process will separate and recover more metals [41]. In a purely pyrometallurgical

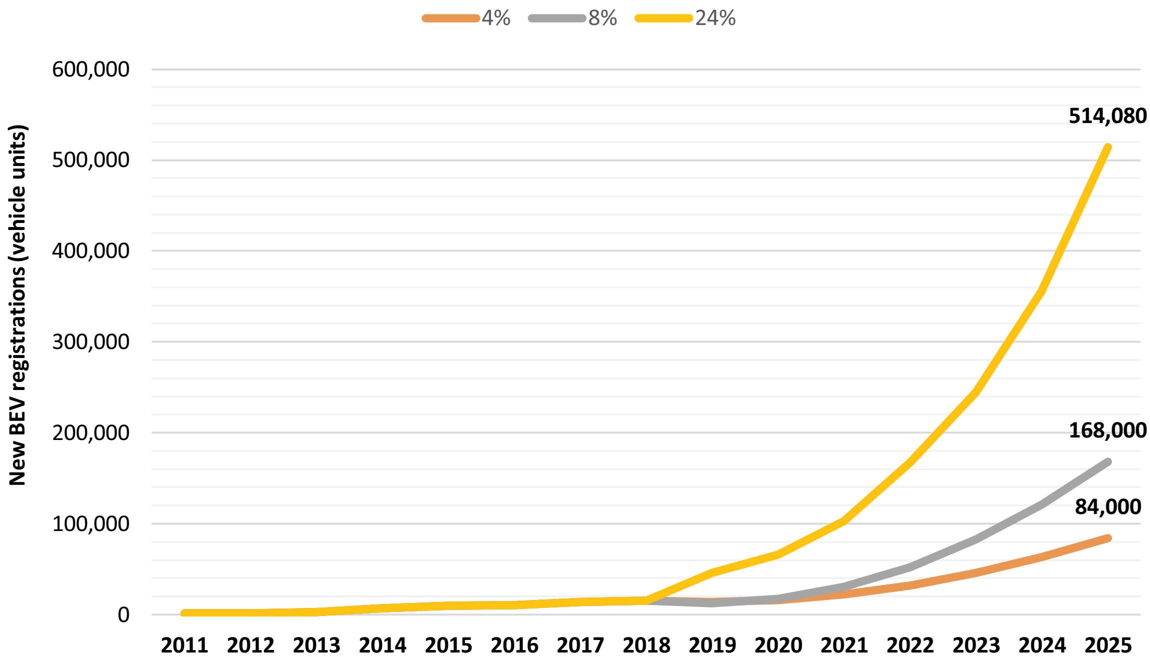


**Fig. 4.** Predicted volume of new BEV registrations in the UK up until 2025 based on penetration rates (share of total new registrations) of 4%, 8% and 24%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

process, burning the plastics from the recycled OLIBs helps sustain the furnace's high operating temperatures, and reduces the overall energy consumption of the smelting process [33]. It must also be noted that unrecovered cobalt and lithium from OLIBs are considered hazardous waste materials [91]. At present, the UK's principal disposal route is exportation to the European Union, where OLIB waste is treated at Umicore. However, the UK's future arrangements for OLIBs may likely change post-Brexit.

Although the recycling processes described above already exist within the EU, they are still quite inefficient, and are not optimized for high value metal recovery (e.g. lithium) [41,48]. Also, more strategic battery design could permit for OLIB components to be more easily separated or even robotically disassembled, thereby facilitating the recovery of the various metal fractions [44,92].

Strategic chemical selection for LIB manufacturing could also affect the economic feasibility of recycling OLIBs that ultimately ending up in the waste stream [93]. For example, in a scenario where OLIBs of Li2CO3 – Lithium Carbonate – (LCO) or mixed metal (NCM) cathode chemistries are dominant, currently recycled materials might constitute 50% of the mass of materials in the waste stream, but account for 86% of the economic value of that stream. However, as LIB manufacturers push to improve performance and mitigate against the high cost and

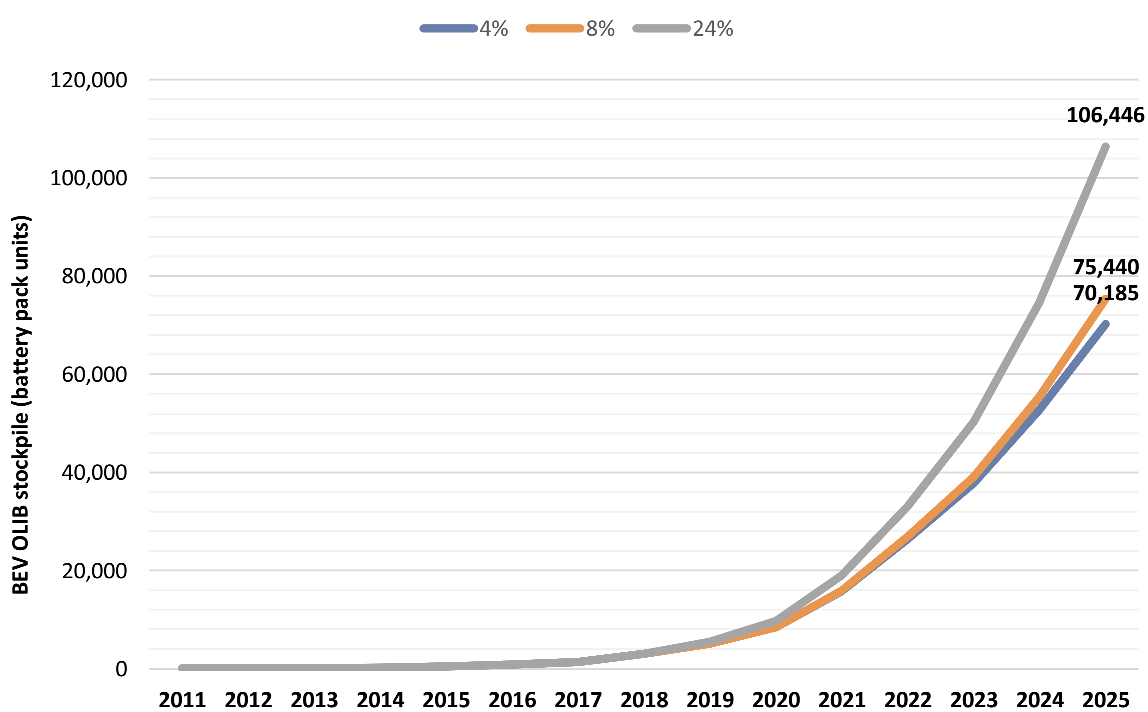


**Fig. 5.** Estimated dynamic stockpile of obsolete (end-of-life) lithium-ion battery packs (OLIBs) from UK BEVs from 2011 - 2025.

scarcity of Critical Raw Materials (CRMs) [94] by transitioning to cheaper chemistries such as LiMn2O4 – Lithium Manganese Oxide – (LMO) or LiFePO4 – Lithium Iron Phosphate – (LFP), the resulting value of the currently recycled and recovered materials could be reduced [4]. Thus, the principal insight from this example is that a high percentage of recovery by weight of recycled materials in the OLIB waste stream may not translate into high economic returns from OLIB recycling, and this is why some industry stakeholders are proposing value based recyclability targets for CRMs instead of mass based targets. Nevertheless, the development of cost-efficient recycling methods that recover high value materials such as lithium and manganese could incentivize the recycling of economically unattractive OLIB chemistries in the future. The possibility of a change in rates of recycling due to the changing value of recoverable materials implies the possibility of peaks in the recycling of OLIBs based on desirable chemistries.

Another major issue that is frustrating the recycling and recovery of OLIBs is the proper sorting and identification of the battery's chemistry, as the more specific the process is, the more effective the recovery of materials will be. Although sorting machines have begun appearing on the market in the hopes of reducing sorting and identification times, the need for a universal mixed-waste processing technology that can take into account the different OLIB chemistries and form factors remains an urgent priority [18].

It should be highlighted that recycling as a secondary supply of CRMs (in addition to primary supply) would be an important source for any future LIB manufacturing in the UK. Our results show that there is not yet a significant volume of OLIBs on the market and the UK's current recycling infrastructure is non-existent. The increasing ubiquity of LIB applications is driving advances in recycling [48] and the waste industry in the UK should be acutely aware of the looming volumes of OLIBs from BEVs.

### 5.2. OLIB reuse: 'Second life', stationary storage and remanufacture

Currently, recycling is the primary end-of-life management pathway for OLIBs, however both industry stakeholders and researchers agree that OLIBs retain approximately 70% - 80% of their initial capacity intact [41,92]. Furthermore, beyond the initial 8 year calendar lifecycle that is guaranteed by most OEMs via warranty, it is also estimated that OLIBs used in second-life stationary storage applications can be of service for a further 10 years before reaching their absolute end-of-life [95]. From a sustainability standpoint, reuse is generally more efficient than remanufacturing, which is more efficient than recycling [44].

Therefore, the reuse of OLIBs in these less demanding second-life applications could provide environmental and economic benefits by substituting the production of new LIB packs, as well as reducing direct energy consumption from the electricity grid [96]. The problem is however, that according to the EU Waste Batteries Directive (Directive, 2006/66/EC), OLIBS must be appropriately collected and recycled; and thus the reuse of such batteries is yet to be accounted for in current EU regulations [92]. In addition to this gap in regulations, there exists no second-life standards guaranteeing the quality or performance of this repurposed technology [96,97].

According to our results shown in Fig. 5, the first generation (cohort) of OLIBs in the UK are about to enter their end-of-life condition in 2019. While this may be an indicator of economic value for the stationary energy storage market, second-life applications face an additional challenge which is the falling costs of new LIBs. According to analysts [97], this cost gap must remain sufficiently wide to warrant the performance trade-off in second-life LIBs relative to new alternatives.

Now some in the industry believe that second-life applications are the first logical port of call (as opposed to recycling) for OLIBs retiring from traction duty, and this sentiment has been alluded to above. It is also felt that second-life applications will "buy time" for the recycling industry to get the appropriate infrastructure and efficient processes in place. However, consider the following: Global EV battery sales (measured in power capacity) are expected to range between 400–1000 GWh/y in 2030, with OLIB volumes reaching the same order of magnitude a decade or so later. However, the stationary storage battery market in the EU is projected at or below 10 GWh /y for that same time period [98]. This means that while second-life OLIBs could have a positive impact on this market segment, the need for OLIB recyclability will necessitate that recycling facilities remain the de facto destination for OLIBs, due to their significant excess in quantity.

A final challenge to consider in second-life applications is the time delay between new LIB production and OLIB availability for reuse. Consider that design decisions for new car models are made several years before they arrive on showroom floors. These new models generally have a production life of up to seven years, longer for heavy vehicles. Let us assume that OEM warranties on high voltage LIBs remain at eight years, and estimate the average natural lifespan of BEVs between 8 and 25 years [44]. Taking our forecasts into consideration, we can expect the large-scale reuse and remanufacturing of OLIBs to begin 10 years after their design, with full-cohort recycling occurring around the 20-year mark, and then declining 30 years post-design. The problem with this scenario is the very real possibility that specific reuse, and second-life applications may become technologically obsolete and/or commercially irrelevant during this timeframe. Therefore, LIB designs should be 'futureproofed' with as much flexibility, reconfigurability and modularity as possible given the clear need to plan LIB end-of-life processing decades in advance.

### 5.4. OLIB regulatory framework

A key lesson learned from the recycling of Pb-acid batteries has been that favourable economics alone are insufficient and that context-specific environmental policies are necessary to ensure that all recyclable materials in end-of-life batteries are processed for recovery [4,33]. In short, new regulatory drivers will be necessary for the development of a thriving LIB recycling industry that will in turn keep OLIBs out of landfills.

The main EU policies / regulations / agendas concerning LIB end-of-life [41] in the UK are:

- Batteries Directive (2006/66/EC) – is currently under review, with lithium-ion battery collection and recycling efficiency rates under consideration.
- Extended Producer Responsibility (EPR) under the above Batteries Directive, is aimed at making producers responsible for the environmental impacts of their products right up until the end-of-lifecycle. OEMs are already in the habit of entering EPR schemes to meet similar obligations in other sectors.
- European Commission's 2nd Innovation Deal, which aims to assess whether existing EU law hampers the recycling or reuse (second-life) of EV OLIBs. The outcome of this assessment may result in changes in EU law, of particular interest is the transfer of liability when OLIBs enter second-life service.
- Ecodesign Directive (2009/125/EC) establishes a framework for setting mandatory ecodesign requirements for energy-related products sold on the EU market. Automotive LIBs are not specifically regulated here, but there have been suggestions about requiring OEMs to provide technical documentation and make information about EV batteries publicly available. Future amendments could also include circularity requirements for EV batteries, for example on durability, repairability and recyclability standards.

Currently, due to the EU's nascent regulatory regime in this area, there exists no regulation that deals explicitly with lithium-ion batteries. Our forecasts, however, indicate the rapid expansion of OLIBs on the market from 2019 onwards, and hence, it is important that the EU get its regulations and policies in place.[10] It must be noted here that

[10] An observation: The relevance of EU policies (to the UK) in the long run is uncertain given the tumult that is Brexit.

some EU rules address OLIBs non-explicitly, with the scope to regulate further [41].

An additional concern for OLIB policy is that there is no clear differentiation between their status as "used batteries" or as "waste". Some industry stakeholders [98] believe this policy gap exposes EU (and UK) firms to unfair competition regionally and internationally for used, reused or repurposed waste batteries. In this respect, the European Commission has signalled that they intend to establish lithium-ion batteries as a distinct category within the Batteries Directive as well as including provisions that will accommodate OLIB reuse.

From the UK perspective, its Resources and Waste Strategy includes a commitment to review domestic regulations that applies to producer responsibility for LIBs in 2020. According to The Department for Environment, Food and Rural Affairs (DEFRA), it is the UK Government's view that producers should take greater responsibility for the products they put onto the market, especially once they reach their end-of-life. Extended producer responsibility (EPR) is a well-established principle that has been adopted by many countries, and in this case, the UK government is also motivated to ensure security of resources, specifically CRMs, for its domestic industry [48].

In China, the EPR programme known as "Interim Measures for the Management of the Recycling and Utilization of Power Batteries for New Energy Vehicles" was implemented to reduce OLIB waste. However, it goes further by encouraging LIB manufacturers to design batteries with easy disassembly and dismantling in mind. Manufacturers must also make the technical details of their battery and its dismantling available to the firms they supply. The “Interim Measures” programme also aims to improve the traceability network that has been developed by several supply chain stakeholders [99].

Regarding battery traceability more specifically, some EU firms in consultation with the European Commission have proposed that some minimum information be registered about each LIB/OLIB pack [96]. Suggestions have included chemical composition, capacity, weight and (national) producer, with the option to update the latter if at any point during its technical lifespan, the battery/modules/cells enter second-life service.

European firms have also identified the burdensome transport requirements of OLIBs within Europe as an area where additional updated policies may be useful [35]. The transportation of OLIB batteries across borders within Europe has been described as overly expensive and fraught with needless delays. One example is the inconsistent classification of OLIBs by EU Member States, where certain OLIBs with ‘green-listed’ chemistries are ‘amber-listed’ under hazardous waste codes. A second complaint is that the notification for shipping hazardous battery waste across Member States is overly complex and slow. Costs can reach several hundred euros per shipment, which is disproportionate given that OLIBs are typically shipped individually rather than in bulk due to presently low volumes. It is argued that these costs and delays lower European firm competitiveness, and stakeholders suggest that under the Waste Shipments Regulation, hazardous waste can be ‘fast tracked’ to high-quality recyclers that have been audited as ‘pre-consented recovery facilities’ [35].

Finally, various industry stakeholders have been trying to negotiate with the European Commission over some form of minimum standards for recyclers and OLIB material recovery [35,96]. The shared sentiment is that the EU should require that OLIBs only be treated by compliant recyclers that meet minimum standards of efficiency and environmental performance such as state-of-the-art processes that maximize the recovery of valuable metals and ensure the safe disposal of hazardous substances.

It is also important to note here that the EU's End of Life Vehicles Directive does not provide any economic incentives for industry, compared to EU regulation 443/2009 that is currently driving the transition to electrified automobility in Europe by imposing heavy fines on OEMs whose fleet average tailpipe emissions exceed 95 g CO2/km as of 2021 [6,44].

### 5.4. Theoretical reflections and limitations

We recognize that the conceptualization of a ‘dynamic OLIB stockpile’ is not perfect. After all, can the battery pack in a 10-year-old BEV that is still in use be considered to be part of the dynamic stockpile? Furthermore, could any out-of-warranty vehicle be considered as part of some similar conceptual stockpile? We argue yes and no respectively.

We have seen in the literature that there can be a mismatch between the life cycles of components in a single product [57], where the function of that product partially depends on the functionality of its constituent components. Products with multiple components become obsolete over time in multiple stages, and this is defined as technological obsolescence [54]. Crucially, it is the inability to obtain and replace parts that accelerates this process [58,59].

Our key argument here is that the lack of modularity and serviceability inherent in current automotive LIB pack designs, leads to an inability to (easily or affordably) procure and replace lithium-ion cells, modules or battery packs in BEVs. As the technology is in its relative infancy, Service Maintenance and Repair (SMR) infrastructures do not exist at scale for the diagnosis, repair and remanufacture of LIBs. Furthermore, some manufacturers have adopted overly cautionary protectionist approaches around the repair of their vehicles, which may control the market, drive up costs, and increase the rate of OLIB scrappage. The resulting ‘EV skills gap’, also means that there is not a sufficiently trained workforce, and given that some operations around LIBs are inherently risky, it may not be desirable for these tasks to be carried out by human operatives [100].

Therefore, upon the expiry of a BEV's LIB warranty (8 years), the entire vehicle's life cycle becomes tied to that of its OLIB, and thus is a major contributor of technological obsolesce and early retirement [58] in BEVs. The lack of backward or forward compatibility between older and newer model battery packs or modules in BEVs, or even between different models of BEVs, also arguably contributes to these vehicles' premature retirement [62]. More recent electric vehicle research by Richa et al. [4] seems to strongly support this core argument, first by establishing a similar differentiation between *Type 1* and *Type 2 EOL*[11] *EV batteries* (capacity fade and insurance write off respectively). Richa et al. [4] go on to conclude that because of the “lifespan mismatch” between LIBs and their host vehicles, batteries with high reuse potential will prematurely enter the OLIB waste stream.

In the meantime, what do these bundled / mismatched lifecycles mean for the future of BEV adoption? Especially when some argue that BEVs must operate for at least 150,000 km before showing significant environmental benefits over owning petrol or diesel vehicle [15,101]? If a global standard [102] for LIB packs or modules were established, then OLIBs would no longer condemn BEVs to product-level obsolesce [54]. However, we are currently in the midst of a lithium-ion battery ‘arms race’ between manufacturers, and history has shown that the steep slope of the technological s-curve is often characterized by the wasteful incompatibility of proprietary systems [62].

The concerns that stem from our results also mirror a growing sentiment in recent literature that while the majority of EV batteries on the market have not yet reached their end-of-life, the EU's recycling industry is not yet adequately equipped to meet the expected volumes of OLIBs in years to come [41]. These concerns have also begun to emerge in recent industry press releases where first generation Nissan Leaf electric vehicles have been described as ‘barrelling’ toward their end-of-life, as they approach their first decade on U.S. and EU roads [103]. The article describes owners being worried about battery degradation and desperately searching for an affordable replacement, given that the battery pack is the most expensive component on an EV. First generation Nissan Leaf models – arguably considered the first mainstream BEVs – are the proverbial ‘canaries in the coal mine’ as

[11] End of Life

their LIBs' fading charge capacity signals what is certain to become an industrywide concern. One Nissan Leaf owner revealed that his 24-kilowatt-hour battery had lost half its charging capacity by 60,000 miles. Up next on the dynamic OLIB stockpile are the first-generation Tesla vehicles (Model S) launched in 2012, followed closely by BMW's full-electric i3 launched in 2014, amongst others. The number of BEVs that will need replacement batteries is approaching critical mass as their eight-year battery warranty mark draws near [103]. Thus, keeping a reasonably accurate account of this accumulation in the form of a dynamic stockpile is our contribution to mitigating against a growing problem that is certain to affect the United Kingdom in the near future.

## 6. Conclusion and considerations for the future of OLIBs

Our study shows that OLIBs will increasingly present themselves as a future waste management challenge due to high volumes, complexity, heterogenous chemistries and variety of materials forecast in the OLIB waste stream. Thus, multiple waste management strategies must be developed for OLIBs that include:

- Reuse pathways for healthy OLIBs packs, modules or cells.
- Recycling regimes capable of recovering high value materials from heterogeneous OLIB feedstock, i.e. multiple electrode chemistries and form factors (e.g. cylindrical, prismatic, and pouch) [97].
- Updated environmental regulations that drive the efficient collection and sorting of OLIBs, and the maximum recovery of all recyclable materials, despite low initial OLIB volumes and uncertainty regarding the full costs recycling [33].
- Safe disposal routes for materials with negligible secondary value or non-existent means of recovery [4].

### 6.1. Traceability

Traceability of LIBs throughout their lifecycle has been flagged by stakeholders as a feature that could have a significant impact on how OLIB stockpile waste flows are managed in the future. The current absence of reporting mechanisms or certification schemes is causing a lack of traceability across the LIB lifecycle, resulting in materials leakage and economic/value loss. The implementation of battery identification e.g. a Quick Response (QR) code or via blockchain technologies could provide a range of valuable data such as state-of-health (usage, performance, charging history, charging capacity), chemistry type, and can ideally be paired with common testing methods and measurement standards [44,98,104]. This kind of battery data could be crucial to the future of OLIB waste management particularly for reuse or second-life endeavours in the UK.

### 6.2. Metals recovery

The dynamic OLIB stockpile is also a means of mitigating against negative impacts to automotive and battery manufacturer supply chains. Cobalt, lithium and rare earths take the highest priority, given the projected future demand and supply risks of these metals [48]. Recovered cathode materials from OLIBs could reduce total LIB pack cost by more than 20% [33], and by 2030, it is estimated that OLIB recycling could generate approximately 10% of Europe's cobalt consumption by the automotive sector [25]. Thus, OLIB recycling could be especially beneficial to future LIB manufacturing in the UK by helping to overcoming a key barrier to domestic LIB production; the lack of a primary component raw material supply chain (Mayyas et al., 2019).

In the long-term, the uncertainty of future LIB chemical compositions remains the biggest challenge to OLIB recycling. If the industry pursuit of decreasing cobalt content in LIBs is successful, then the future economic viability of OLIB recycling could be in jeopardy. This concern therefore brings into question the wisdom of developing costly and highly specialized recycling processes, as the need for them could be obviated in as little as a decade from implementation. Some suggest that flexible, low cost recycling of as many products as possible is the way to go [33].

### 6.3. Closed-loop systems

One factor that our dynamic stockpile forecast cannot account for is closed-loop systems. A closed-loop system is a take-back and recycling scheme established by OEMs that can be integrated with the LIB manufacturing process. For example, Tesla's recycling program physically separates electronic components and cases for reuse and recycles the remaining OLIB. Tesla's aim is to create a closed-loop system that recycles OLIBs – and in the same factory – reuse those recovered materials in new batteries [48]. Closed-loop systems can also be comprised of allied firms, as is the case with Umicore (material recovery) and LG Chem (battery manufacturer) [105] or Umicore and Audi (OEM) who are collaborating on a closed-loop battery cycle in an effort to increase recycling rates and material traceability. Testing of this optimized process indicates that 95% of the cobalt, nickel and copper in the OLIBs used can be recovered [99]. While our dynamic OLIB stockpile estimate cannot account for closed-loop OLIBs that will never make it onto the 'open market', future databases may be able to subtract closed-loop units from OLIB market forecasts.

### 6.4. Sustainable design: efficiency or modularity?

While exploring the difficulties in recycling OLIBs and efficient material recovery, we came across a nuanced debate which we would like to expand on here briefly. According to researchers, 'rest-of-pack' costs (not related to cell or cell chemistry), which includes energy consumption and weight cost, can account for between 45% to 61% of the total service life cost of the battery pack [44,106]. Thus, given the significant potential for cost reduction, OEMs are increasingly integrating battery pack design and assembly as part of their core competence.

However other industry stakeholders posit whether a dominant design (chemistry and/or prismatic form factor) LIB could improve the recyclability of the waste stream [4]. One supporting argument is that currently in Information and communications technology (ICT) product design, smartphones, laptops and tablets make it difficult or impossible to replace the battery without proprietary tools. This has led to advocacy for the easy and non-destructive removal of consumer electronics LIBs by end-users in order to facilitate the successful and cost-effective repair, refurbishment or re-use of these batteries and their host products. Specific suggestions include removable batteries becoming a standard and banning the use of soldering and glue in battery fitment [107]. While these comments seem to be aimed more at ICT products specifically, it does foreshadow a dilemma we believe will be relevant to automotive LIB design, which is the tension between OEMs' optimising for battery efficiency with 'sealed-in' LIBs versus an 'Eco-design' approach that prioritizes disassembly and material recovery at end-of-life.

### 6.5. Final thoughts

If we assume that BEV market penetration in the UK achieves an optimistic 8% of total new car registrations in 2025, then our forecast indicates that the dynamic OLIB stockpile would have reached approximately 75,000 units, or 28,000 t[12] of lithium-ion batteries that are eligible for end-of-life processing. While the economic viability of these figures is beyond the scope of this paper, consider the following: If the global stockpile of 'retired' BEV batteries is forecast to exceed 3.4 million units by 2025 [108], then according to our estimates, the UK's share of OLIBs will represent approximately 2.5% of that global

[12] Based on the average weight of the following battery packs: 1st gen Nissan Leaf, 2nd gen Nissan Leaf, Tesla Model X and Geely 300 (approx. 380kg per unit). Figures obtained from 3rd party teardown reports.

stockpile. Future industry research in the UK should consider what these estimates represent, especially given the limited availability of information on the economics of recycling, amongst other things that may be stifling investment in the sector [33].

As we debate these and other issues about the future of OLIB management, it is worth repeating the two key lessons learned from Pb-acid battery recycling: 1. Sustainability solutions require sustainable business models [30], and 2. Despite favourable economics, regulations are likely necessary to develop and maintain a viable end-of-life infrastructure [33].

Regarding this paper's potential to generalize about the wider population of OLIBs and their end-of-life challenges; most of the automotive industry's major stakeholders (automakers and suppliers) are multinational firms [109], whose technologies are increasingly homogenized through the practice of "platform sharing" [110]. This is aimed at cost reduction and simultaneous compliance with (often harmonized) regulations [6] in several regional markets. Thus, we argue that due to this industry's international portfolio, many of the arguments and concerns presented in this paper will hold true beyond the United Kingdom's national borders. This study's major limitation is a direct reflection of the LIB 'futureproofing' dilemma discussed above. Because of the need to plan LIB end-of-life processing decades in advance, some of the proposed solutions (and debates around them found in this paper) may become obsolete or irrelevant by the time they are needed.

## Declaration of Competing Interest

None to declare.

## Appendix A

Fig. A.1.
Table A.1, Table A.2, Table A.3.

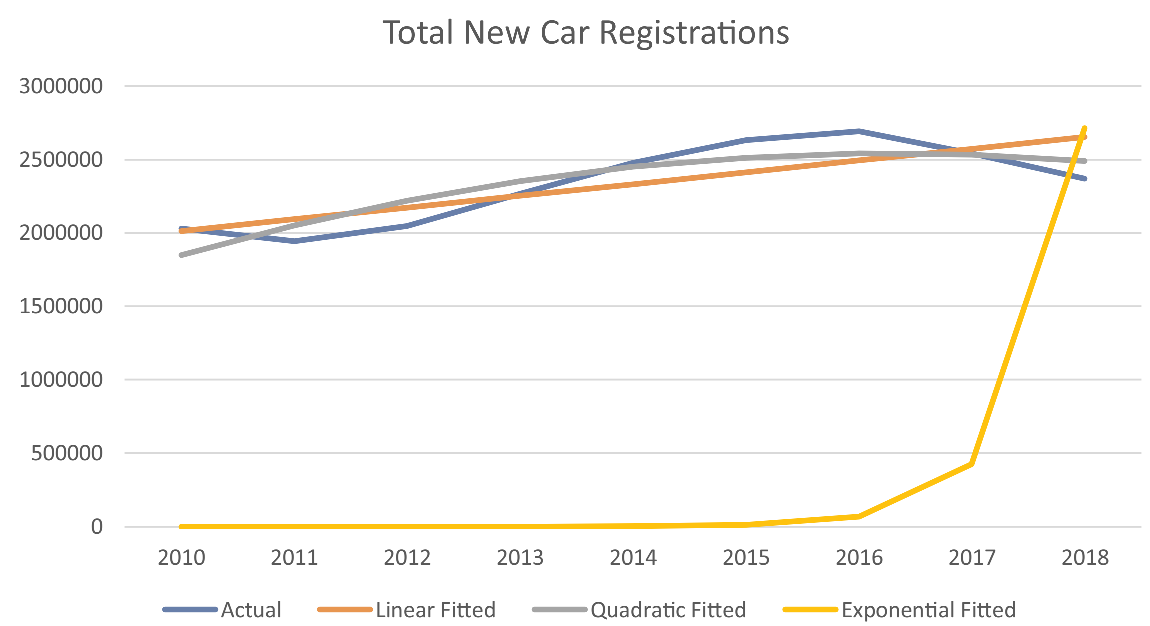


**Fig. A.1.** AIC and SIC criteria for the linear, quadratic and exponential trend models applied to total new car registrations 2011 - 2018.

**Table A.1**
Historical and predicted new vehicle registrations from 2011 - 2025.

| Year | Total New Car Registrations |
|---|---|
| 2011 | 1941,253 |
| 2012 | 2044,609 |
| 2013 | 2264,737 |
| 2014 | 2476,435 |
| 2015 | 2633,503 |
| 2016 | 2692,786 |
| 2017 | 2540,617 |
| 2018 | 2367,147 |
| 2019f[a] | 2373,018 |
| 2020f | 2364,211 |
| 2021f | 2340,726 |
| 2022f | 2302,562 |
| 2023f | 2249,720 |
| 2024f | 2182,199 |
| 2025f | 2100,000 |

[a] f is Forecast of all new car registrations that year.

**Table A.2**
Historical and predicted uptake of UK BEVs as a percentage (4%, 8% and 24%) of all new vehicle registrations in 2025.

| BEV Cohort Year | Total new BEV registrations @ 4% penetration in 2025 | Total new BEV registrations @ 8% penetration in 2025 | Total new BEV registrations @ 24% penetration in 2025 |
|---|---|---|---|
| 2011 | 1082 | 1082 | 1082 |
| 2012 | 1262 | 1262 | 1262 |
| 2013 | 2512 | 2512 | 2512 |
| 2014 | 6697 | 6697 | 6697 |
| 2015 | 9934 | 9934 | 9934 |
| 2016 | 10,264 | 10,264 | 10,264 |
| 2017 | 13,597 | 13,597 | 13,597 |
| 2018 | 15,474 | 15,474 | 15,474 |
| 2019f[a] | 15,892 | 16,321 | 45,562 |
| 2020f | 16,227 | 17,150 | 66,198 |
| 2021f | 22,251 | 30,559 | 102,992 |
| 2022f | 32,041 | 52,348 | 167,627 |
| 2023f | 45,595 | 82,518 | 244,770 |
| 2024f | 62,915 | 121,069 | 356,135 |
| 2025f | 84,000 | 168,000 | 514,080 |

[a] f is Forecast of new BEV registrations that year, based on a corresponding percentage forecast of total new registrations in the future.

**Table A.3**
List of secondary data sources (reports) projecting BEV penetration as a share (%) of new car sales in 2025.

| Organization | Year of report | 2025 BEV penetration forecast (share of new sales) |
|---|---|---|
| Energy Policy Simulator (EPS) | 2017 | 6 −7% (US) |
| Goldman Sachs | 2017 | 4% (Global) |
| Morgan Stanley | 2017 | 9% (Global) |
| UBS | 2017 | 24% (EU) |
| Bloomberg (BNEF) | 2018 | 11% (EU) |
| BMO Capital Markets | 2018 | 6% (Global) |
| Boston Consulting Group | 2018 | 6% (Global) |
| J.P. Morgan | 2018 | 9% (Global) |
| RBC Capital Markets | 2018 | 8% (Western Europe) |
| IEA | 2018 | 12% (Global) |

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