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RESEARCH AND ANALYSIS

Estimating stocks and flows of electric passenger vehicle batteries in the Norwegian fleet from 2011 to 2030

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Abstract

Retired passenger battery electric vehicles (BEVs) are expected to generate significant volumes of lithium-ion batteries (LIBs), opening business opportunities for second life and recycling. In order to evaluate these, robust estimates of the future quantity and composition of LIBs are imperative. Here, we analyzed BEV fate in the Norwegian passenger vehicle fleet and estimated the corresponding battery capacity in retired vehicles from 2011 to 2030, using a stock-flow vehicle cohort model linked to analysis of the battery types and sizes contained in different BEVs. Results based on this combination of modeled and highly disaggregated technical data show that (i) the LIB energy capacity available for second use or recycling from end-of-life vehicles is expected to reach 0.6 GWh in 2025 and 2.1 GWh in 2030 (not accounting for any losses); (ii) most LIBs are currently contained within the weight segment 1500–1599 kg followed by 2000+ kg; (iii) highest sales currently exist for BEVs containing lithium nickel manganese cobalt oxide (NMC) batteries; and (iv) lithium nickel cobalt aluminum oxide batteries initially constitute the largest overall capacity in retired vehicles, but will later be surpassed by NMCs. The results demonstrate rapidly growing opportunities for businesses to make use of retired batteries and a necessity to adapt to changing battery types and sizes.

KEYWORDS
batteries, dynamic modeling, electric vehicles, industrial ecology, recycling, reuse

1 | INTRODUCTION

Users need vehicles that can solve transport tasks efficiently, reliably, and comfortably. To address this, a vehicle and transport culture has been developed based on internal combustion engines (ICEs) that largely relies on fossil fuels. As part of the current shift to a greener society, zero exhaust emission vehicles, hereafter referred to as zero emission vehicles, are now replacing those powered by ICE to reduce local air pollution and greenhouse gas emissions.

Norway is a leading nation in the drive to zero emission transport with ambitious targets set in the Norwegian National Transport Plan (NTP), including that all new passenger vehicles should be zero emission by 2025 (Norwegian Ministry of Transport, 2017). Battery electric technology is currently the most mature zero emission technology in use, relying primarily on lithium-ion batteries (LIBs). Between 2011 and 2019, Norwegian passenger battery electric vehicle (BEV) sales rose from approximately 2000 to 60,345, with BEVs representing about 42% of the passenger vehicle market in 2019 (OFV, 2019). This represents one of the highest market shares worldwide (IRENA, 2017). Consequently, Norway is expected to be one of the first countries with a significant number of retired batteries (Casals et al., 2017), giving rise to major opportunities that include recycling with material recovery (Velazquez-Martinez et al., 2019) or second use as stationary energy storage applications (Ahmadi et al., 2017; Cusenza et al., 2019).

Recycling and second use of BEV batteries is already ongoing, albeit with a relatively low number of end-of-life BEV inflows. Information from "Batteriretur," a Norwegian company responsible for collection and treatment of used batteries, reveals that Norwegian BEV LIBs are generally collected and dismantled to module level in Norway before export to the European Union (EU) for recycling (Svendsen, T. H., personal communication, September 14, 2020). The recycling process is mainly focused on thermal pretreatment before crushing, or batteries may be refurbished/repaired and re-used in vehicles or for other second uses. However, this is dependent on levels of degradation and other faults. Since end-of-life volumes of BEV LIB are currently small, most batteries currently collected derive from accidents and take-back campaigns, but volumes are expected to increase rapidly in the next decade as the market share increases, sales rise, and vehicles retire (Hao et al., 2015; Palencia et al., 2012; Richa et al., 2014; Sato & Nakata, 2020). Quantitative information about the expected future development of retired batteries and an understanding of their drivers is needed to grasp these opportunities, for example, for planning investments in recycling or reuse infrastructures.

Dynamic stock modeling, including material flow analysis, has been used to assess the development of future electric vehicle fleets and forecast end-of-life vehicle and battery flows (Hao et al., 2015; Palencia et al., 2012; Richa et al., 2014; Sato & Nakata, 2020). These models can be based on cohorts where each cohort is assigned an expected lifetime and the cohort's use phase ends when its lifetime elapses. Using sales scenarios and a discrete lifetime distribution for batteries, Bobba et al. (2019) estimated that a total of around 450,000 battery units will leave the European fleet in 2030, and that under two scenarios with low and high second use the actual battery capacity available for second use will be 1.99 and 8.75 GWh (70,400 and 311,500 units), respectively. Other studies based on sales scenarios combined with typical vehicle exit curves or average battery lifetimes, respectively, conclude more conservatively that a total of 125,000 electric vehicles (EV) and the batteries they contain will be scrapped in 2030 in Europe (Element Energy, 2019), or less conservatively that a total of 1.2 million EV batteries (47 GWh) will reach end-of-life in Europe in 2030 (Drabik & Rizos, 2018). Of the former, the authors expect that 15% of battery units may be sent to recycling due to deterioration, and 2.25 GWh (representing 105,000 batteries) may be available for second life. At the combined Nordic level, Dahllöf et al. (2019) estimated from historical vehicle sales and battery lifetime data that around 50,000 and 20,000 battery units would be available together in 2030 for second life and recycling, respectively, but this only accounts for batteries already placed on the Nordic market in 2018. The wide variation in results reflect variation in scope, system boundaries, and inherent uncertainties.

Even though reuse and recycling opportunities are likely to arise first in Norway, no studies to the authors' knowledge have yet fully quantified the Norwegian battery volumes arising to 2030. In addition, no studies estimating battery capacity in retired vehicles in Europe could be found that are fully based on the historical differentiation of vehicles arriving into the market and the individual technical battery characteristics linked to each vehicle make/model and sales year. Here, in addition to providing new analysis of the state of the art of battery use in Norway, we estimate the quantity of LIBs entering and leaving the Norwegian passenger vehicle fleet annually until 2030. The target is to investigate short- to medium-term potentials for recycling opportunities for Norwegian industries, so a dynamic stock model is consequently used to build realistic scenarios for the battery capacity becoming available for recycling in future years. The strength of our approach is the combination of modeled data with a large amount of real, technical data at a vehicle model level, based on individual battery characteristics of each BEV sold in Norway. The result is a battery capacity stock and flow model specific to Norway, although the approach could further be applied to other regions to explore their own potential for recycling.

2 | METHODOLOGY

Results of a vehicle stocks and flows cohort model based on the Norwegian market were linked together with supplementary battery analysis based on BEV historical data and anticipated battery development. An overview of the model and analysis linkage is shown in Figure 1.

2.1 | Application of the stocks and flows cohort model

Passenger BEV stocks and flows were projected to 2030 using a previously developed cohort model that accounts for all initial BEV stocks introduced since 1981 when the first registered electric vehicle sales in Norway occurred (L. Fridstrøm, 2019; L. Fridstrøm et al., 2016). The model splits the fleet by vehicle age and projects new vehicle sales (vehicle age < 1 year) and stock change of older BEV stocks (vehicle age > 1 year) in the Norwegian fleet by year of first registration and weight segment until 2030. Segments defined for the model include 0–999, 1000–1199, 1200–1299, 1300–1399, 1400–1499, 1500–1599, 1600–1799, 1800–1999 and >2000 kg. These segments relate to the vehicle curb weights, the vehicle

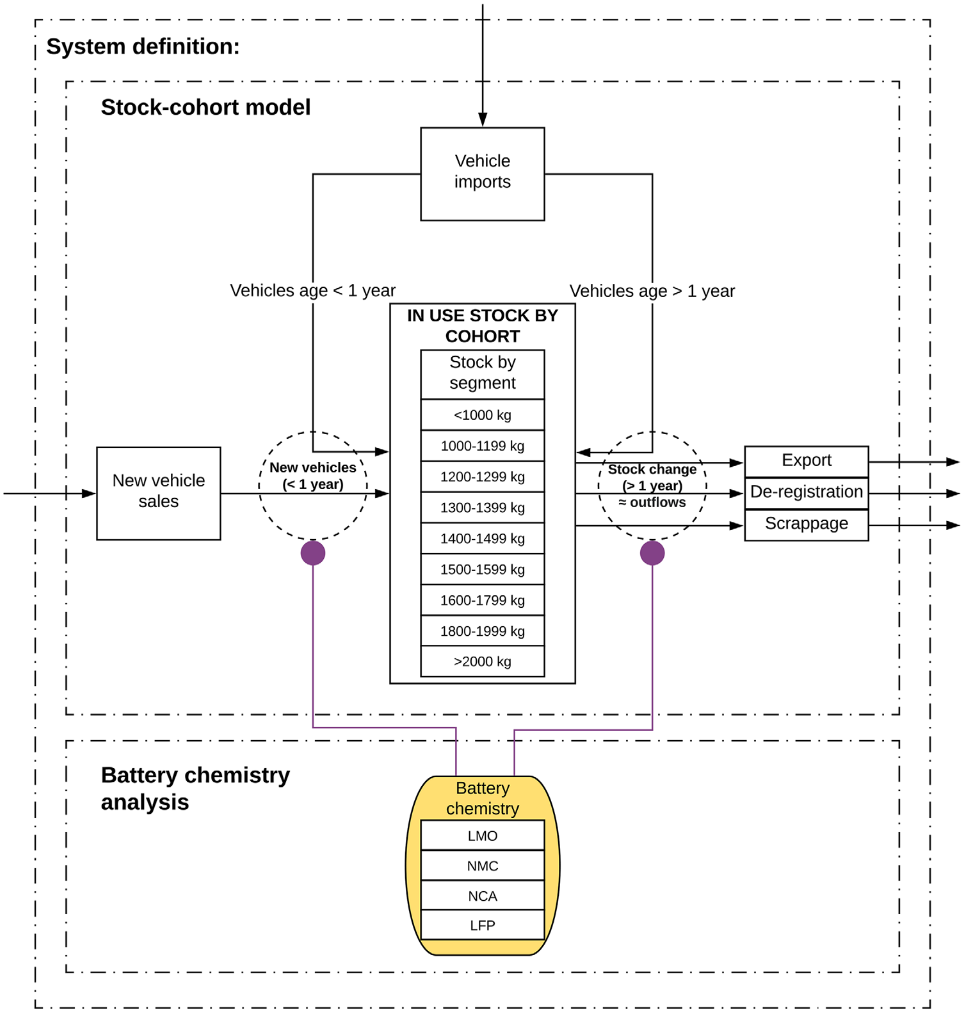

FIGURE 1 System definition of the vehicle fleet model and its link to the battery chemistry analysis. New vehicles (age < 1 year) entering use, in-use stock, and the stock change of vehicles older than one year (age > 1 year) that is assumed to approximate the outflow from the stock. The arrows represent flows, while the dots illustrate parameters that were retro-actively applied to the model results
Note: Although the weight segment <1000 kg is included in the vehicle model, this category was excluded from the LIBs analysis since it was assumed that vehicles in this category are registered as four-wheel motorcycles and not passenger vehicles

weight with all equipment, and also include a 75 kg driver. The model estimates in-use stocks as a balance of new vehicle sales and net stock change values over time.

New vehicle sales per year and weight segment are defined in the model as the number of vehicles sold with age < 1 year ($I_{t<1}$), which includes both vehicles sold first in Norway and "nearly new" vehicles first registered elsewhere before being imported secondhand to Norway and re-registered the same year. To estimate annual new vehicle sales, the model accounts for market uptake of electric vehicles using the assumptions in the National Budget 2019 (Royal Ministry of Finance, 2019). Based on this, Fridstrøm (2019) constructed a long-term scenario which was used for the calculations here; in this scenario BEV sales reach 70 % in 2025 and 74.3 % in 2030, meaning that fleet BEVs equate to approximately 800,000 and 1,354,000 in 2025 and 2030, respectively. This is a slower market uptake of electric vehicles than is suggested by Norwegian National targets, but a conservative outlook is favored for this study. The model was also calibrated around historical sales data with a vehicle model-by-model level of disaggregation.

The net stock change of older BEV stocks follow from transition rates calculated on empirical stock data taken from the national motor vehicle register for the years 2012 to 2017, and are defined per year and weight segment as the sum of the number of vehicles imported and registered in Norway with age > 1 year ($I_{t>1}$), minus those exported, deregistered and scrapped (O). Deregistered BEVs are considered negligible. New vehicle sales are thus excluded from this sum and a negative value equates to a decrease in vehicle numbers. Only net flows are calculated by the model, but it is assumed that among younger vehicles, secondhand import is the dominant gross flow, while among older BEVs, scrapping would dwarf all other gross flows.

In essence, survival rates are calculated by observing the change in the stock of a given cohort of vehicles from one year to the next. There is currently limited data available to calculate the survival rates of passenger BEVs older than 6–8 years, but since there is rapid technological development that means that models soon become outdated, BEV survival rates for each weight segment were set in the model similar but somewhat lower to those of correspondingly sized petrol-driven vehicles. The limited evidence so far suggests that BEV batteries last the life of the vehicles, which is consequently assumed here. Survival curves for different BEV weight segments used in the model, as well as a discussion of assumptions, are shown in Supporting Information S1. Knowing the survival rate of each vehicle segment to the next year, and accounting for secondhand sales of imports, allowed us to estimate annual fleet stock changes for all vehicles older than 1 year. In this way, estimates were made of the change in the number of vehicles from different first registration years and for different weight segments.

Equation (1) shows the relationship between the defined annual stock change of these vehicles $dS_{t>1}$ and the outflows O which aggregates exports, deregistration, and scrappage. This suggests that for small numbers of vehicle imports older than 1 year (which we assume here), the stock change can be set equal to the outflows. Total stock change for the whole fleet (dS_{total}) can be thereafter calculated by summing up the inflow of vehicle sales and imports of vehicles less than 1 year old ($I_{t<1}$) with the stock change of older vehicles (Equation 2). dS_{total} was not needed for this study, so Equation (2) serves only to demonstrate the difference between dS_{total} and $dS_{t>1}$. Finally, Equation (3) shows how the vehicle outflows are calculated using a survival function $sf(s)_{t,c}$ specific for each vehicle segment s, which is applied to the stock S. This function determines the share of vehicles of a given cohort that remain in the fleet at any given time.

$$d\,S_{t>1} = I_{t>1} - O, \tag{1}$$

$$d\,S_{\text{total}} = I_{t<1} + dS_{t>1}, \tag{2}$$

$$O = sf(s)_{t,c} \cdot S_{t,c}. \tag{3}$$

The stocks and flows cohort model itself does not make any assumptions about battery characteristics of the vehicles, but this analysis relating to battery quantities was retro-actively performed using the output (see Sections 2.2 and 2.3). Although the weight segment <1000 kg is included in the model as standard, this category was excluded from subsequent analysis since it was assumed that these vehicles in this category are registered as four-wheel motorcycles and not passenger vehicles. Note that "age" in the model is defined as the number of years completed by December 31 from initial registration, rounded upward to the nearest integer. For example, vehicles aged "3 years" in 2021 are those first registered in 2019. Although the model includes electric vehicles produced from the year 1981, significant LIB BEV annual sales did not occur until after 2010/2011.

2.2 | Assessment of electric vehicle battery characteristics

Analysis to estimate LIB capacity from the cohort model results was performed based on historical and statistical data of Norwegian vehicle sales (at a vehicle model level), their associated battery characteristics and expected future battery development.

Historical data on all electric vehicle make/model characteristics (including nominal battery capacity, kWh) that have been available on the market was first obtained from the Electric Vehicle Database (EV Database, 2019). This was supplemented with information about the battery type for each vehicle make/model sourced from Kelleher Environmental (2019), Wagner et al. (2019) and other open sources. Battery types in use in passenger BEVs include lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), and combinations thereof. Lithium iron phosphate (LFP) has also been used for the <1000 kg segment. In this analysis only overarching battery material types are considered (i.e., NMC is not categorized according to NMC111, NMC622 or NMC811, etc.), due to a lack of reliable and consistent data. Where no data about battery chemistries was available, vehicle battery types were set to "unknown Li-ion type."

Historical sales data of Norwegian passenger BEVs between the years 2011 to 2018 was obtained from Opplysningsrådet for Veitrafikken AS (OFV, 2019). Vehicles <1000 kg were excluded as before. It was also assumed that electric vehicles sold prior to 2011 when the modern BEV was launched were either not of LIB type, or were registered as four-wheel motorcycles, and were excluded. The sales data was thereafter combined with the background data of battery type and size for different vehicle makes/models to assign a battery capacity and type to each vehicle sold. Examples of data for the five most popular passenger BEV models, reflecting around 70% of all vehicles sold in Norway between 2011 and 2018, are shown in Table S2 in Supporting Information S1. The combined historical sales and background battery data was used to estimate the amount of type of batteries introduced into the Norwegian passenger vehicle fleet between 2011 and 2018.

In preparation for combination with the stocks-flows cohort model results, the sales of passenger BEVs and associated battery characteristics were grouped into the same weight segments as for the cohort model by using associated vehicle curb weights in the EV database (and accounting for a 75 kg driver). The data was also transformed to calculate the sales weighted average battery capacity and type for Norwegian passenger BEVs purchased in each weight segment and for each vehicle sale year. Where several battery types were used for vehicles sold within one weight segment (and for one vehicle sale year), a weighting factor was determined to estimate the distribution of vehicles actually sold according to battery type. Any gaps in weight segments/years were filled with data from an adjacent weight segment, and data for the year 2019 was assumed the same as 2018.

The estimated battery characteristics were extended to 2030. Although the Electric Vehicle Database also contains the available information about known models arriving to the market in future years (to 2022), few models beyond 2021 have been announced and there is thus little concrete information available about the growth in battery capacity to 2030. Within each segment there is a band of battery capacities; we therefore assumed for this analysis that the maximum capacity in each segment will continue to increase and that the sales weighted average battery capacity will converge toward the upper end of these bands in all segments by 2030, with the phasing out of older vehicle models and the demand for long-range driving. We also assume that large and luxury vehicles will develop an even larger battery capacity, in the region of 90–120 kWh. Resulting assumptions of battery capacity growth used in the analysis here to 2022—and beyond to 2030—are shown in Table S1 in Supporting Information S1, with linear approximation used to extend current capacity values from today. Due to a lack of reliable data on the battery types of future models, battery types for years 2020–2030 were set to unknown Li-ion.

2.3 | Estimation of new batteries and stock change annually until 2030

The number and capacity of batteries of different types entering the electric passenger vehicle fleet, as well as the stock change, were estimated for years 2011–2030 by combining results from the stock-flow cohort model with the assumptions of battery type and size for each weight segment and cohort year in the battery analysis. Uncertainties in the final results stem mainly from (1) model uncertainties in the estimated stocks and flows of vehicle numbers toward 2030, and (2) uncertainties in the assumptions of the battery capacity of vehicle models toward 2030.

Model uncertainties (1) originate from the fact that only one scenario of BEV penetration was investigated, and that the modeled stock change of vehicles older than 1 year (i.e., excluding new vehicle sales) was assumed to equate to scrappage. In reality the stock change of these vehicles is also affected by imports and exports, as well as other contributions from deregistration, but these individual flows are not estimated by the model. To establish how the import/export flows may affect total vehicle outflows estimated by the stocks-flows model, these flows were investigated further using data from the year as an example (SSB, 2020a).

Uncertainties in battery capacity development (2) also affect results, reflecting underlying complex dynamics beyond the scope of this study. For example, as technology advances and batteries become more efficient, several trends can unfold. First, the efficiency gains can be used to further increase battery capacity and driving range. However, this may be limited in the medium, compact, and smaller vehicles compared to larger vehicles due to costs (potentially exacerbated by constraints in raw material and battery supply) and improvements in charging infrastructure. Second, efficiency gains can be used to reduce the battery size. This option would reduce battery and vehicle weight and consequently also increase the range while keeping costs low, but could lead to the stagnation of the maximum battery capacity.

3 | RESULTS AND DISCUSSION

3.1 | Application of the stocks and flows cohort model

The total Norwegian fleet of passenger BEVs to 2030 based on the Norwegian National budget, estimated by the stocks and flows cohort model, is shown in Figure 2. Up to and including 2018, actual data on the number of vehicles of different technologies that have been registered each year has been used, based on data from the national vehicle register.

Annual results from the model of total new passenger BEV sales, and stock change of older vehicles (age > 1 year), are shown in Figure 3. According to the model, new BEV sales in 2018 summed for all weight segments >1000 kg (Figure 3a) amounted to around 57,000, rising to 116,000 in 2025 and 163,000 in 2030. Figures related to a single cohort should be interpreted with caution, since survival rates for vehicles older than 3–4 years rely on a relatively small number of cases.

Model estimates for new BEV sales for the years 2011 to 2018 were compared to historical passenger BEV sales data. Modeled new vehicles are approximately 10–25% higher than new vehicle sales registered by OFV, but when the number of new registrations from secondhand imports registered by OFV is also considered (as also implemented in the cohort model), than the difference is <4%. See Table S3 in Supporting Information S1 for more details. Many of these latter vehicles have already been registered abroad once before during the same year and have been imported secondhand due to the high demand for some popular models in Norway that have not been available in sufficient volumes. The fact that BEVs are

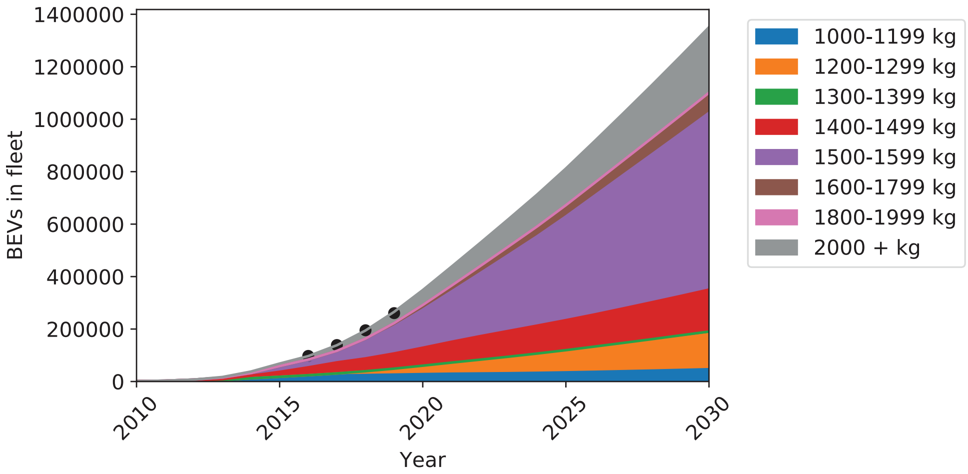

FIGURE 2 The estimated number of electric passenger vehicles in the Norwegian fleet until 2030, broken down by weight segment. Historical data, as of December 31 for each year, is shown by black circles for comparison (SSB, 2020b). Data underlying this figure are available in Supporting Information S2

subsidized in many countries, but not directly in Norway, gives rise to business opportunities particularly within secondhand import. In some cases, vehicles have been registered in an EU country for just a day to be counted toward the EU CO_2 requirement before being exported to Norway. This translates to a double benefit for Norwegian BEV owners, who take advantage of both the purchase subsidies in the EU and the exemption from taxes and other incentives of the like when registering the vehicle in Norway.

When considering the model output for outflows from the Norwegian passenger BEV fleet for weight segments >1000 kg (Figure 3b), the model estimates around (–) 1200 vehicles in 2018, rising to (–) 17,000 in 2025 and (–) 51,000 in 2030. The numbers here represent the stock change per year of passenger BEVs older than 1 year, that is, the net stock change of the older vehicles that were already in the fleet each year, excluding new vehicle sales that year. Since we assume here that imports of older vehicles are negligible, this equates to fleet outflows due to scrappage, deregistration or export. The numbers also directly equate to the number of battery packs in these vehicles (i.e., one per vehicle).

For this article, the assumption is that vehicles in the outflows are mostly scrapped in Norway rather than exported. Historically this has been the case due to the high taxes on passenger vehicles compared to other countries, which make old used vehicles more valuable in Norway than in other countries. Since BEVs do not have purchase taxes in Norway, they could potentially be exported to other countries. However, the user demand for BEVs has been much higher in Norway than elsewhere, which makes it reasonable to assume these flows to be negligible. For battery electric trucks and buses the situation may be different. For verification, comparisons were made of the total net vehicle stock change estimated by the model for all vehicle types and ages with historical scrappage data from years 2010 to 2018 (SSB, 2019). Results, shown in Figure 3c, are comparable. Whilst inferring that other flows contributing to the stock change for these older vehicles are small in comparison to scrappage, the data reflects the situation for the entire vehicle fleet and not specifically for BEVs. This is since scrappage data specifically of passenger BEVs in Norway is not publicly available for detailed comparisons.

3.2 | Effects of imports and exports on estimated outflows

It was assumed for this work that imports of older vehicles than 1 year, and exports of all ages, are negligible, which makes the stock change (vehicle age > 1 year) equate to outflows (cf. Equation 1). These assumptions are investigated here in more detail. Figure 4 shows estimated outflows from the stocks and flows cohort model broken down by vehicle age. For 2015 and 2020 a significant fraction of the outflow is constituted by vehicles younger than 7 years. This is expected, since the majority of EVs have not yet reached end-of-life and therefore the main cause of outflows are accidents, callbacks, or malfunctions of any nature. For 2025 and 2030 these outflows make up for a smaller share and the main outflow of BEVs is around 10 years old. Although these vehicles are still short of their full lifetime, the reason for this trend lies in the relative differences in cohort abundance: BEVs aged 10 years are still the most scrapped in 2030 because they are more numerous than older vehicles. Correspondingly, even if their scrappage rate is low, the absolute number of those scrapped is higher than for older vehicles. Differences in the spread of vehicle ages can also be seen in the figures. In 2015 many older vehicles (dating back to 1981) were phased out due to the rapid market development. Between 2020 and 2030, the spread of vehicle outflow age is anticipated to widen as time increases from 2011 when the rapid BEV introduction began, and the vehicles are able to progress along their survival curves.

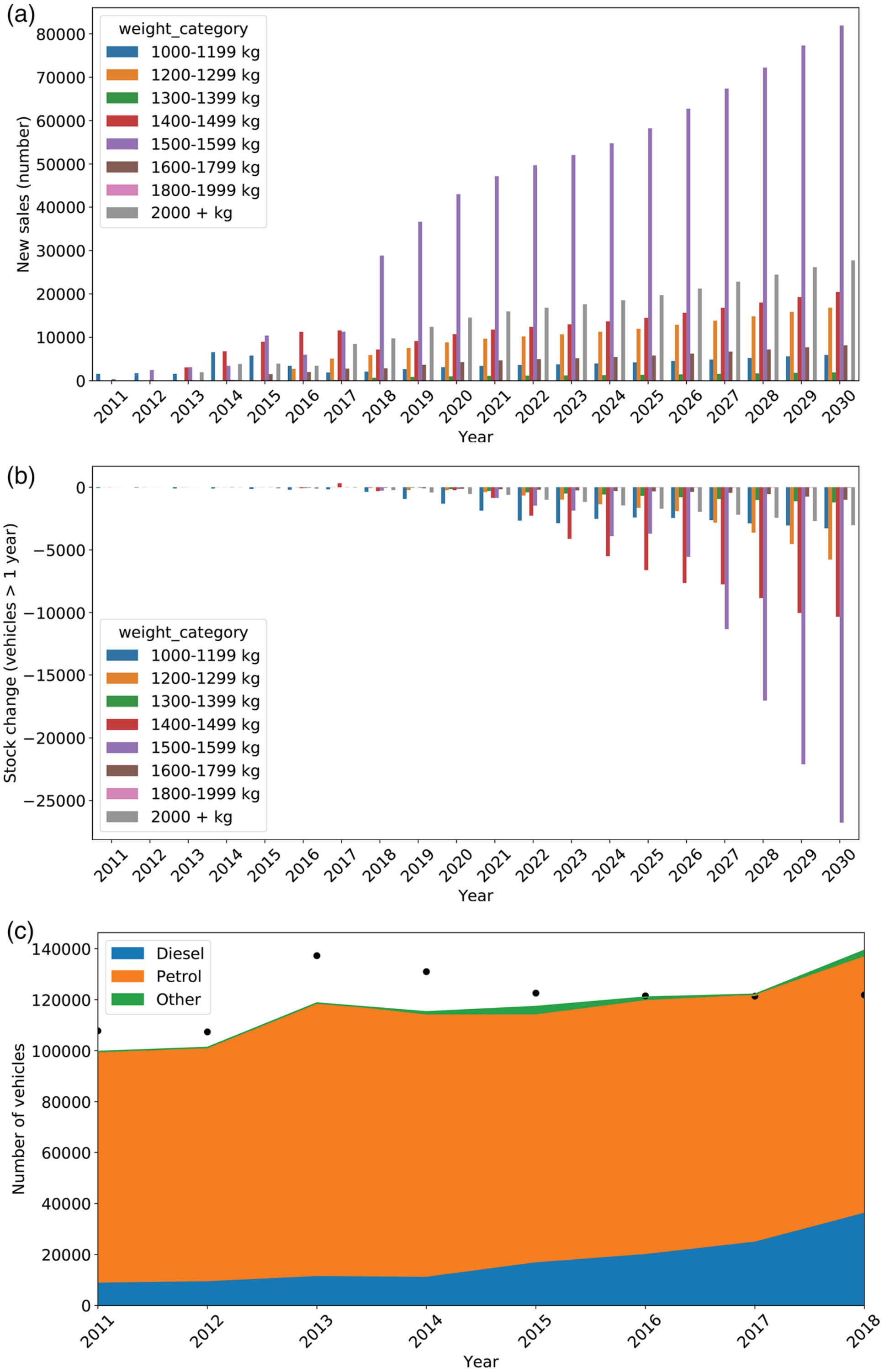

FIGURE 3 The estimated number of (a) total new electric passenger vehicle sales, and (b) stock change from the Norwegian electric passenger vehicle fleet (for vehicles older than 1 year), annually until 2030. (c) The modeled net vehicle stock change data for vehicles older than 1 year of all vehicles in the Norwegian passenger vehicle fleet, compared with actual fleet scrappage numbers for years 2010–2018 (black, open circles). Data underlying this figure are available in Supporting Information S2

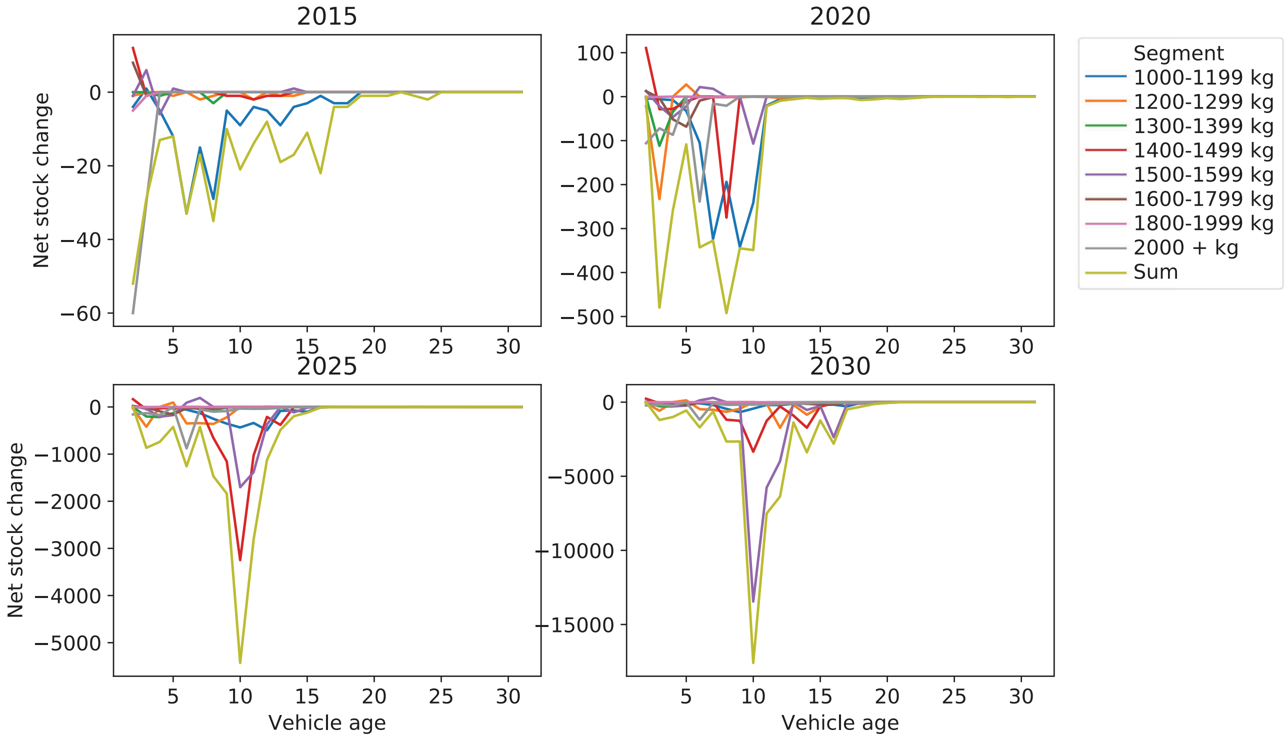

FIGURE 4 Net stock change (number) of vehicles older than 1 year, by vehicle age. Vehicle age is age at year end, rounded upward to nearest integer. Years 2015, 2020, 2025, and 2030 are selected and shown for comparison. Note that the curves oscillate widely between years since they are calibrated in part on historical data (thus large trends only should be focused upon). Data underlying this figure are available in Supporting Information S2

The majority of imported/exported vehicles can be assumed to be relatively young, for example, less than 5 years old, and hence they are unlikely to significantly affect the main outflows shown in Figure 3b. However, to establish how import/export flows may affect total vehicle outflows, these flows were investigated further using the year 2018 as an example. For this year, total recorded imports of new and used vehicles to Norway equaled 50,840 and 11,913, respectively, whilst exports of new and used vehicles from Norway were much lower at 10 and 46, respectively (SSB, 2020a). This imbalance is not unexpected and is due to the subsidies paid out in many countries that make it profitable to import BEVs into Norway coupled with high demand in Norway compared to other countries.

Since export flows of BEVs are almost negligible and imports dominate, the calculations for BEV scrappage, and associated estimates of the batteries they contain, may be underestimated. However, most imported vehicles to Norway are likely to be nearly new (age $<$ 1 year) and were therefore accounted together with new BEV sales in the model. Recorded data shows that for the year 2018, there were 11,899 first time registrations of imported vehicles in Norway (OFV, 2020). Although these do not necessarily derive from the total pool of 11,913 used vehicles imported during 2018 (vehicles can also derive from previous year imports), the difference is small. Since vehicles of age $>$ 1 year are directly counted along with new sales in the stocks-flow cohort model as "new vehicles," it is unlikely that used imports have a large impact on the estimates of vehicle scrappage in this study.

3.3 | Assessment of electric vehicle battery characteristics

Data of the development in battery capacity for all vehicles available on the market, including BEVs known to be arriving on the market in the next years, is shown in Figure 5. Both the average and maximum battery capacity of BEVs available on the market per year has in general shown an upward growth trend since BEV introduction, although the growth can in most cases be described as stepwise. Little is known about models arriving on the market after 2021, aside from several examples in the 1400–1499 kg and >2000 kg segments. For the latter, the large increase in maximum capacity relates to the announcement of the new Tesla Roadster, anticipated in 2022, with 200 kWh battery capacity per vehicle. However, this is unlikely to be representative of the whole segment.

Estimates of the types of batteries entering the fleet based on historical sales data combined directly with known battery characteristics for these vehicle models are shown in Figure 6. According to these results, NMC and NCA are battery types currently used in greatest amounts, with around 0.9 and 0.7 GWh entering the fleet in new passenger BEV sales in 2018, respectively (Figure 6a). There is also a division of battery types by

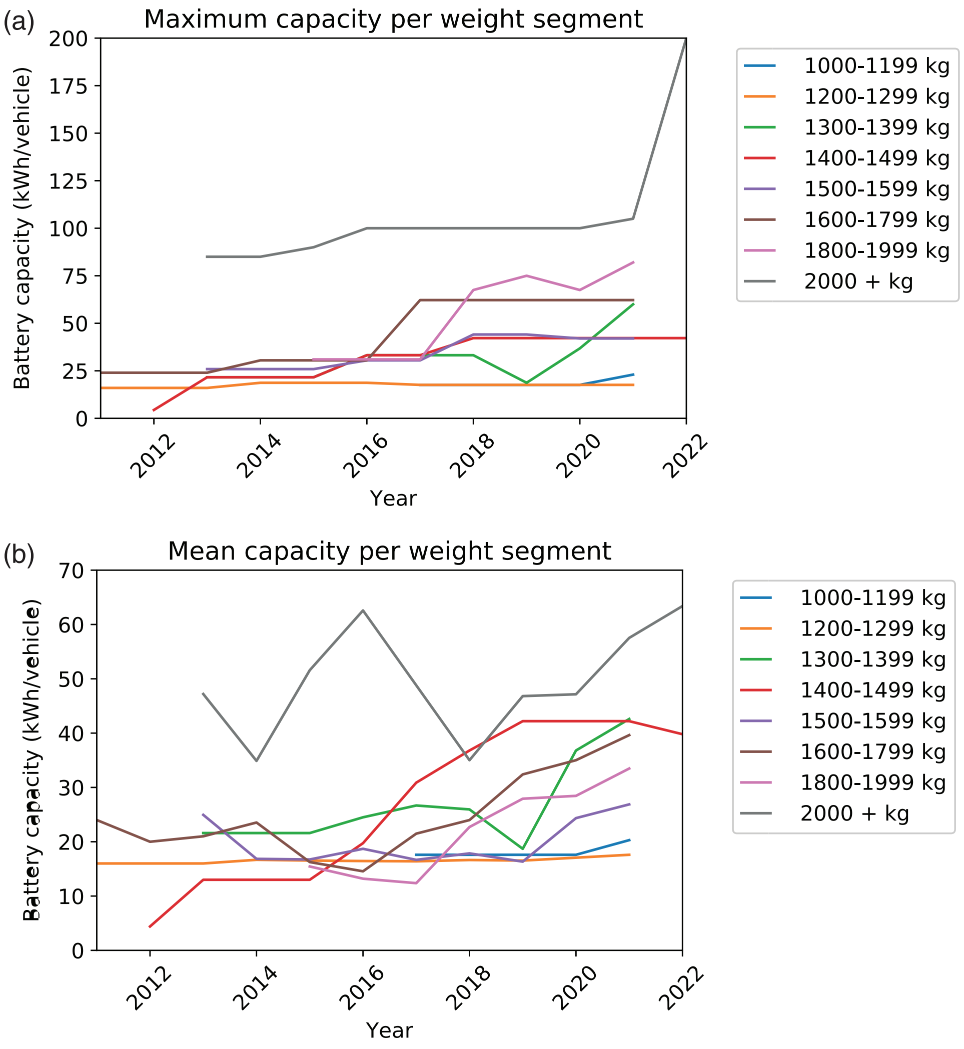

FIGURE 5 Change in (a) maximum and (b) average (mean) battery capacity per BEV with time, when assessing data from all vehicle makes/models/variants known to be available on the market between 2011 and 2022. Data derives from EV Database (2019). Data underlying this figure are available in Supporting Information S2

weight segment evident, with NCA in use for heavier weight segments and NMC in use for lighter weight segments. Although a small amount of LFP has been used in vehicles <1000 kg, these vehicles are excluded here since they are assumed to be registered as four-wheeled motorcycles.

The stark increase in available battery capacity can open possibilities for the vehicle fleet to participate in the ancillary services market for the grid through technologies such as vehicle-to-grid or reuse of batteries in stationary applications. In terms of the number of battery packs (Figure 6b), around 25,000 NCA battery packs were introduced into the Norwegian fleet in 2018 alone. Between 2011 and 2018 combined, over 50,000 battery packs were introduced in the 1500–1599 kg segment, and around 30,000 in the >2000 kg segment. These mostly correspond to sales of Nissan Leaf that contains NMC batteries and lies in the 1500–1599 kg segment, and Tesla models X and S that contain NCA batteries and lie in the >2000 kg segment. Together, these vehicles have accounted for around 41% of market sales between 2011 and 2018. The average energy density of battery packs in new vehicle sales has increased between 2011 and 2018 for all battery chemistries (Figure 6c), with the largest battery capacities evident in the largest vehicle segments. The growth in battery capacity entering the fleet can therefore be explained by growth in the number of battery packs entering the fleet coupled with an increase in battery size. As technology improves it can be expected that lighter batteries will be able to deliver the same energy capacity, resulting in a positive rebound effect in which fewer materials are required to provide the same service. The range of modern BEVs is already approaching that of ICE vehicles, suggesting that further developments will soon focus on reducing battery sizes and therewith EV prices.

There is large uncertainty regarding future battery chemistries, but an overall trend to move away from cobalt seems to be dominant throughout the industry as can be seen by efforts to move from NMC111 to NMC811 (Alves Dias et al., 2018; Azevedo et al., 2018). Tesla, the main NCA battery user, has also expressed commitment to reducing cobalt use through increased use of nickel and, as has been seen in the Chinese market, moving

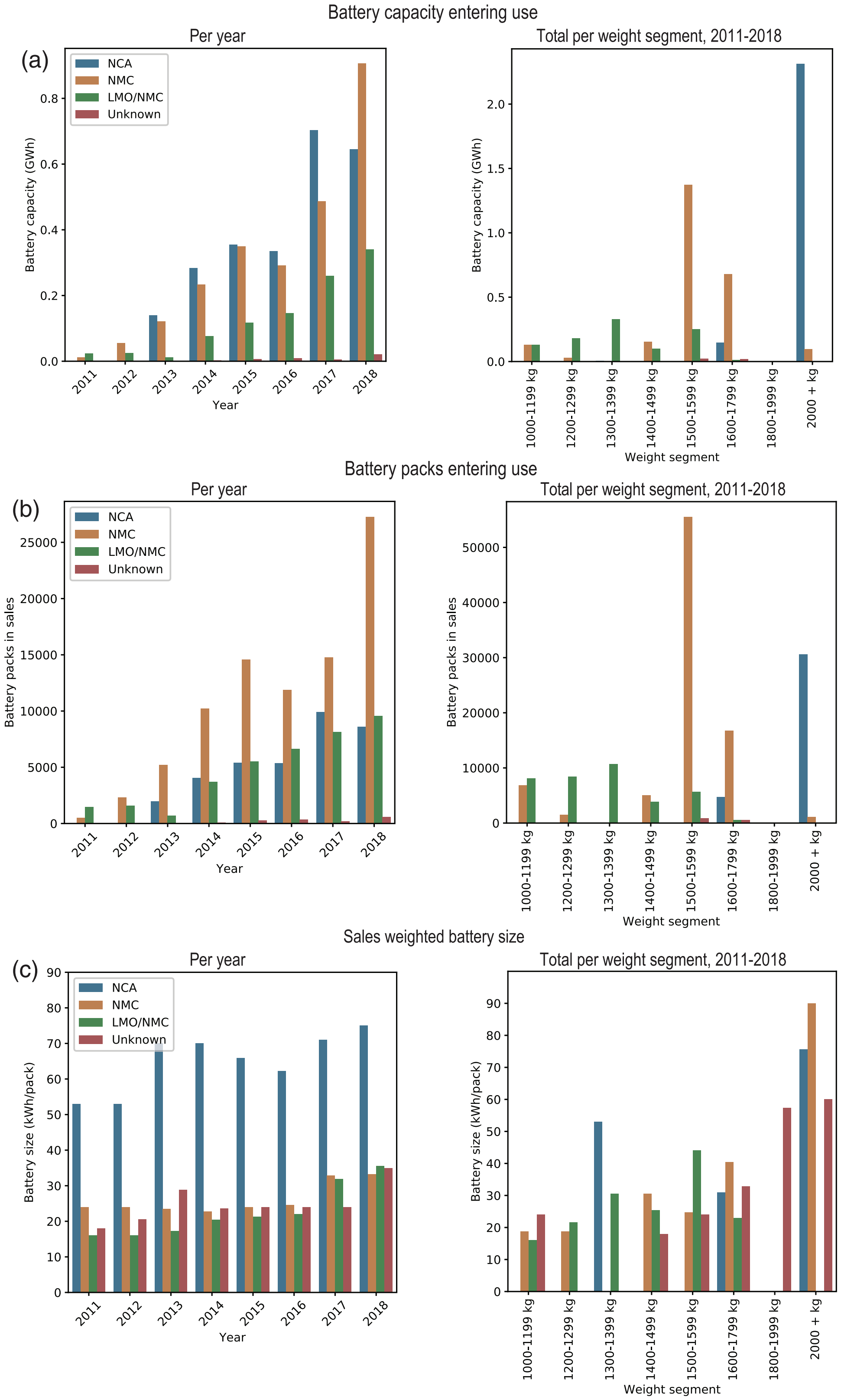

FIGURE 6 The estimated inflow of (a) battery capacity (GWh), (b) number of battery packs, and (c) sales weighted battery size (kWh/pack) introduced to the Norwegian electric passenger vehicle fleet, both annually between 2011 and 2018 and by weight segment (total for all years). Data are based on historical sales data (OFV, 2019b) and background battery characteristics data (Kelleher Environmental, 2019; Wagner et al., 2019; EV Database, 2019). "Unknown" refers to unknown Li-ion type. Data underlying this figure are available in Supporting Information S2

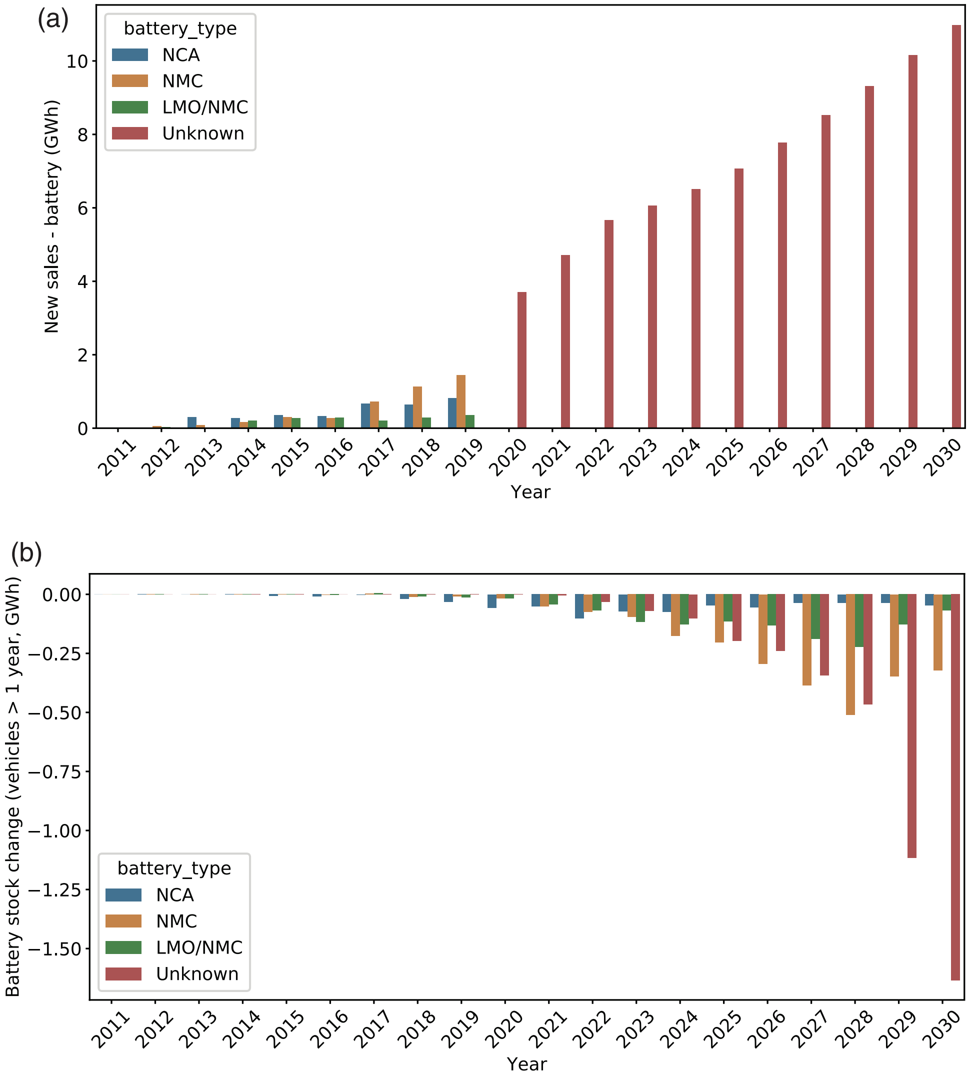

FIGURE 7 The estimated (a) total battery (GWh) introduced to the Norwegian electric vehicle fleet through new electric passenger vehicle sales, and (b) battery stock change (GWh) from the Norwegian electric passenger vehicle fleet (from vehicles older than 1 year), annually until 2030. "Unknown" refers to unknown Li-ion type. Data underlying this figure are available in Supporting Information S2

toward LFP batteries (Holland, 2020). While this trend strengthens raw material supply security, it may result in problem-shifting toward scarcity of nickel supply.

3.4 | Estimation of new batteries and net change annually until 2030

Output from the stocks and flows cohort model was combined with the supplementary battery analysis to estimate the respective battery flows until 2030. Results are shown in Figure 7, with an in-depth summary of annual net stock change for the years 2017–2025 given in Figure S3 in Supporting Information S1 that represents the arising Norwegian “window of opportunity” for end-of-life BEV, for both recycling and second-life purposes. The large increase in battery capacity entering the fleet between 2019 and 2022 is due to the increase in assumed battery sizes in many weight classes to 85% of their 2030 value, as described in Table S1 in Supporting Information S1. According to results, total battery amount used in new vehicle sales across all vehicle segments and battery types is estimated to be around 2.1 GWh in 2018, rising to 11 GWh in the year 2030. The assumed annual end-of-life summed battery quantity from BEVs older than 1 year (i.e., fleet outflows) is estimated to be around 0.6 GWh in 2025, and 2.1 GWh in 2030. Comparisons of these estimates with historical data for years 2011–2019 are not yet possible due to a lack of scrappage data. A summary of the results in terms of inflows, outflows and in-use battery stock for years 2018 and 2030 is given in Figure 8.

Recycling and second-life battery concepts are currently in relative infancy due to low battery volumes, but are gaining in popularity across Europe with developmental work being carried out by key industrial players that include Northvolt and Hydro in Scandinavia (Hossain et al., 2019;

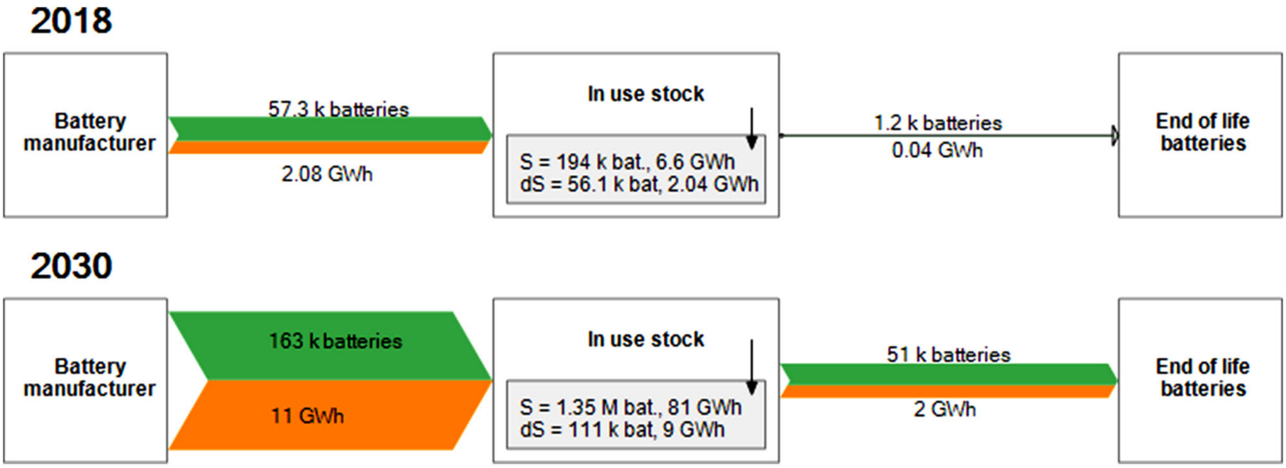

FIGURE 8 Summary of estimated inflows, outflows and in-use battery stock within the Norwegian electric passenger vehicle fleet for years 2018 and 2030. Data underlying this figure are available in Supporting Information S2

Walz, 2018). Together these companies have announced the formation of a joint venture to enable recycling of battery materials and aluminum from electric vehicles by building a pilot battery recycling plant, which will be the first of its kind in Norway (Hydro, 2020). The quantity of assumed end-of-life batteries estimated here represents the potential total available for both recycling and second-life concepts. If the quantity of batteries assumed going mostly to scrap is instead allocated wholly for second-life purposes, these batteries could potentially feed 70,000 and 260,000 typical home/cabin battery energy systems of 8 kWh in 2025 and 2030, respectively (Alternativ Energi AS, 2020). Nevertheless, far from all batteries can be re-used due to degradation or other faults (Svendsen, T. H., personal communication, September 14, 2020). These applications are still in an early phase and the dynamics will depend on a range of factors from policy to business opportunities. Based on the recently released EU proposal for the battery legislation it seems that incentives are targeted toward recycling, while reuse will be rather market regulated. Reuse can be seen as delaying the availability of secondary raw materials for automakers, while potentially also reducing the demand for new batteries for stationary applications. Thus, there is a need to further study these dynamics and better understand the impact of reuse and recycling for material security.

Complicating the picture, differences in recycling and reuse economic viability are relatively unknown at present, and other types of losses will also affect the actual total quantity of batteries available for recycling and second life. It is assumed in many studies that around 10% of vehicles are lost and not collected when scrapped, and there is widespread criteria established in the literature for EV battery retirement that capacity is reduced to 70—80% at first end-of-life (Martinez-Laserna et al., 2018; Saxena et al., 2015; Zhao, 2017). Applying these values means that battery capacity available for second use in 2025 and 2030 without refurbishments or repairs is reduced to 0.4 GWh and 1.5 GWh, respectively. Nevertheless, battery repair via refurbishment involving assembly of used cells/modules in a pack followed by calibrating and balancing can in many cases reincrease the capacity (Svendsen, T. H., personal communication, September 14, 2020).

No calculations have been made here for Europe as a whole. Although findings vary, other studies have previously indicated that between approximately 2 and 8.75 GWh may be available in 2030 for second use from end-of-life EV batteries (Bobba et al., 2019; Element Energy, 2019). Comparisons of Norwegian market data (number of new EV vehicle sales and new vehicle sales corrected for secondhand export/import) with the total EU+EFTA market from Figenbaum et al. (2020) indicate that the battery volumes becoming available for reuse or recycling elsewhere in Europe could be about double the Norwegian volume in 2025 and about quadruple the Norwegian volume in 2030. This picture, along with the results from the other studies, fit relatively well with the model estimates here. After 2030, volumes for reuse/recycling should grow much more rapidly outside of Norway as the market is expected to increase faster in other EU-EFTA (European Free Trade Association) countries from 2020 onward due to the already high domestic Norwegian market BEV saturation.

4 | CONCLUSIONS

Short- to medium-term potentials for recycling opportunities for Norwegian industries were investigated in this study; the total number of battery packs in new passenger BEV sales in Norway was estimated to be 116,000 in 2025 and 163,000 in 2030, and the number in retired vehicles to be approximately 17,000 in 2025 and 51,000 in 2030. In terms of battery capacity, this equates in new sales to 2.1 GWh in 2025 and 11.0 GWh in 2030, and in retired vehicles, 0.6 GWh in 2025 and 2.1 GWh in 2030 (not accounting for losses). Results show that NMC and NCA are battery types currently used in greatest amounts, and that there is also a division by weight segment evident. Most LIBs are currently contained within the weight segment 1500–1599 kg followed by the weight segment 2000+ kg. NCA is in use for heavier weight segments and LMO/NMC in use for lighter weight segments. In terms of LIB types in retired vehicles, NCA batteries initially constitute the largest overall capacity, but we estimate they will be surpassed by NMCs in later years. Not included in calculations are batteries from plug-in hybrid electric vehicles (PHEVs) and batteries from battery electric light commercial vehicles (BE-LCVs). However, these constitute lower fleet vehicle volumes; at end of year 2019 there were 116,042 PHEVs and 7332 BE-LCVs versus 260,292 BEVs (SSB, 2020b), with PHEVs also having smaller battery capacity than BEVs per vehicle.

Since the study builds on multiple modeling processes, various uncertainties are present. Although an overall trend to move away from cobalt seems to be dominant throughout the industry, very little concrete data is publicly available about the specific type of Li-ion batteries future BEV models will utilize. Thus all batteries arriving into the fleet between 2020 and 2030 were assigned in this study as unknown Li-ion type. This simplification allows the forecast uncertainty to be reduced but leaves unanswered questions about the end-of-life materials available. Other key uncertainties relate to the lack of differentiation of import and export flows in the stocks-flow model output, and the non-inclusion of other detailed types of outflows (e.g., vehicle and battery capacity losses), that will also affect the main results. For the former uncertainty, the available data suggest that exports are currently low and the majority of used vehicles imported in recent years are less than 1 year old, which significantly reduces the model uncertainty. Nevertheless, this may change over time.

In summary, this analysis based on a combination of vehicle-specific data and assumptions of BEV market uptake from the Norwegian national budget estimates that the battery capacity and pack number in retired BEVs will increase dramatically toward 2030, indicating great potential for domestic markets to develop around battery recycling and reuse. Further, it provides insights into the materials embedded in the batteries as well as a theoretical framework that can be applied to other regions. The results also indicate that it will be necessary to adapt to changing battery types and sizes of the retired batteries. Making use of business opportunities activities will require a large amount of infrastructure, as well as new regulations, for which the estimates provided here can act as a guide.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Opplysningsrådet for veitrafikken (OFV) and EV Database. Restrictions apply to the availability of these data, which were used under license for this study. Data are available directly from OFV and EV Database.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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