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Research paper

Beyond Recycling Bicycles: Circular Economy Implications of Increasing Ebike Uptake in Ireland

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Abstract
Recent years have seen an upsurge in the micromobility sector. Ebikes are gaining ground to become viable alternatives to private car commuter transport and last-mile delivery in cities. An underrepresented environmental concern, particularly in European literature, is the end-of-life management of ebikes as ewaste. The current trend towards road transport electrification raises concerns regarding ambitions towards becoming a green and circular economy as well as meeting resource management targets. This paper addresses the material circularity of increasing ebike uptake. This is achieved through an examination of the ebike product lifecycle in Ireland through organisational qualitative research, an examination of the ebike market share, and a case study of ebike fleet management on a university campus. It argues that policy makers need to engage with the ebike retail and repair sector to address concerns they have regarding repairability of ebikes, quality, and insurance. Policies that encourage uptake of ebikes such as Cycle-to-Work schemes should facilitate the circular economy through innovative initiatives such as facilitation of resale of remanufactured, and refurbished ebikes and incentivising product longevity through repair vouchers. From this study it appears that basic mechanical features of ebikes are more likely to fail than ebike batteries. The exclusion of light means of transport such as ebikes from the Ecodesign Directive should be reconsidered given the quantities of ebikes placed on market and the need to address repairability in the sector. Island nations, such as Ireland, may need further enhancements and initiatives such as additive manufacturing to ensure timely repairs to ebikes, thereby extending product lifetimes and circularity.

Keywords: Transport · Micromobility · E-bike · Circular Economy

1 INTRODUCTION
The purpose of this paper is to evaluate potential rebound impacts of increased ebiking, taking a product lifetime perspective to determine longer-term circular economy implications. Ultimately the aim is to provide evidence-based guidance and economic impact assessment to policy makers to implement sustainable ebike policies into the future. We explore circular economy practices and perspectives with respect to the lifetime of ebikes in the Irish context from the point of view of organisations involved in the import, distribution, sales, repair, and ultimate disposal and recovery of ebike parts such as scrap metals, batteries, and other electronic components.

1.1 Increased Ebike Uptake
An estimated 5.5 million ebikes were sold in the EU in 2022 (CONEBI, 2023) compared to 98,000 in 2006 (Maria & Bjornavold, 2019) whilst forecasted sales are expected to exceed 17 million units annually by 2030 (European Cyclists Confederation, 2020). Ebikes are expected to play a vital role in realising EU ambitions to reduce transport-sector carbon emissions by 90% before 2050 (European Commission, 2021). In Ireland, ebike

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sales were reported to be growing by 20% each year pre-Covid (O'Sullivan, 2019) and the so-called "Covid boom" in cycling (Younes et al., 2023) resulted in a further surge of ebiking and ebike ownership (Reynolds, 2020). Ebike advocacy groups were formed (Laffan, 2020), Irish ebike brands and designs were established (O'Brien, 2020), and local authorities across the country advanced plans to pilot ebike shared schemes (Aodha, 2021; Gleeson, 2021; McGee, 2021; Taylor, 2021a, 2021b). To promote cycling the government offers a tax incentive scheme, Cycle-to-Work, for taxable employees to purchase a bike at a reduced cost through salary repayments over a maximum of 12 months. In recent years the scheme has been updated to include ebiking, allowing for subsidised purchases up to limits of €3,000 for cargo and ecargo bikes, €1,500 for pedelecs / ebikes, and €1,250 for other bikes (Office of the Revenue Commissioners, 2024).

1.2 Ebike Circularity

The recent European Declaration on Cycling (Official Journal of the European Union, 2024) recognises the role of the cycling industry in providing green and "high-quality local jobs" and aims to support the circular use of bicycles. The circular economy describes the operation of an economic system which prioritises maintaining resources at their highest level of utility for the longest possible time. Thus, as expressed in Figure 1, the transition from a linear economy to a circular economy involves slowing, narrowing and closing material flows. "Slowing" includes measures to deliver longer life products such as enhanced durability, repair availability and remanufacturing. "Narrowing" means utilising fewer resources per product. Finally, "closing" incorporates advanced recycling measures and preparation for reuse of componentry (Bocken et al., 2016). Innovation and new business models can deliver on the "refuse" and "rethink" R strategies, where product-as-a-service business models offer the outcome of the product without material responsibility (Kirchherr et al., 2017; Kishita et al., 2021). Increased uptake and use of powered micromobility solutions could represent a circular economy rebound phenomenon if unaddressed. In this case the unintended consequence, or rebound, occurs where demand for critical raw materials and end of life treatment of associated waste could be equal to or greater than the benefit derived from a shift away from fossil fuel-based transport (Zerbino, 2023). Emobility solutions present a great challenge to policy makers to meet resource management targets for batteries and ewaste. Electrical and Electronic Equipment (EEE) are dependent on electric currents or electromagnetic fields to function properly. In general, if an item needs a battery or to be plugged in, it's EEE; when these items are no longer required and become waste then they are referred to as WEEE (waste EEE or ewaste) (European Commission, 2019). WEEE is one of the fastest growing waste streams in the world. Globally, 62 billion kg of ewaste, were generated in 2022 (Baldé et al., 2024). The Recast WEEE Directive (Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE) (Recast), 2012) seeks "to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials" reflecting a shift in EU policy towards circular economy principles. The upward trends in WEEE generated is generally accepted as being likely to continue as new e-products enter the market and technology additions to products increase (European Commission, DG Environmental, 2019; Parajuly et al., 2019). Producers and importers of EEE are required to finance the collection, preparation for reuse and treatment of WEEE. In Ireland this is achieved through registration of EEE items with the Producer Register.

National WEEE collection targets are calculated using consumption-based methods. Tools are available to predict annual WEEE arising based on lifetime distributions that model the progression of EEE to WEEE over time (Baldé et al., 2017; Magalini et al., 2020). However, these models need reliable placed on market data compiled from customs codes based on export and import data plus realistic product lifetime model inputs to provide useful projections, i.e. the country needs annual sales data plus information on the rate at which these products are disposed of, which is usually the point of failure in a products lifetime.

Appropriate end of use management of EEE should provide opportunities to recover critical raw materials, reduce overall environmental impacts, and stave-off demand for virgin raw materials (Chancerel et al., 2015; Ueberschaar et al., 2017; Unger et al., 2017; Zeng et al., 2018). As a resource opportunity the economic value of raw materials present in WEEE arising in 2022 was estimated at approximately 91 billion US dollars (Baldé et al., 2024) Unfortunately many WEEE resources are lost due to inappropriate disposal in household and other waste collections, ultimately ending up in scrap metal or other waste collections (European Commission, DG & DIGITALEUROPE, 2017; Huisman, 2013; Ryan-Fogarty et al., 2020). Given that upwards of 11,000 tonnes of WEEE end up in metal scrap in Ireland each year (Ryan-Fogarty et al., 2021), ebikes present a particular challenge — they look like traditional bikes and their presence in metal scrap may go undetected. Not only is this a lost opportunity to recover materials, if lithium-ion batteries are damaged, either before or during waste management, there is potential for fires and explosions. This is not a theoretical risk: so far, in 2024 alone, two recycling facilities in Ireland suffered extensive fire damage due to thermal runaway from damaged battery cells (Conway, 2024; O'Sullivan, 2024). Although there are numerous studies detailing ebike battery collection in China, the WEEE management system technologies and applications differ vastly to Europe (Cusenza et al., 2019; Elwert et al., 2019; Guo et al., 2021). In Europe the conversation is only just beginning about how to deal with ebike waste, with refurbishment solutions focusing mainly on batteries (van Schaik, 2019). A strategy for e-mobility e-waste has not been formulated for Ireland.

1.2.1 Legislative and Policy Drivers

Two key recently adopted pieces of EU legislation, the Ecodesign for Sustainable Products Regulation (ESPR) in 2024 and The EU Batteries Regulations in 2023, will impact the ebike market in terms of two components: motors and batteries. Replacing the original Ecodesign Directive, the ESPR takes a life cycle approach to product impacts and aims to make sustainable products the norm by integrating sustainability into the product design and improving product information for consumers. The ESPR outlines product exclusions such as construction and packaging products as well as motorised transport and ebikes, categorising such applications as light means of transport (LMT). Similarly, whilst tyres are a priority end use product, tyres for LMT were excluded. Electric motors were part of the original Ecodesign Directive and will continue to be addressed in ESPR. Raw materials and intermediate products like iron, steel and aluminium are a priority in ESPR.

Criticism has been levelled at governments, trading blocks and industry regarding their narrow concern about lithium sourcing based solely on economic and security of supply factors (Agusdinata et al., 2018). Social and environmental impacts associated with the increased demand for lithium include: additional water consumption, potential for contamination of local water supplies, impact on eco-tourism, and localized health implications (Greim et al., 2020; Guo et al., 2021). Furthermore, the capacity of environmental regulators to protect human rights and environmental concerns in countries of primary extraction has been justifiably questioned (Balch, 2020). An average EV battery weighs between 385-544 kg (Berjoza & Jurgena, 2017) whilst a standard ebike battery is around 2.5-3.5 kg (Bosch eBike Systems, 2021). To address materials efficiency a key focus should be to lower the lithium intensity of transportation services (Greim et al., 2020). Thus, in accessing e-mobility, ebikes represent a massive material efficiency when compared to the private EV, with growing evidence supporting the potential for ebikes to replace private car trips, given the assistance to travel further and load carrying capacity of cargo ebikes (Bjørnarå et al., 2019; Fyhri & Fearnley, 2015; Söderberg f.k.a. Andersson et al., 2021). The EU Batteries Regulation Concerning Batteries and Waste Batteries defines ebike batteries as belonging to the classification of LMT batteries. By 2027, portable batteries in appliances must be designed so that consumers can easily remove and replace them themselves. Only batteries with a capacity greater than 2 kWh will be required to have digital product passports, which will exclude most ebike batteries as the majority are rated as <2 kWh. However, by focussing on a mass of battery rather than volumes of batteries sold metrics, some key opportunities to facilitate greater battery efficiency, reuse and repairability may be missed.

1.2.2 The Need to Address Circular Economy Aspects of Increased Ebike Uptake

Repair and refurbishment of used EEE is essential to create a viable circular economy (European Commission, 2015). Recent Irish research demonstrates the need for consumers to be provided with clear pathways to relinquish EEE for reuse and refurbishment, however it is also recognised that there are limited reuse, preparation for reuse and repair undertaken within the country (Coughlan & Fitzpatrick, 2020; Johnson et al., 2020; Local Government Ireland, 2024; Ryan-Fogarty et al., 2021). Since ebikes are a novel product in the EU, there are few academic studies that address the materials circularity of the entire product and life cycle. To the best of our knowledge, to date Koop et al. (2021) are alone in academically documenting potential circular business models for remanufacturing and additive manufacturing in the ebike industry in Germany. Strupeit et al., (2024) highlight the need for more circular business model research in remote areas, therefore this paper presents insights into circular economy implications of increased ebike use in Ireland.

Because of the current dearth of information, we present three disparate information streams: (1) Researchers interviewed relevant personnel from a range of different types of companies in the ebike and waste recycling sectors in Ireland. (2) We also draw on data from our on-campus fleet of 56 ebikes as part of the Inclusive Sustainable Cycling (ISCycle) Project. ISCycle is funded by the Sustainable Energy Authority of Ireland and the [Irish] Department of Transport and targets behaviour change through interventions based on ebike loans and simulated ownership to elicit modal shift away from private cars. (3) Because e-waste recycling needs to be funded and planned for based on average product lifespans and demand management, knowing the placed-on market figures is essential to planning for a circular economy. It can inform estimates of demand for repair and refurbishment services and predict when end of life treatment is likely to occur. We conducted a preliminary assessment of placed on market data for ebikes in Ireland and demonstrate how data gaps impede the development of circular strategies for ebikes.

This research takes a deeper view of travel sustainability, examining Ireland's capacity to deliver sustainable travel solutions under our Waste Action Plan for a Circular Economy Ireland's National Waste Policy 2020-2025. WEEE is the fastest growing waste stream globally. A transition to e-mobility needs to be carefully balanced with environmental impacts of sourcing raw materials, their use and ultimate disposal. The National Waste Management Plan for a Circular Economy sets targets for reuse, repair, and recycling, this research aims to optimise that potential.

2 METHODS

2.1 Organisational Qualitative Research

Qualitative interviews were conducted with individuals from organisations involved in the ebike waste recycling sector. Purposive sampling was used focussing on the following criteria. First, perspectives from a range of points in the ebike lifetime were targeted, to provide insights into different practices, policies, and attitudes. Second, qualified participants (i.e. retailers and repairers of ebikes) were selected, to generate informed insights on the topic. Consequently, researchers utilised snowball sampling, where initial informants, approached through the researchers' professional networks, were asked to provide referrals to recruit further informants based on the sampling criteria. This enabled the team to employ maximum variation sampling to collect a wider range of views. Around twenty-five potential informants from a variety of sectors within the ebike lifecycle were approached via email or phone. Seventeen agreed to be interviewed and recorded, thirteen virtually through MS Teams, two over the phone and two at face-to-face interviews on their premises. Interviews were conducted between September 2023 and October 2023. Interview duration ranged between 50 minutes and 1.5 hours. Interviews were recorded, and extensive notes were taken. Recordings were used to check the completeness of information and confirm notes where necessary. The interviewer followed a semi-structured format, using a pre-defined topic guide with prompts. The topic guide was designed to prompt discussion on circularity strategies with a production chain, specifically "R strategies" (Kirchherr et al., 2017) applied to ebikes. The topic guide is supplied as Appendix A.

The semi-structured style focussed the interview while allowing the interviewer to pursue any ideas raised by participants that were not anticipated but were nonetheless relevant to the research objectives. Organisations involved in distribution, retail, and repair were asked questions relating to sales and market prediction, refurbishment and resale, repairs, and end of life management of ebikes. All organisations were asked about the potential impacts of ecodesign and batteries regulations on their operations and concerns they had with respect to the ebike market. Table 1 provides a summary of the number of participating organisations involved in activities relating to each stage of the ebike product lifespan. Some organisations were involved in multiple activities such as retail, fleet management and repair.

Table 1. Activities Matching Ebike Lifetime Stages and Number of Organisations Interviewed Involved in Activity. Total Number of Organisations Interviewed, N = 17.

Description of Activities	Point in Ebike Lifetime	Number of organisations
Producer responsibility organisations	Ebikes and batteries placed on market	2
Ebike importer and distributor	Sales	2
Retail and repair	Sales, Repair, Reuse, Refurbishment	8
Renting, leasing, and fleet management	Use	3
Material recovery (battery, metal scrap, ewaste management.	End of Life of bike or bike components	3
Bike mechanic training	Repair	2
Battery supply	Repair, Reuse, Repurpose	2

Interview data were analysed thematically, taking a descriptive, semantic approach to represent the perspectives explicitly conveyed by participants. Given the lack of existing research on the specific topic and therefore exploratory, rather than confirmatory, nature of this investigation, an inductive, bottom-up approach was taken, rather than deductively imposing an existing theoretical framework from the top-down.

The analysis involved searching for and identifying patterns of shared meaning across participants' accounts that addressed the research questions. Candidate themes were generated and then refined, defined and named to form the final themes presented here.

2.2 Establishing Product Lifetimes and Shape and Scale of the Irish Ebike Market

Three sources of data were used to assess ebike product lifetimes and repair factors. Firstly, responses from ebike retailers and repair organisations on ebike lifetime were noted. Secondly data from the management of the ISCycle fleet on campus were analysed. The ISCycle ebike fleet consisted of 56 commuter, folding, and various cargo bikes. These were loaned to staff at the University of Limerick and surrounding workplaces for periods between 4 and 12 weeks. A logbook of breakages, issues, and general observations, alongside costs and time investment in repairs was maintained in MS Excel. Bike maintenance was carried out by the research team with some occasional professional bike mechanic support. The repair logs and observations of the research team were reviewed from initial pilot loans (n=10) from Autumn 2022, full deployment (n=56) in Spring 2023 to time of writing during Summer 2024. Finally, to characterise the Irish market with respect to bike and ebike sales, the Irish Central Statistics Office (CSO) International Trade in Goods Section provided data on goods export and import (CSO, 2024). Three customs declarations codes were examined, CN 87116010 *bicycles, tricycles and quadricycles, with pedal assistance, with an auxiliary electric motor with a continuous rated power not exceeding 250 watts*, CN 87116090 *Motorcycles, incl. mopeds, and cycles fitted with an auxiliary motor, with electric motor for propulsion (excl. bicycles, tricycles and quadricycles, with pedal assistance, with a continuous rated power <= 250 W)* and CN 87120030 *bicycles with ball bearings*. For ease of comparison the aforementioned categories will be referred to as ebikes, speed pedelecs, and bikes respectively in this paper. These data were a combination of customs-based non-EU trade statistics and data from the Intrastat Survey of Irish traders involved in trade with other EU member states and were collected as value in Euro and quantity in tonnes. Much of the data was pre-summarised at source (e.g. was reported in an aggregated way). Figure generation, and the occasional calculation (e.g. converting tonnes of ebikes into estimated numbers of bikes) were conducted in Excel.

3 FINDINGS

3.1 Organisational Qualitative Research

Thematic analysis of interview data generated several themes across the organisational respondents. Themes related to the changing nature of bike retail (Section 3.1.1), the impact of the Cycle to Work scheme (Section 3.1.2), ebike product lifetime (Section 3.1.3), resale, repair, and reuse as a norm in the bike retail sector and expansion into the ebike era (Section 3.1.4), and end of Life management of ebikes and components (Section 3.1.5). Sub themes within these included barriers to circularity in terms of repair and challenges faced by all actors across the life cycle, such as Ireland's geographic location as an Island and the impacts this has on the circular economy of ebikes.

3.1.1 Changing Nature of Ebike Retail

All organisations (O) involved in retail reported an upward trend in ebike sales; some referred to slowdowns in the market, but they are expecting growth in coming years. Some ebike retailers reported diversifying their business models into corporate leasing, ebike rental, and shared scheme ebike maintenance contracts. Retailers noted a shift in sales to younger people as opposed to older people who were perceived as the sole market demographic previously. Youth bike "sales have fallen through the absolute floor" as more young people use scooters (O6). Another informant noted that shared bike schemes are favoured by young people who may not need to own a bike (O5). Most organisations commented on how Ireland was slower to the ebike market than our EU counterparts, lagging between 10 and 15 years behind trends. One (O6) estimated that current sales were a 70/30 percent split between regular bikes versus ebikes.

All retailers expressed concerns regarding online sales. The "Covid boom" in cycling was referred to by some retailers (O5, O9) as driving online sales whilst shops lacked stock. One respondent (O9) noted that whilst demand for bikes was going up, the shape of the market was uncertain, citing recent high-profile UK and EU bike retailer/parts supplier closures in recent months (O9). Many felt that the ebike market was not well understood by the public and policy makers; an example often provided were ebikes in breach of regulations and others sold legally but tampered with to disable the speed/power regulator (O2). Because bike retailers' business model involved selling bikes to a consumer who can physically return the item, they preferred to stock high-end brands, as these are costly, well-regulated and difficult to tamper with. It was speculated that customers with smaller budgets, i.e. less than €1,500 tended to buy online. Some organisations suspected breaches of the EU anti-dumping regulations, and they expressed disbelief as to how bikes could be sold so cheaply within the EU (O2, O5, O8, O9). Minimum safety and CE standards were not viewed to be sufficient for durability for this category of ebike, with many respondents mentioning that standards were a once-off achievement, and the bar was low (O6, O9). Some organisations (O2, O9) even referred to these ebikes as "disposable" providing an example of an acquaintance who bought a cheap folding ebike online almost on an annual basis (O9). Online and distance sales were of great concern to the Producer Responsibility Organisations (O11, O12) as these were potential "free riders" in the battery and WEEE treatment scheme (i.e. the products benefit from free collection and appropriate treatment whilst the producer has not paid the appropriate recycling fees). The unavailability of accurate placed-on market data was of concern for waste treatment facilities. They needed to know the scale of the problem i.e. how many ebikes are in circulation and when they are likely to become waste. This helps producer compliance schemes and waste management organisations to target investment in collection, treatment, and consumer awareness.

3.1.2 Impact of Cycle to Work on Resale of Ebikes

Many customers traded-in their old bike for resale against the purchase of a brand-new bike under the Cycle to Work scheme. However, many viewed Cycle to Work as lowering the value of second-hand bikes (O1). To have a truly circular system for bikes "investment needs to be made somewhere" (O10) and government intervention is needed, i.e. support to incentivise repair, and make cycling accessible to everyone (O9). Suggested changes to the Cycle to Work scheme were proposed by some organisations. The scheme could include vouchers for repair and (O1) suggested that funding could be made available for extensive service or "overhaul" of existing bikes, enabling a more in-depth bike service that would prolong the lifetime of the bike greatly. Others (e.g., O2) suggested extending a three-year service package and extending the Cycle to Work scheme to second-hand bikes and refurbished ebikes; O2 provided the example of *Upway*, an ebike retailer specialising in professionally repaired and certified pre-owned electric bikes. Some suggested that the upper cost limit of the Cycle to Work scheme should be higher to allow access to premium brands that have greater repairability potential and overall durability. One organisation (O9) suggested that the scheme should be annual and greatly increased in both scope and costs as people have diverse cycling needs that change over time. One should, for example, be able to replace children's bikes as they grow, moving from cargo biking to family cycling as needs change.

3.1.3 Ebike Product Lifetime

All ebike retailers (O1-9) stated that ebikes are fundamentally regular bikes with additional electrical components, and basic mechanical apparatuses are all repairable or replaceable. Normal bike maintenance and mechanical aspects need to be addressed such as brake wear, lubrication, and inflating and replacing tyres by the user. Most respondents involved in bike repair indicated that technically all bikes could be repaired (whether repair was worthwhile was a different matter) and one offered that "frame failure" was the only way that a bike's lifespan ends (O4).

Of the electrical components (i.e. motor, controller, and battery) motors were viewed by the majority as being extremely reliable and where failure occurred, they were almost all repairable. Motor technology was well understood and whilst repair might be time-consuming and costly, it was possible. One difficulty identified were the cases of rear hub motors, where decoupling from the wheel was difficult (O1). The system controllers were generally perceived to be reliable, but difficult to repair on failure (O2). The lifetime of an ebike battery was proffered to be 4-5 years before a user noticed considerable depletion (O1, O3, O5). On replacement of a battery many believed that the ebike would last another 5 years minimum, bringing the average lifetime to ~10 years (O2, O6, O7) provided that the ebike was properly maintained mechanically. O3 stated that they observed ebikes >15 years old that worked well without having undergone battery replacement due to good maintenance and user behaviour. A key factor in the ebike lifetime described by all organisations, was the brand, quality of components, and operating system of the ebike. All sales/repair organisations referred to Bosch as the leading ebike system brand, although other brands held in high esteem included Bafang, Shimano, and Yamaha. O1 pointed out that the key to lifetime extension was consumer behaviour in ebike maintenance and repairability and that "the consumer drives both" when buying a durable, repairable bike. All 9 ebike retailers asserted in some manner that consumer behaviour around ebike battery maintenance (storage, charging cycles etc.) was essential to prolonging the battery lifetime. Consumer education was viewed to be key to this across the board of ebike retailers.

3.1.4 Resale, Repair, and Reuse as a Norm in the Bike Retail Sector and Expansion Into the Ebike Era

Retailers interviewed accepted regular bikes as trade-ins and refurbished, repaired, and upgraded these for resale. This was the norm at the high-end sport and premium side of the bike retail business (O2, O4). However, when it came to ebikes several factors were identified that disrupted this norm. Some organisations expressed that they did not see consumer demand for second-hand ebikes (O1), while others observed that consumers seemed to want new bikes after 4 years (O2), following the timing of the Cycle to Work scheme which renews after 4 years. Provenance was extremely important when it came to resale of ebikes. One stated that they only resold ebikes from their own rental fleet as they knew exactly how the battery was stored and maintained and had confidence reselling this stock and even went so far as to offer a warranty to consumers (O7). Another (O5) would only re-sell an ebike that they were very familiar with and sure of, i.e. they sold the bike previously, knew the owner and /or had maintained the bike over the years. Other barriers to resale were identified as replacement of batteries, compatibility with operating systems, and non-standardised charging cables and adapters where charging cables were lost. One expressed concern regarding insurance issues and certification (O9). Of the 9 retail organisations, 3 (O3, O6, O7) explicitly stated that they only repaired ebikes they sold. Many reported that they cannot repair certain brands of ebikes, with at least 3 naming a particular brand sold exclusively online (O3, O7 and O9). One even stated that they knew of other bike shops who refuse to repair these brands stating that they would “not touch them” (O3). Some respondents observed occasional sales of ebikes through general (non-bike) stores. Stores engaged in these sales do not provide aftersales services to consumers, adding an additional barrier to repair for the consumer (O1).

A major barrier identified were costs and an unwillingness amongst consumers to pay for repair. The cost benefit to the consumer was often not evident. Examples offered by organisations centred on battery replacement, with costs between €300-€600, yet consumers opted to buy new ebikes. Even when consumers were willing to pay for repair, several other barriers arose such as: sourcing staff and expertise to repair bikes (O2, O4, O6), a disparity between brands and ease of repair (O1-7), access to diagnostic equipment and software for battery management systems (O1, O2, O3, O6), access to product manuals (O1) and an unwillingness to repair batteries in house (O1).

Whilst one or two bike repair organisations stated that battery repair wasn’t possible (O1 O2) for certain brands, even for premium brands, there were others that engaged the services of battery replacement and repair specialists (O3). Two battery replacement and refurbishment organisations interviewed noted that ebike battery replacement and refurbishment had more than doubled in recent years. They had specialist access to battery management systems software and could perform most battery refurbishment operations that were required for ebikes (O16, O17).

Standardisation of parts was frequently mentioned by retail and repair organisations; a specific example mentioned by two interviewees was non-standardised tyres and subsequent cost and difficulty in replacing them (O2, O7). Many bike repair shops previously stocked a range of spare parts but found this impossible due to non-standardisation, meaning that parts were ordered on demand. This produced another barrier to repair; delayed delivery times, particularly for obscure brands where respondents experienced 6–8-week delivery delays (O3, O10). This could also be due to additional shipping and forwarding time to Ireland. One respondent (O7) observed deterioration in parts and components quality since the Covid crisis. They have less confidence in replacement components and queried the quality of recycled steel content of parts. For battery repair, refurbishment and reuse, standardisation was key, and access via bolts and screws as opposed to glues and resins facilitated circularity (O17).

Almost all bike repair and retailers were in favour of standardisation, although policing and checking of this was viewed as near impossible. However, 3 organisations (O2, O4, O10) disagreed with standardisation to a degree. One feared that standardisation may facilitate bike theft if batteries were universally interchangeable (O2). They maintained that innovation in the sector should not be impaired (O2, O4, O10). Surprisingly one of the organisations had previously provided an example of a Van Moof bike which they could not repair because specific tools were required. Nonetheless, an unauthorised vendor could not engage in repair, as at the time an authorised repair facility was not available locally. Similar access issues were observed by almost all retail and repair organisations when accessing manuals, diagnostic software, and training. Bosch was cited as an example where repair organisations invested heavily in annual training, equipment and software subscriptions to be able to provide repair services to consumers.

3.1.5 End of Life Management of Ebikes and Components

Almost all bike shops reported very little handling of end-of-life or waste ebikes. Most stated that if a consumer chose not to repair a bike, they took it away with them to use as a spare (O7). As with high-end push bikes, there tended to be a second-hand market or trade-in value, so consumers were reluctant to relinquish them for free even to social enterprises (O10).

Where ebike retailers had occasion to dispose of ebikes, many were aware of a need to handle ebike batteries appropriately, for example O9 brings ebike batteries to a civic amenity site, and O2 knew that batteries should be collected, and they brought these to an ewaste treatment facility. O11 and O12 were clear that ebike retailers need to accept both ebikes and batteries back from the public for collection, yet they know from engagement that many bike shops are unaware of this requirement. Retailers are appropriately compensated for collecting WEEE through the compliance schemes. However, in terms of financing appropriate collection and quantification of EEE and WEEE generated, both ebikes and batteries need to be reported to the producer register on manufacture or import for sale or lease. The uncertainty around ebike product lifetimes and lack of data made it hard to predict when the peak of ebike end of life products would arise and to plan accordingly for that (O11, O12, O13).

Waste management facilities and producer compliance organisations (O11, O12, O13, O14, O15) were concerned about safety and fire risk from thermal runaway associated with damaged lithium-ion batteries. One respondent stated that scooters and hoverboard batteries were riskier due to their lower position and increased likelihood of damage. O15 were not authorised to accept ewaste or batteries, yet they were concerned about ebikes – especially those with integrated batteries. Waste management facilities observed very low numbers of ebikes within waste streams. Waste management organisations involved in battery collection at end of life (O11, O12, O13, O14) highlighted the lack of lithium battery treatment in Ireland. Batteries must be assessed, packed carefully, and shipped overseas as hazardous and high-risk waste, often at huge cost per shipment. A proposed stabilisation facility was mentioned (O13), and almost all highlighted the need to keep lithium in use as long as possible to extract the maximum benefit from the material, including second life purposes such as energy storage systems (O11-14, O17) within Ireland.

3.2 Placed on Market Data Interpretation

Placed on market, or sales, data were established by subtracting exports from imports (CSO, 2024). Placed-on market data in tonnes for ebikes, speed pedelecs, and bikes are shown in Figure 1. Note that it shows that in 2020 Ireland had net export of ebikes, which could be explained by cross border sales. Combined ebike and speed pedelec sales increased from 5% of total tonnes of pedal mobility sales in 2018 to 15% in 2023. The CSO asks companies to submit data as unit sales, these data are supplementary and were found to be incomplete in the CSO data supplied to the research team.

We therefore employed proxy weights to establish a range of unit ebike placed on market figures. Ebikes have greater variance in weight ranges compared to conventional bikes. We built 3 scenarios to ascertain maximum and minimum ebike numbers placed on market. Shared scheme ebikes weighing 20 kg, ecommuter bikes weighing 25 kg and ecargo bikes weighing 48 kg (Valeski, 2019). Figure 2 shows these scenarios and potential units placed on market. For the five years where imports exceeded exports, ebikes placed on market could have ranged between 63,837 and 26,599 units between the lightest ebikes in share schemes and the heaviest ecargo bikes. Sharp increases in sales in 2021 and 2022 may be attributed to Local Authority funding for shared ebike schemes, increased ebike tourism businesses, and the addition of ebikes to the cycle to work scheme. However, it is difficult to establish trends from such a limited data set. Product code CN878116010, which represents what constitutes as an ebike under EU legislation, was first used in 2017 and therefore data were available from 2018 onwards only. What this analysis demonstrates however is that at present, placed on market data is unreliable for estimating WEEE generated especially for Category 4 large equipment in the absence of further studies and modelling.

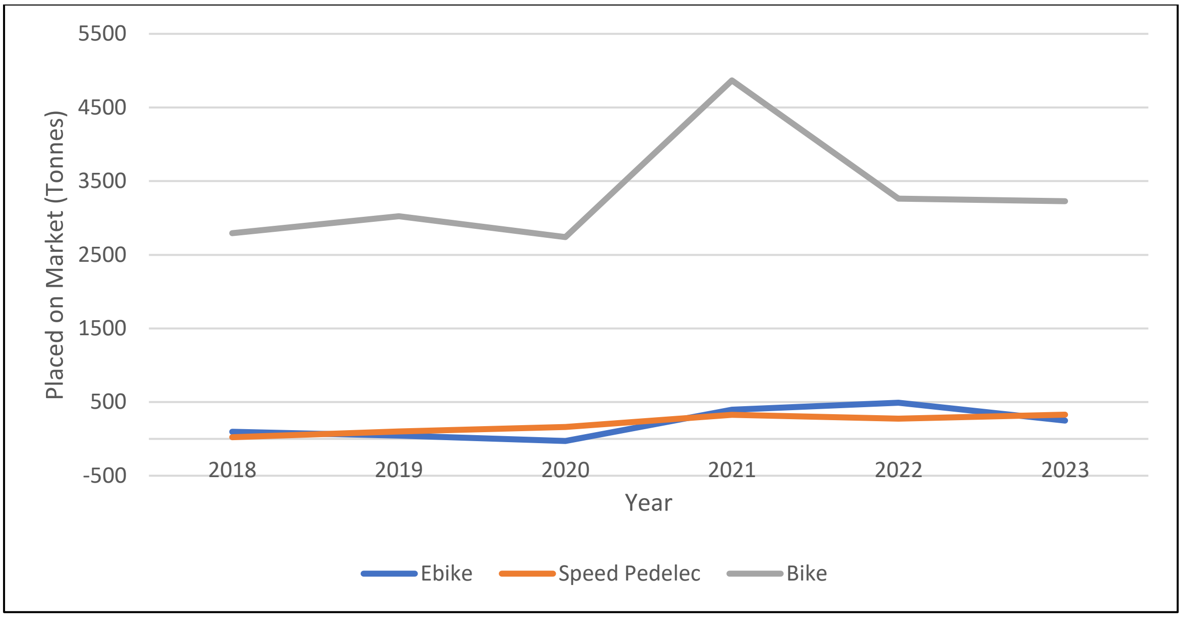

Figure 1. Ebike, Speed Pedelec, and Bike Tonnes Placed on Market Ireland 2018-2023 (CSO, 2024)

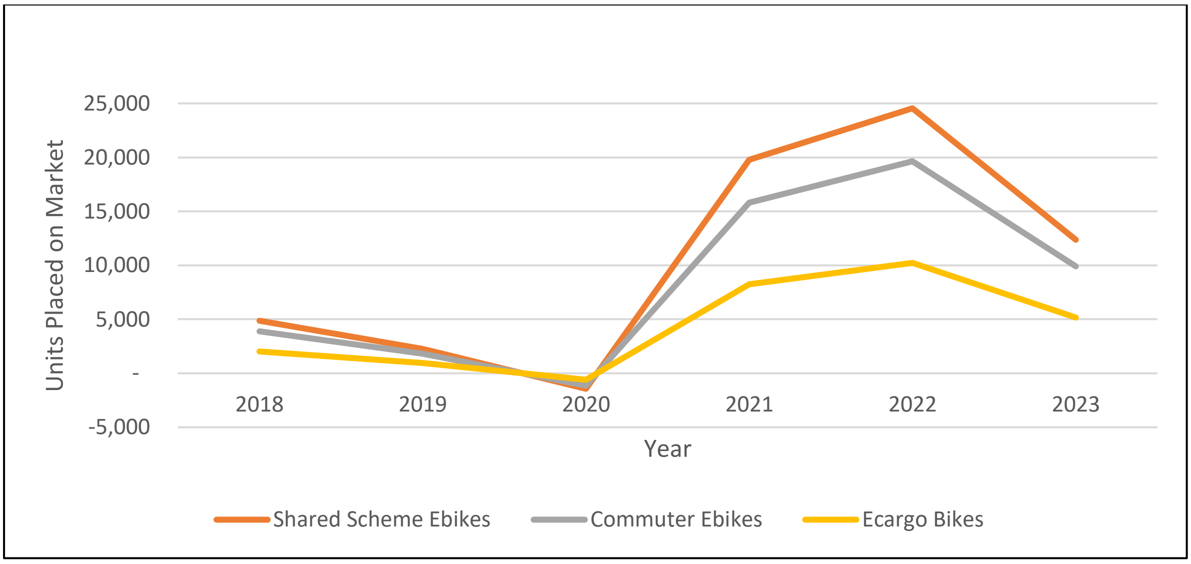

Figure 2. Units of Ebikes Placed on Market in Ireland 2018-2023 as Shared Scheme Ebikes, Commuter Ebikes and Ecargo Bikes Estimated Using Approximate Weights of Ebikes

3.3 Management of ISCycle Fleet

Table 2 summarises the ISCycle ebike study fleet. At the time of writing the ISCycle ebikes were in use for ~24 months and no battery, motor or sensor issues were recorded. The only electrical faults came from accidental wire tugs where plugs loosened. Peripheral electronics such as lights had issues with water ingress (~5) and one display controller failed due to water ingress. For the lights, it was evident that poor design contributed to this failure. The ebikes were bought from a retail and fleet management business in Ireland and many of the mechanical issues were repaired or replaced under warranty. Minor mechanical issues such as broken stands did not render a bike unusable and were fixed upon return to the University. Mechanical failures requiring immediate repair included snapped chains, punctures and spoke replacements. Wheels and tyres presented challenges. Most punctures were in the rear tyres which complicates repair, especially in ebikes with rear hub motors because in addition to the normal practice of taking a rear bike wheel off, such as getting the chain and derailleur off, the motor needs to be unplugged, and the motor also makes the wheel heavy. One of the models had a bespoke tyre and tube size which was unique to that bike. It is much more difficult to find parts for because they could only be bought from the manufacturer. In addition, this tyre was like a car tyre, it was strongly attached to the rim and took more force to remove for repair. There were several spoke breakages; although we cannot be certain of the causes most seemed to be accidental e.g. getting a wide cargo bike through a narrow gap, moving a bike with the café lock deployed and moving a folding ebike in and out of car boots. In addition to the unique tyre/tube size, many of the bikes had more unusual tyre wheel sizes, which were harder to source, and not in stock even in large bike stores. In overcoming off-specification or difficult to source parts, the ISCycle team used 3D printing (available as part of the University's Library service) to replace unsuitable attachment points for baskets and small plastic parts breakages. The ISCycle team accessed Bafang and Bosch battery management systems for the ebikes. The Bosch system was only available to mechanics completing annual training. Information from the Bosch system was viewed through the supplier of the fleet. In contrast, the Bafang diagnostic system was publicly available. Diagnostic systems provided a range of information on battery health, number of charge cycles, and exposure to temperature extremes. The lack of standard chargers and batteries meant that many batteries were bike / brand specific, and the fleet had over 5 different charging packs for batteries to manage.

Table 2. ISCycle Ebike Fleet Summary and Description of Component, Failure, Repair, and Maintenance

Bike Type Description	**Number in fleet (Total = 49)**	**Mechanical and Electrical Failure and Maintenance**
Step-through commuter ebike	20	• Punctures • Broken stands • Rear cover of taillight fell off • Broken spokes (probably café lock) • Chain wear • Rubber cover for charging port broken off • Lost suspension fork caps • Derailleur and brake adjustments
Folding ebike	11	• Snapped chain • Punctures/tube valve issues • Derailleur and brake adjustments • Broken rear spokes
Folding ebike	5	• Punctures • Chain wear • Damage to spring protecting cabling inside the main hinge • Hinge-locking mechanism • Derailleur and brake adjustments
Utility ebike	6	• Punctures • Slow leaks • Battery fuse covers lost • Derailleur and brake adjustments
eCargo: Box Bike	1	• Derailleur and brake adjustments
eCargo: Box Bike	1	• Derailleur and brake adjustments
eCargo: Trike	1	• Broken spokes • Punctures • Derailleur and brake adjustments
eCargo: Longtail	10	• Punctures • Display controller 1 LCD screen water ingress • Front lights with water ingress issues • Battery fuse covers lost • Derailleur and brake adjustments
eCargo: Longtail	1	• Snapped chain • Completely worn rear brake pads • Derailleur and brake adjustments

4 DISCUSSION

Quantitative examination of bike imports and exports confirm that Ireland is following EU trends such as the Covid boom and subsequent post pandemic decline in bike sales. The still low proportion of ebike sales in comparison to regular bike sales confirms reports from ebike retailers, that the Irish ebike market is lagging behind mainland Europe. More than half of all adult bikes sold in the Netherlands in 2018 were ebikes and in 2023 in Austria ebikes took 52% of the bike market (Ebikes International, 2024; Reid, 2019).

A detailed understanding of bike market segmentation in Ireland like those described by the Confederation of the European Bicycle Industry in Figure 3 would be useful to policy makers in transport, urban planning, education, and circular economy. The lag in sales and uptake is borne out in terms of ewaste and battery waste observed by interviewees working in these areas. Ebikes are classed as Category 4 and 4a *sports equipment, electric bikes, and juke boxes* under the WEEE Directive and are therefore not delineated in placed on market data received by the Producer Register. The impact of the scale of the emobility and ebike future waste is therefore not clear yet to policy makers. This lag experienced in Ireland provides a timely opportunity for policy makers to deploy preventative actions to drive circularity and prevent resource loss. Worrying however is the evidence from bike retailers regarding the increases in numbers of online sales and perceived volume of so-called “free riders” who have not contributed to the financing of WEEE management costs and recovery initiatives. Meeting the collection targets of 51% by 2028 and 61% by 2031 for LMT batteries when placed on market rates are unclear will be challenging (WEEE Forum, 2023).

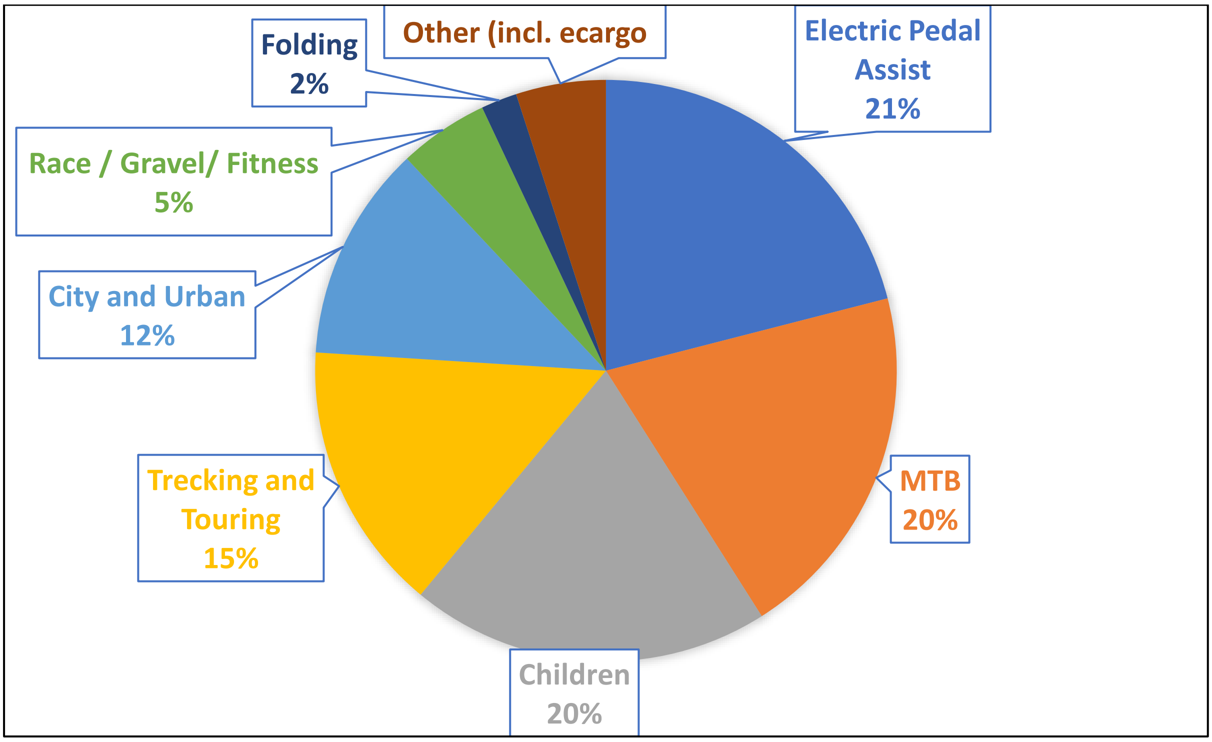

Figure 3. 2020 EU Overview of Bicycle Segments by Units (CONEBI: Confederation of the European Bicycle Industry, 2021)

This research reports concerns from retailers and waste management actors alike regarding online sales, poor quality components and turnover rates and identifies a potential rebound effect from emobility. Furthermore, the organisational research and management of the ISCycle fleet highlights components of concern, such as the design and compatibility of tyres that similarly fall outside of the scope of regulations. Therefore, measures that place more emphasis on their design, cross-compatibility, and potential for circularity are absent. The role of policy making, legislative drivers, subsidies and initiatives cannot be ignored. Ebikes fall between many legislative cracks. Their exclusion along with escooters from ESPR is unfortunate. Ebike sales are out pacing electric vehicle sales in many countries, sometimes by multiple figures (Toll, 2023).

As highlighted throughout the organisational qualitative research, bike retailer and repair organisations rarely dealt with waste bikes; reuse and recycling have long been the norm in the sector and the product lifetimes of bikes were hard to define for them. For a long time, the bike sector was inherently circular incorporating resale, refurbishment, repair and reuse. We observed evidence that bike retailers in Ireland were starting to adopt new business models, such as fleet management, mobile repairs, investing in training on ebike platforms e.g. Bosch and Shimano systems, and integrating new actors into their repair activities like battery specialists. However, not all retailers were aware that refurbishment and repair were viable options for batteries and so there is work to be done to connect various actors to fully realise a circular economy for ebikes in Ireland.

Ebike brands have also shifted their business models from primarily sales driven to service models. For example, consumers of the ebike brand “Cowboy” pay a service subscription facilitating initiatives like mobile bike mechanics to the consumers home to perform repair, set up and accessories installation (Morley, 2024). VanMoof employs a similar model through service partners who are authorised to carry out repairs and stock unique parts. VanMoof state that they are “dedicating significant resources to redesigning and enhancing parts….making them more robust and easier to fix” (VanMoof, 2024). Respondents reported that they repaired a wide variety of bikes and ebikes. They mentioned that Bosch were beginning to charge for access to training and software; in one way this creates a niche and unique selling point for retailers and repairers. These service models may work where population density can sustain them, but they might not be suitable for islands or rural areas – for example, Ireland currently has only one VanMoof Service Partner for the whole country. There needs to be a critical mass of demand, plus expertise to support the diversity and range of ebikes on the market. Whilst a company may proport to have employed circular business models, the deployment of these may be limited in practice based on regional and geographic factors.

Additive manufacturing was integrated into hypothetical sales and service circular business models for the ebike industry by Koop et al. (2021). The ISCycle team employed a degree of additive manufacturing using 3D printing available on site in the University. Our research supports additive manufacturing as essential for bike retailers and repair organisations in the future, especially for island states like Ireland. Delays in sourcing parts reported by several respondents could be overcome through additive manufacturing. Fundamentally though, the ebike needs to be of sufficient quality to be repaired, plus the necessary CAD files and data need to be available. These are key aspects that ESPR could address if it were applicable to LMT and ebikes. Safeguarding intellectual property rights and restricting access to software may come into conflict with additive manufacturing and making design manuals available. In some cases the protection of access to software is well intentioned, for example Bosch outline that for brand reputation, they do not want bikes tampered with and made illegal in terms of speed and power and therefore have tampering recognition embedded (Sutton, 2024). However, tampering recognition presented difficulties for repair as outlined by respondents in this study.

Ebikes have become increasingly sleek in design (Sutton, 2024) and in some cases appear indistinguishable from regular bikes. Education and facilitation of consumers and retailers will be key to ebike battery recovery. Computer vision and AI could play a role in recognising ebikes and batteries before processing at waste management facilities through QR codes or other markers. Whilst LMT batteries will be subject to digital product passports under the EU Batteries Regulations (European Parliament, 2022), ebike batteries typically having capacities smaller than 2 kWh will not. Also, LMT is excluded under the ESPR and LMT tyres similarly fall below regulatory thresholds. Yet, many bike brands such as Giant already use QR codes on frames to help consumers register bikes and access technical specifications. These could be expanded to provide information connecting the entire product lifetime, including repair manuals, service history and repair options. Similarly, further innovative features are continually in development, examples include ABS braking, digital safety shields to enhance cyclist visibility and integration with driver safety systems. Servitisation models like digital locks and bike location features that secure consumer investment into ebike technology and may entice people to invest in high end, durable ebikes. However, this is not an affordable or inclusive option for all, especially those outside the cycle to work scheme or economically disadvantaged.

Policy makers can play a key role in the circular economy of ebikes by 1. Facilitating a diversity of ebike users to loan or lease an ebike according to their needs and moving away from ownership models. 2. Amending the Cycle to Work scheme to include second-hand, remanufactured and refurbished bikes. Organisations offered several recommendations to improve the cycle to work scheme including repair vouchers, increasing monetary limits, making the scheme annual, and inclusion of children’s bikes. 3. Addressing the product safety, standards and eco-design aspect of ebikes placed on market to ensure that products are safe, durable, repairable and recyclable at end of life. 4. Investing in the repair sector to include certification of ebike mechanics to address insurance concerns and greater investment in localised battery lifetime extension and treatment.

5 CONCLUSION

Our work outlines the potential rebound impacts of increased ebiking in Ireland, emphasising the need for a comprehensive understanding of the ebike market and its segmentation. Despite following EU trends, Ireland's ebike market lags behind mainland Europe, presenting both challenges and opportunities for policy makers. The lag in ebike sales and uptake is reflected in observations from waste management facilities and producer compliance schemes. This again highlights the importance of preventative actions to drive circularity and prevent resource loss.

The research identifies several key areas of concern, including the impact of online sales, quality standards with respect to components, and the challenges of meeting future WEEE collection targets. The study also reveals the importance of design, cross-compatibility, and circularity in ebike compositions, which are currently lacking in regulatory measures. The role of policymaking, legislative drivers, subsidies, and initiatives is crucial in addressing these gaps.

The shift in business models from sales-driven to service-oriented approaches, as seen with brands like Cowboy and VanMoof, indicates moves towards circular business models. However, the success of these models depends on population density and regional factors, which may limit their applicability in rural areas. However, the bike sector is inherently circular with repair and refurbishment often regarded as a central and vital service provided by bike retailers.

Additive manufacturing is identified as a potential solution to overcome delays in sourcing parts, particularly for island states like Ireland. The quality of ebikes and the availability of necessary CAD files and data are critical factors for the success of this approach. The study also notes the potential conflicts between safeguarding intellectual property rights and enabling additive remanufacturing.

Education and facilitation of consumers and retailers are essential for effective ebike battery recovery. Innovative technologies such as computer vision and AI could play a role in recognizing ebikes and batteries at waste management facilities. The use of QR codes and digital product passports could enhance the traceability and management of ebike components throughout their lifecycle. While the ebike market in Ireland faces several challenges, there are significant opportunities for policy makers, retailers, and other stakeholders to lever innovative technologies and circular business models.

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DECLARATIONS

Competing interests: The authors declare no competing interests.

APPENDIX 1: STAKEHOLDER INTERVIEW GUIDE

General questions

- What is your organisation's role in the ebike/waste/resource management sector?
- What does this role/organisation entail?

Sales of Ebikes and Ebike Market forecast (where applicable)

- How have ebike sales grown over the last number of years?
- How would you forecast sales of ebikes in the coming years?

Resale, repair, refurbishment (mechanics, ebike shops)

- How long does a typical e bike last?
- What are the common reasons for failure of an ebike?
- What parts of an ebike can be repaired?
- How does repair impact the lifespan of an ebike?
- What are drivers of repair of ebikes?
- Is it costly for certain repairs?
- Are consumers likely to repair or replace an ebike?
- Why do they opt for either repair or replacement?
- What parts of an ebike are currently unrepairable once a failure has occurred?
- What are the barriers preventing the repair of these outlined components?
- How can repairability of an ebike be improved?
- What happens to an ebike that cannot be repaired?

Questions relating to refurbishment and resale of ebikes

- Does your outlet undertake refurbishment and resale of used ebikes?
- Are e bikes easily refurbished?
- How do you assess if an ebike is suitable for refurbishment?
- What are the barriers to refurbishment?
- What are the drivers to refurbishment?

Questions for stakeholder in the waste and resource management sector

- How have ebikes in the waste stream grown over the last number of years?
- How would you forecast waste generation of ebikes in the coming years?
- How are ebikes currently treated at the end of their user phase?
- Can you outline the steps involved in recycling an ebike?
- What are the problems associated with recycling an ebike?
- What percentage of ebike material do you aim to recycle?
- What strategies do you employ to meet this aim in material recovery?
- Is your overall end of life treatment sustainable?
- Are there other more efficient end of life treatment options available for ebikes?
- Have you recycled ebikes that were functional?
- What barriers to optimal recycling of ebike components exist if any and how can they be removed/mitigated in the sector?
- What drives ebike recycling?

Questions for stakeholders in battery sector

- Have you seen an increase in battery refurbishment and/or repair in the last number of years?
- Do you expect to be undertaking a greater number of ebike battery refurbishment/repair in the future?
- Can you elaborate on the approach to ebike or e bike component refurbishment you undertake?
- Can all e bike batteries/ be refurbished or repaired?
- What are the barriers to refurbishing certain ebike batteries?
- What are the drivers of ebike refurbishment?

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