Second life batteries: The potential for new energy storage solutions from re-use of Norwegian electric vehicle and maritime batteries

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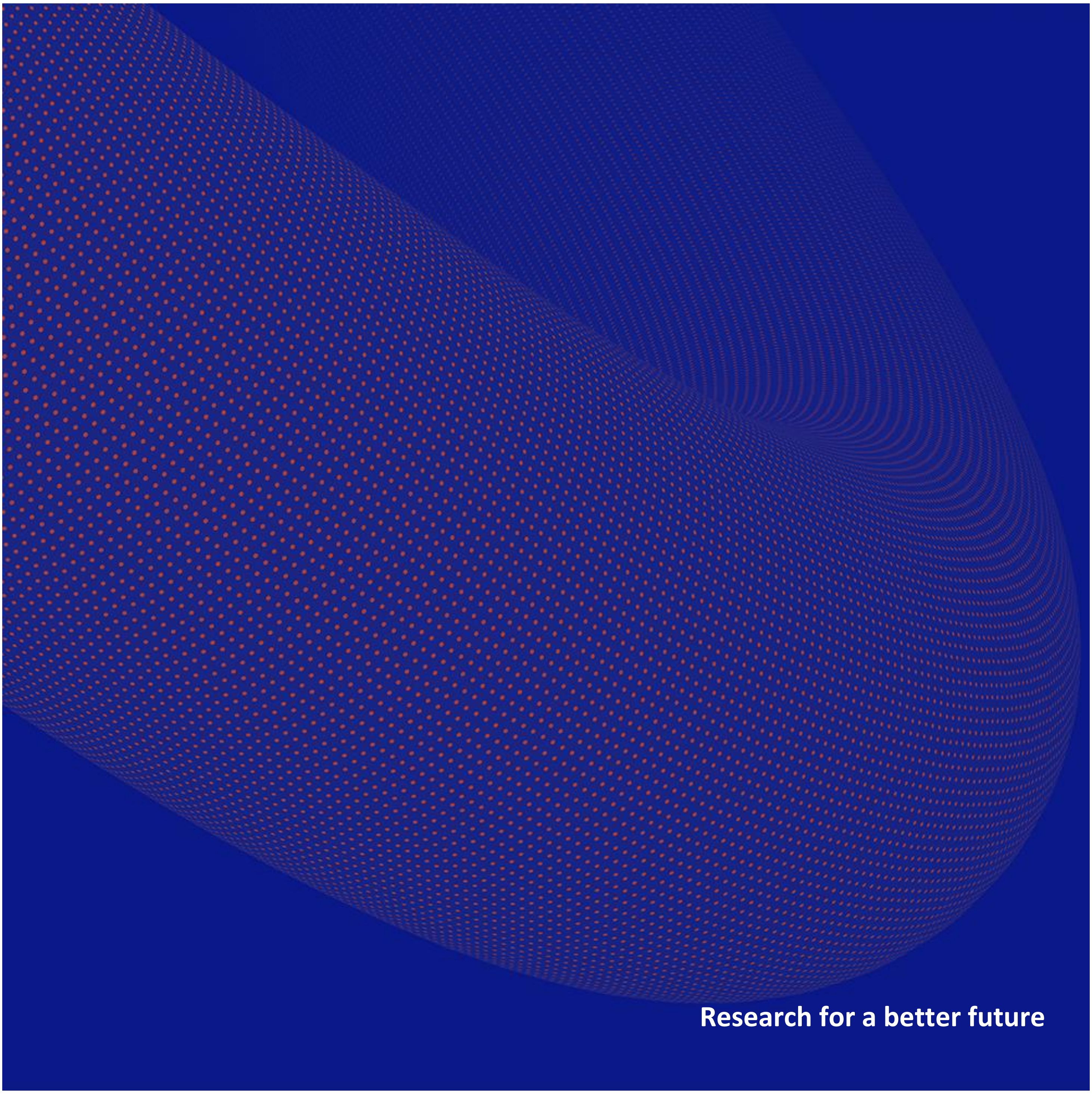

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Title:
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Summary:
The market potential for batteries is expected to surge towards 2050, with an estimated demand growth of 25 times today's capacity. However, the rising demand for batteries bring challenges to the battery value chain, both in terms of shortages in raw material supply, as well as environmental and social impacts of battery manufacturing. Second life batteries provide one solution to mitigate these concerns. The aim of the 2ND LIFE project is to identify and quantify opportunities and barriers of re-utilizing batteries from electric vehicles to enable new energy storage solutions. As part of the project, this report provides an overview of the current situation and an assessment of future development in available batteries for second-life applications in Norway. By 2030, the battery capacity from passenger vehicles in Norway is expected to be 81 GWh, of which capacity for 2nd life applications from used EVs is estimated to 1.5 GWh. The quality of these batteries will highly depend on its 1st life operational conditions, in which studies show that cycling at lower SoC and DoD levels are beneficial. In terms of second life applications, the most common use cases in Europe today are small scale distributed energy storage for residential buildings, large-scale stationary energy storage for commercial buildings, grid stabilization, and powering EV charging stations.

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List of abbreviations

BEV	Battery Electric Vehicle
DST	Dynamic Stress Test
DoD	Depth of Discharge
EoL	End of Life
ESS	Energy Stationary Storage
EU	European Union
EV	Electric Vehicle
IFE	Institute for Energy Technology
ITEM	Integrated Transport and Energy Modelling
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate Oxide
NCA	Lithium Nickel-Cobalt-Aluminum Oxide
NMC	Nickel Manganese Cobalt
OEM	Original Equipment Manufacturer
SoC	State of Charge
SoH	State of Health
TØI	The Institute of Transport Economics
V2G	Vehicle-to-grid

1 Research questions

This outlook report is made as part of the work package 1 “Assessment of future development” belonging to “2ND Life” project funded by the Research Council of Norway (project no. 320760). The objective of the project is to understand better the opportunities and barriers of re-utilizing batteries from electric vehicles when no longer meeting the operational requirements of this application. In this report, batteries from the maritime industry are also included. The project consists of leading Norwegian research institutions and relevant industry partners and is managed by IFE. In work package 5 the acquired knowledge about 2nd life batteries is set in a broader context by analyzing its potential role in the energy system considering both national and international markets.

The purpose of this report is to provide an overview of the current situation and perform an assessment of the future development in Norway with regards to available batteries for second life applications. The report builds on information collected from literature studies, discussions with partners and industry actors, historical data, and future projections to form a credible outlook.

The outlook report aims at answering the following research questions:
How will used EV and maritime batteries in Norway develop in terms of battery type, timing and capacity?

- What are the characteristics (and quantities) of used Norwegian EV and maritime batteries today and towards 2030?
- What are the corresponding trends, drivers and uncertainties?

2 The Norwegian electric vehicle stock

Norway is a leading nation in the drive towards zero emission transport, targeting sales of solely zero emission passenger vehicles by 2025. There exist several zero-emission technologies relevant for the transport sector, however lithium-ion batteries are by far the most mature technology for passenger vehicles today. Between 2010 and 2020, the number of registered passenger battery electric vehicles (BEVs) in Norway rose by 165 times, from about 2000 to 330,000 [1]. The breakdown of registered passenger vehicles per fuel type in 2020 is illustrated in Figure 1, whereof BEVs constituted 12% [2]. Of all new passenger vehicle sales in 2020, BEVs made up 54.3% of the market share [3].

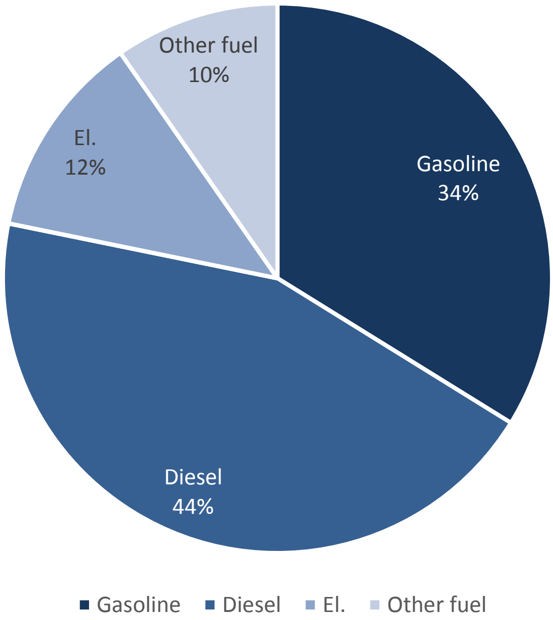

Figure 1: Breakdown of passenger vehicles by fuel type in 2020 [2].

2.1 Development in battery electric vehicle stock towards 2050

In the project "Integrated Transport and Energy Modelling (ITEM)", published in August 2021, IFE and TØI developed different pathways for the future transport sector towards 2050, relying on a stock-flow projection model [1]. This is one of several articles published by TØI, using the same model to forecast the national passenger and electric car fleet in Norway [4-7]. Three scenarios were presented, 1) Slow decarbonization, 2) Fast decarbonization, and 3) Extra fast decarbonization. The slow scenario assumes a technology driven market with constant tax rates, while the fast scenario uses increased CO_2 taxes on fuel and ICE vehicles. In the case with extra fast decarbonization, 90% of new passenger cars are assumed to be zero emission in 2025, with 95% in 2030. Considering only battery electric vehicles, the market share of new passenger vehicles reaches 69% (slow), 80% (fast) and 95% (extra fast) in 2030. The total number of BEVs is projected to reach 1.2, 1.4 and 1.7 million the same year, constituting respectively 42%, 47% and 56% of the entire fleet. Further analysis has also been conducted towards 2050, where the number of BEVs are projected to reach almost 3,160,000 in the case of an extra fast decarbonization. Comparing the numbers to 2020 values, BEVs have the potential to fivefold by 2030 and tenfold by 2050. The development for the three scenarios is illustrated in Figure 2.

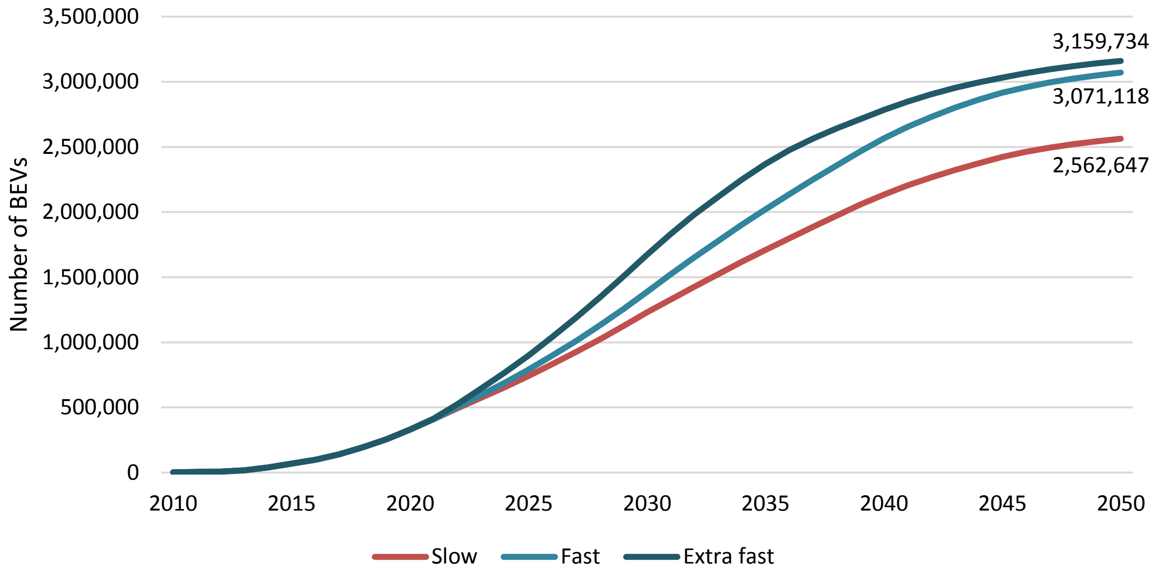

Figure 2: Stock of battery electric vehicles (BEVs) in the passenger vehicle fleet 2010-2050 [1].

In addition to estimating the number of battery electric vehicles in the future Norwegian passenger transport fleet, TØI has conducted a more detailed study on the characteristics of new BEVs [5]. The study focuses particularly on weight class[1], battery type, battery age and battery capacity of existing and new electric vehicles.

In terms of vehicle weight, it is forecasted that the weight class 1500-1599 kg holds the highest share in new sales with approximately 50% in 2025 and 2030. Considering the curb weight of today's EV's, cars like Peugeot e-208, Hyundai Ioniq or Nissan Leaf with 40 kWh battery belong within this weight segment [8]. As illustrated in Figure 3, future BEVs are anticipated to contain larger batteries. While vehicles below 1200 kg were dominating up to 2015, larger vehicles have started to enter the fleet the last decade. This trend is anticipated to continue, with vehicle weights above 2000 kg holding the second largest share in 2030, with about 18%. Based on TØI's classification, the most common weight segments in the next decade will correspond to nominal battery sizes of 45 kWh (1500-1599 kg) and 90 kWh (2000+ kg) [5].

The constant battery capacity per weight segment is however a simplification. With battery-cell energy density having almost tripled since 2010, longer range electric vehicles has made their way to the market without needing larger and heavier battery packs [9]. As an example in practice, the Nissan Leaf range[2] per charging cycle has increased from 117 km in 2011 to 243 km in 2018, with a capacity growth from 24 kWh to 40 kWh, while its curb weight increased only marginally [10]. Based on the historical evolution, it is reasonable to assume that battery capacities will increase also within the same weight class, however at a more modest rate compared to the increase over the past decade. If so, this will further enhance the available capacity from 2nd life batteries going forward.

[1] Considering curb weight, i.e. the weight of the vehicle including all its equipment and a 75 kg driver
[2] According to USA Environmental Protection Agency (EPA) range estimations

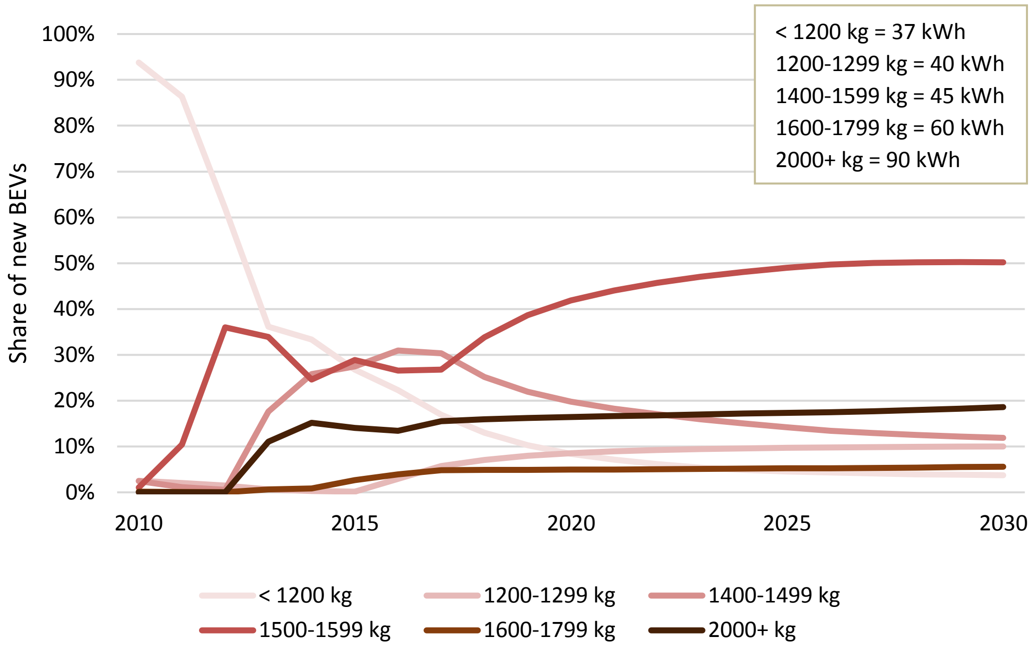

Figure 3: Share of new battery electric vehicles by weight group. Based on data from [5].

In terms of vehicle age, TØI estimated the stock change of vehicles older than 1 year. Figure 4 present the net stock change of electric vehicles by vehicle age for 2015, 2020, 2025 and 2030. Results show that scrapped vehicles in 2015 and 2020 constituted largely vehicles younger than 7 years. For these years, the outflow is caused mainly by accidents, callbacks, or malfunctions, as the majority of EVs had not reached their end-of-life by then. For 2025 and 2030, the largest fraction of scrapped vehicles is expected to be around 10 years old. Noteworthy, these numbers are largely uncertain as electric vehicles have not been in the market long enough to have sufficient and reliable data on historical scrapping trends. Some manufacturers have already reported EV battery lifespan exceeding 10 years. In Tesla's impact report from 2020, the capacity retention averaged approximately 90% after 320,000 km of usage. Assuming a yearly driving distance of 19,000 km, this equates to nearly 17 years before being scrapped [11]. With these estimates, it is possible that the lifetime of future EV's will approach that of ICE vehicles (18 years in 2021 [12]), however numbers will depend on uncertain parameters such as battery chemistry, capacity, operational conditions etc. A more detailed discussion on the impact of different parameters can be found in Section 3.

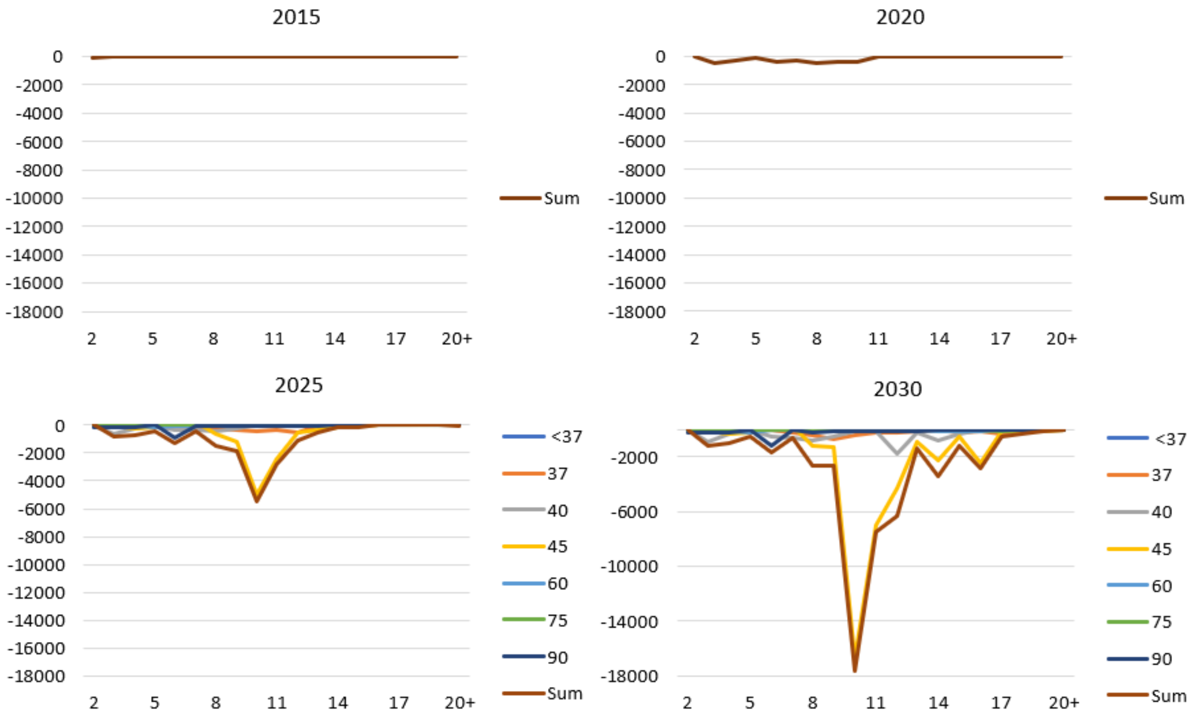

Figure 4: Net stock change (# of electric vehicles) by vehicle age and battery capacity (37-90 kWh) for 2015, 2020, 2025 and 2030 [5].

2.2 Battery stock available for 2nd life in 2030/2050

For the total battery stock from the BEV fleet, TØI estimate 13 GWh in 2020, of which 3.70 GWh was introduced through new vehicles the same year. Moreover, the capacity is projected to more than triple by 2025 and sixfold by 2030, reaching 41 GWh and 81 GWh, respectively. The amount of capacity entering the fleet also increases throughout the years, with 7 GWh and 11 GWh in 2025 and 2030. As illustrated in Figure 5, the growth in battery capacity from 2018 to 2030 follows a second order polynomial. By assuming continuous development towards 2050, we use trend extrapolation to give an indication of the long-term future battery capacity accumulating from battery electric vehicles. By 2050, in-use battery stock can potentially reach 370 GWh. Assuming a more conservative outlook, using a linear approximation, the potential reaches 200 GWh.

The forecasts towards 2050 is complemented by a different methodology to also incorporate battery volumes from the rest of the Norwegian vehicle fleet segments. Based on the forecasts of vehicle kilometers in the national transport plan 2022-2033 [13], and the assumption of a fully electrified road transport sector, the fleet size and its total battery capacity was calculated. By assuming that the average battery size of passenger cars will range between 60-120 kWh, vans between 75-150 kWh and trucks and busses between 300-600 kWh, the results are presented in a low and high scenario in Figure 6. The forecasts for total battery capacity of the passenger car fleet in 2050 from the different methodologies shown in Figure 5 and Figure 6 are relatively similar. The illustration of Figure 6 however complements the picture that a significant battery capacity and thus battery flow from scrapped vehicles can come both from vans and trucks once a significant share of these sectors will have transited to battery electric power train.

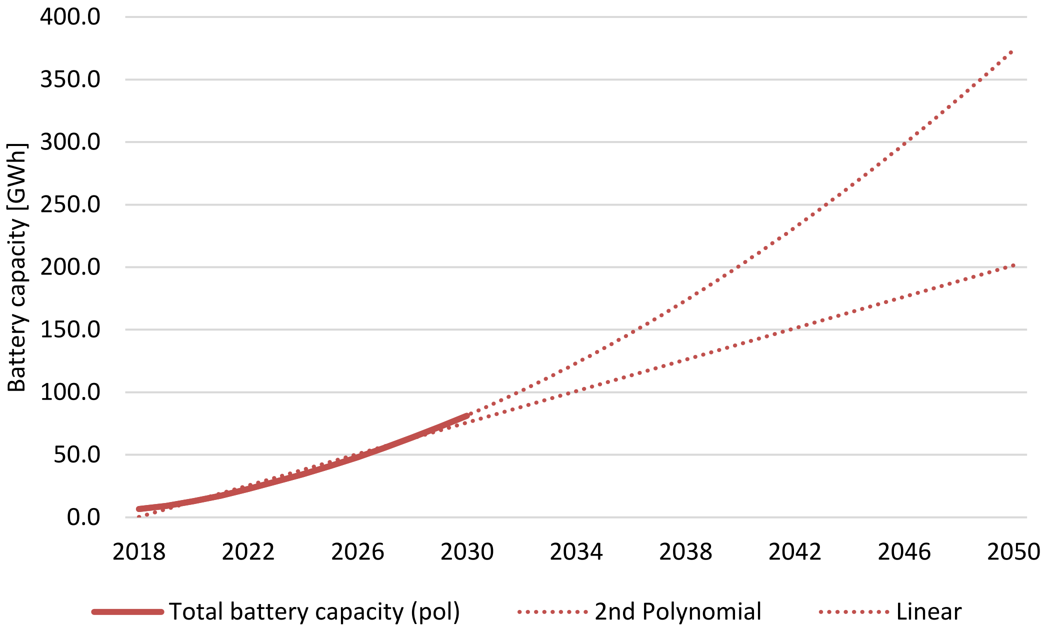

Figure 5: Total battery capacity for passenger vehicles towards 2030 (TØI analysis [5]) and 2050 (projections).

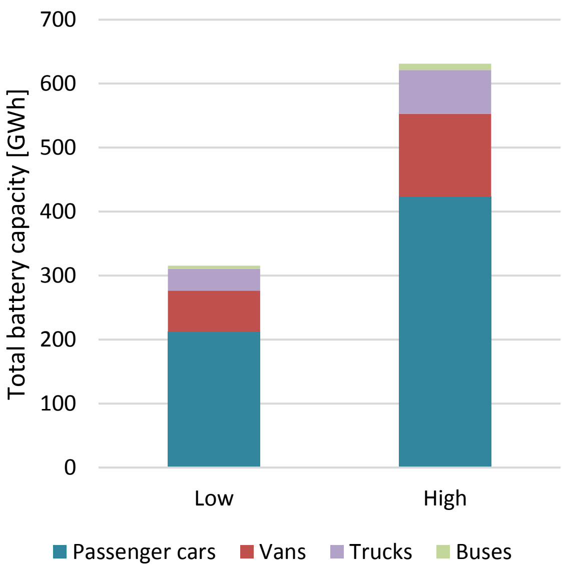

Figure 6: Estimation of battery volumes in the Norwegian vehicle fleet by 2050 based on full electrification of the sector.

In terms of battery technology, the dominating chemistry used in electric vehicles to date has been NMC, followed by NCA and LMO/NMC. As it remains large uncertainty regarding future chemistries, TØI has labelled new capacity as "unknown" in their projections. Historical data does, however, give an indication on the characteristics of 2nd life batteries being available in the next decade. Based on empirical stock data from the national motor vehicle register from 2012 to 2017, TØI has used transition rates to estimate the net stock change of older BEVs. This represents the potential available capacity for recycling or reusage in second-life applications. The quantity of estimated end-of-life batteries is illustrated in Figure 7, including the respective battery chemistry. The sum of scrapped vehicles potentially available for 2nd life purposes is estimated to be around 0.6 GWh in 2025 and 2.1 GWh in 2030. Nevertheless, TØI emphasizes that far from all batteries can be re-used due to degradation or other faults. Several studies have estimated that about 10% of vehicles are lost and not collected when reaching end of life. Moreover, degradation leads to capacity reduction which is often estimated to 70-80% after first end-of-life. Applying these values reduces the available capacity for second use to 0.4 GWh and 1.5 GWh in 2025 and 2030. Battery repair through refurbishment (i.e. assembly of used cells/modules in a pack followed by calibrating and balancing) can however re-increase the capacity [5].

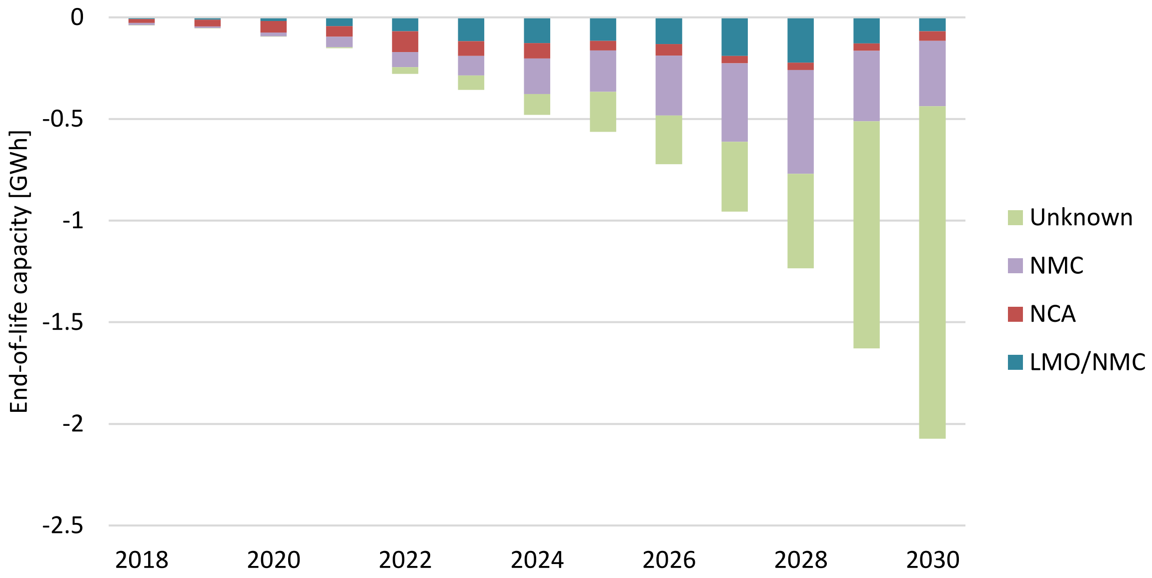

Figure 7: End-of-life capacity from scrapped vehicles by battery chemistry [5].

2.3 The impact of future EU regulation

On 10 December 2020, the European Commission proposed a new battery regulation [14] which is expected to be applied uniformly across the EU single market from 2023 (initially 2022). The regulation aims to ensure sustainable and safe batteries throughout their entire life cycle, with a particular focus on circularity. As of today, OEMs in Europe need to ensure that 50% of the total weight of the battery is recycled [15]. With the new proposed regulation, recycling processes shall achieve a minimum recycling efficiency of 65% for Li-ion batteries by 2025 and 70% by 2030. In addition to percentage requirements of total battery weight, recycling targets are changed to also include recovery percentage levels per material[3]. Moreover, the proposal adds another feature that has previously not been regulated by the EU, namely requirements for the use of recycled materials in the production of new industrial, EV and automotive batteries with capacity above 2 kWh. Specifically, mandatory levels of recycled content in [2030,2035] involves [12%,20%] cobalt, [85%, 85%] lead and [4%, 10%] lithium and/or [4%, 12%] nickel provided that the battery contains these materials [14].

The new EU regulation does not require a certain degree of second use, however measures are given to help facilitate repurposing of batteries. The battery passport, an electronic record including information about the basic characteristics and values for performance and durability parameters [14], should help second life purchasers, users and operators to make informed decisions and to make used batteries more marketable. In addition, the regulation proposes that second life batteries need to fulfil specific EoL (end of life) criteria before being repurposed, including a SoH check to confirm the capability to deliver the specified performance relevant for its use. In this regard, a battery

[3] Levels of materials recovery by 2026: cobalt: 90%, copper: 90%, lead: 90%, lithium: 35%, nickel: 90%,
Levels of materials recovery by 2030: cobalt: 95%, copper: 95%, lead: 95%, lithium: 70%, nickel: 95%,

management system is proposed to be made available for battery owners and operators to store information required to determine the SoH of the battery [16]. Noteworthy, the EU commission seeks to facilitate both reuse and recycling of batteries, however, they emphasize that it should be up to private actors to decide what the solution of the two will be.

It can be expected that the future recycling initiatives will affect lithium-ion battery volumes that will be repurposed before recycling or directly recycled after consumption. In particular, the choice of recycling versus repurposing will be influenced by factors such as demand for and prices of virgin raw materials, and increasingly by demand and prices for secondary raw materials [15]. The extent to which automakers will seek to retain control over the car battery throughout the car's life cycle will also be of importance.

3 Quality of EV batteries at End-of-Life

Even though projections indicate that a large amount of battery capacity will be available for second-life purposes in the decades to come, the applications of these batteries highly depend on their remaining quality and performance. Extensive studies have been carried out for the degradation behaviors of lithium-ion batteries under different ambient conditions and operation patterns. Xu et al. [17] proposes a degradation model that is formulated based on fundamental theories and their own observations in battery aging test results. Similarly, Wikner and Thiringer [18] developed an empirical ageing model for electric vehicles based on cell test data at different SoC levels, C-rates and temperature. The results of these studies will act as a first indicator for the degradation rates of EV batteries, while new ageing models for 2nd life cycling will be developed as part of work package 4 in the "2ND life" project. These ageing models will build on the fundamentals of the established models for 1st life ageing and will be based on test data from the battery laboratory at IFE.

The three factors that are most evaluated when estimating battery degradation relate to the depth of discharge (DoD), the operating temperature and the state of charge (SoC). The depth of discharge expresses how deeply the battery is discharged and is directly connected to the number of charging cycles the battery can deliver before reaching end-of-life (EoL). Partial discharge reduces the stress on the battery, prolonging the lifetime. Moreover, exposing the battery to high temperatures and dwelling in a full state-of-charge over an extended time can cause significant capacity loss [18]. The charging profile of the battery during 1st life will therefore impact its suitability in a 2nd life application.

3.1 Aging by State of Charge (SoC)

Using test data from [17], the remaining capacity of the battery over a duration of 10 years is presented in **Error! Reference source not found.** when stored at SoC levels between 50 and 100%. T he results indicate a higher degradation at high SoC levels, in which storing the battery fully charged leads to a capacity loss of almost 25% compared to 17% at half full charge. Moreover, the curve shows a higher degradation rate during the first years of operation. This is in accordance with the findings of Wikner and Thiringer [18], where lower SoC levels were less detrimental compared to higher SoC levels. In this study, tests were also conducted for different C-rate levels. As shown in Figure 9, charging at higher C-rates substantially accelerates the degradation of the battery. Nevertheless, even cases of higher C-rates show less ageing compared to the tests conducted in higher SoC levels. Comparing the test runs in Figure 9, the fastest ageing is obtained for all three C-rates in 80-90% SOC. Moreover, cases with higher SoC but lower C-rate (e.g., 0.5C 80-90% vs. 1C 40-50%) show faster ageing. These results indicate that the SoC level is more important than the C-rate.

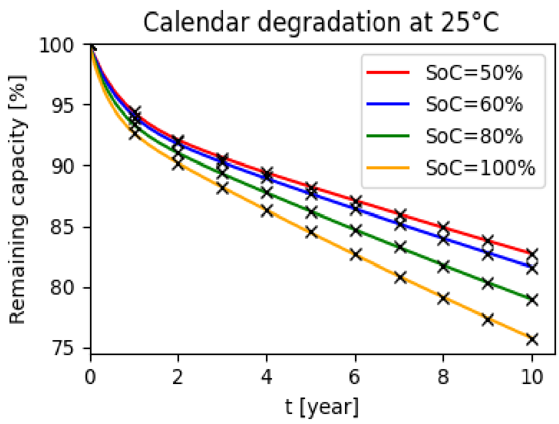

Figure 8: Calendar aging with varying SoC at 25 °C [17].

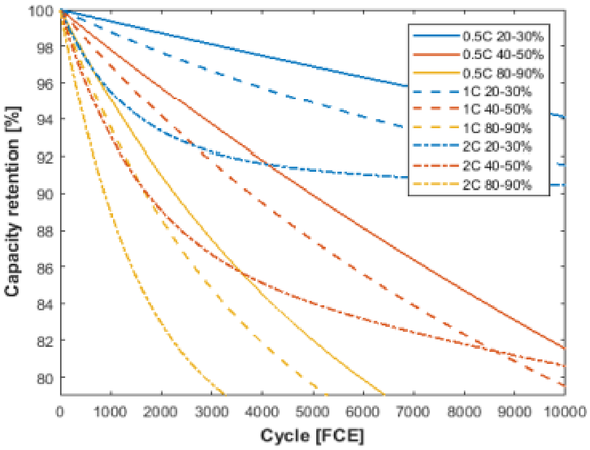

Figure 9: Cycling ageing at 10% DoD with different SoC and C-rate levels [18].

3.2 Aging by temperature

The operating temperature is another factor that can adversely affect the battery life. Results presented in Figure 10 clearly illustrates the benefits of operating EVs at medium-low temperatures. At high temperatures, the speed of the chemical reactions within the battery increases, leading to a higher self-discharge rate and correspondingly battery degradation. For the temperature range of 15-55 °C, results showed a significant higher degradation rate at higher temperatures, with remaining capacity of 61% after 5 years at the highest temperature level. In comparison, the battery operating at an ambient temperature of 15 °C had a remaining capacity above 90% for the same time period. Wikner and Thiringer had the same conclusion, comparing test runs at 25 °C and 35 °C.

According to Xu et al., temperatures below 15-20 °C has a similarly negative impact on battery performance as a result of increasing internal resistance. This is illustrated by the temperature stress model in Figure 10. The hypothesis of low temperature impact was, however, not validated in the model of [17] as test data was not available for temperatures below 15 °C. Researchers at the Institute for Energy Technology (IFE) have conducted tests on battery cells at temperatures ranging down to 5 °C. Results indicate an accelerated cycling ageing in the first years of operation, being even more significant than that of 35 °C. Nevertheless, the ageing curve tends to flatten out with time, implying a longer calendar life compared to higher temperature levels. Despite the promising results of the lab test, further research and evaluation is needed to assess the safety conditions when operating batteries at such low temperatures.

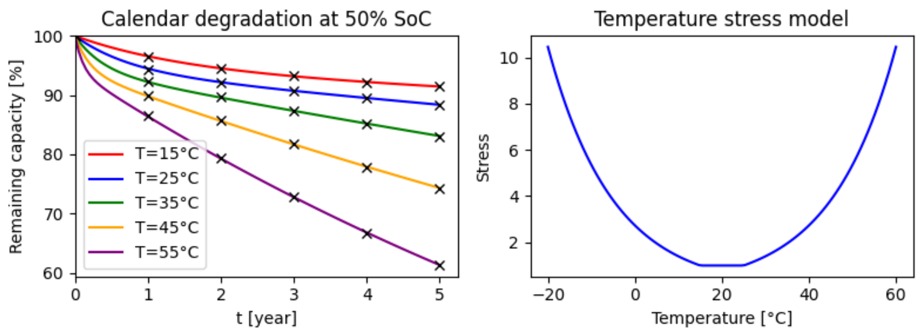

Figure 10: Left: Calendar aging with varying temperature at 50% SoC.
Right: Temperature stress model used as input for the degradation rate

3.3 Aging by Depth of Discharge (DoD)

Lastly, Xu et al. [17] reported the capacity loss when cycling the battery at various charge and discharge bandwidths based on dynamic stress test (DST) results. The different curves represent variations in SoC operating windows at an ambient temperature of 20 °C. The largest capacity loss occurs when the battery is cycled between 25-100% SoC (red), which is the largest discharge depth in which also the battery is operated at its upper capacity. Lowering the depth of discharge leads to better battery performance, as seen by the blue and orange curve. The best battery quality is attained when operating the battery at a 10% DoD (65-75% SoC). Similar results were found by Wikner and Thiringer [18], where 20% and 50% DoD ranges where tested at different SoC levels. Figure 12 show the fastest ageing in the case of 50% DoD at 40-90% SoC, while the same DoD, though in 0-50% SoC, manages more than double the number of full cycle equivalents until reaching 80% capacity retention. This further highlight the larger impact of SoC on battery aging. The slowest degradation was achieved at 20% DoD in 10-30% SoC.

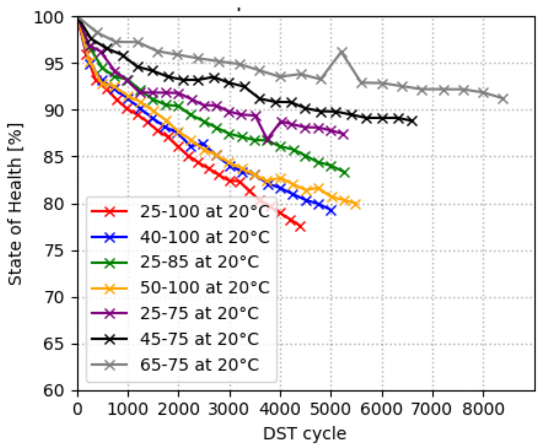

Figure 11: Capacity retention for different DoD and SoC levels [17].

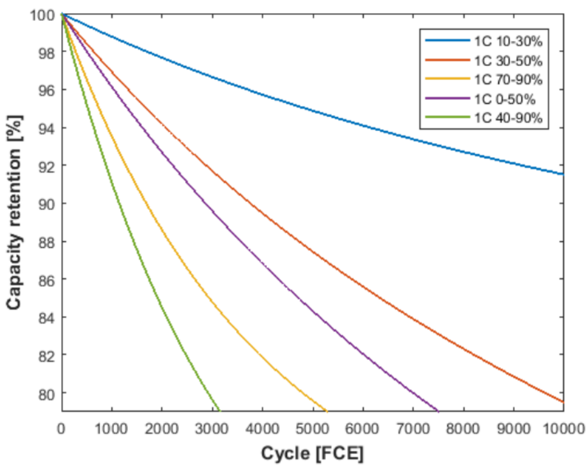

Figure 12: Capacity retention for different DoD and SoC levels [18].

Based on the results of Xu et al. [17] and Wikner and Thiringer [18], the quality of second-life batteries will differ largely depending on the temperature conditions and the charging strategy of its first-life application. In general, the SoC level seem to be the factor with the largest impact on battery aging, where lower levels are more favorable. Moreover, charging at lower C-rates and using smaller DoD will decelerate battery degradation. The increasing awareness of optimal EV battery operation in recent years, in which also smart monitoring and charging mechanisms have emerged, can positively impact the State of Health of 2nd life batteries. However, other changes to battery characteristics, such as the push for higher cell energy density, often comes with a compromise in life and it is therefore difficult to draw any conclusions about the overall lifetime development. Changes in battery chemistry will also be an important factor, where a new degradation test study from 2020 [19] found the capacity retention of the LFP chemistry to be superior to NMC with considerably longer cycle life span. Under the examined conditions of this study, the NMC aged almost twice as quickly as the LFP. NCA was also part of the experiment, showing similar or worse performance compared to the NMC battery. Lastly, results show large differences in aging depending on the operating temperature. As the average temperature in Norway is lower than 20 °C, the aging can differ slightly from that presented here. Moreover, there are large temperature differences both on a regional and seasonal level.

4 Maritime batteries

Even though electrification of the transport sector has mainly focused on electric vehicles the past decades, actions on reducing emissions and finding clean power solutions for the marine sector are emerging. Accounting for approximately 10% of transportation emissions globally, actors worldwide have initiated efforts in decarbonization solutions such as batteries, ammonia and liquid hydrogen. Batteries are particularly gaining momentum in the maritime industry, taking advantage of the technology learnings and scale of production from the automotive industry. According to DNV GL's databases, more than 400 ships with batteries are currently in operation and 135 are under construction (Figure 13). Of these, 46% are hybrid applications, while 26% are pure electrified [20]. With new regulations requiring low-emission or emission-free operation, and with steadily improvement in charging infrastructure, batteries are set to become even more attractive. On a global and European level, Norway is at the forefront of the transition, holding a share of 41% and 65% of all ships with batteries, respectively [20].

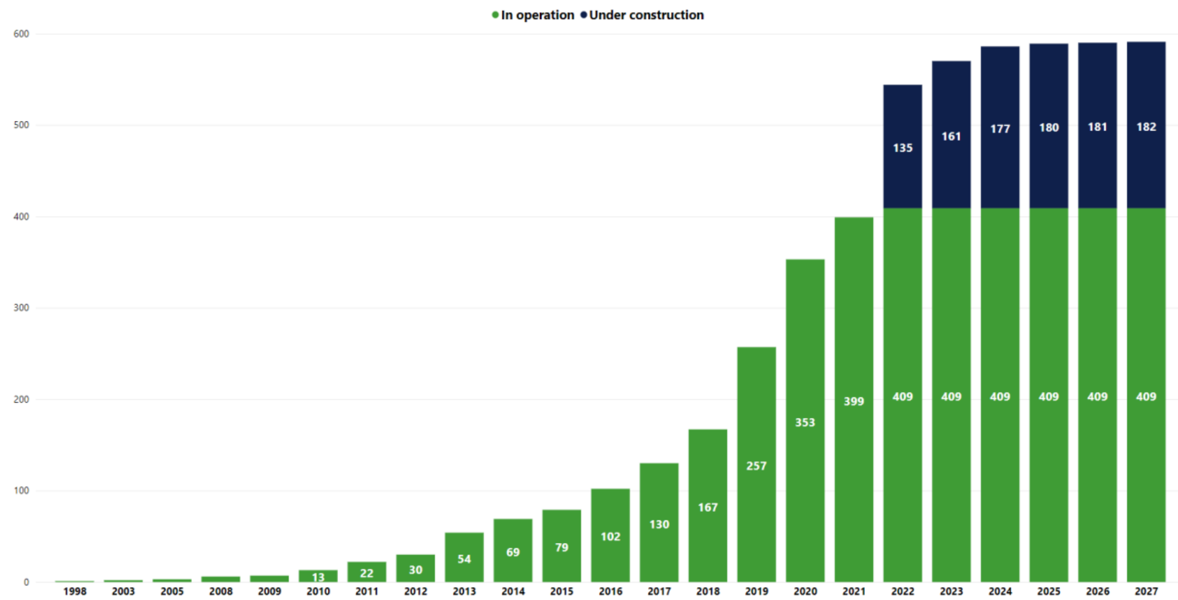

Figure 13: Number of ships with batteries in operation and under construction [20]. Does not consider the potential of upscaling aside from those already planned.

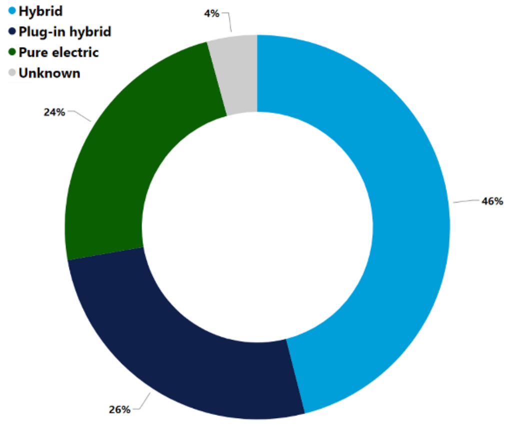

Figure 14: Battery application [20].

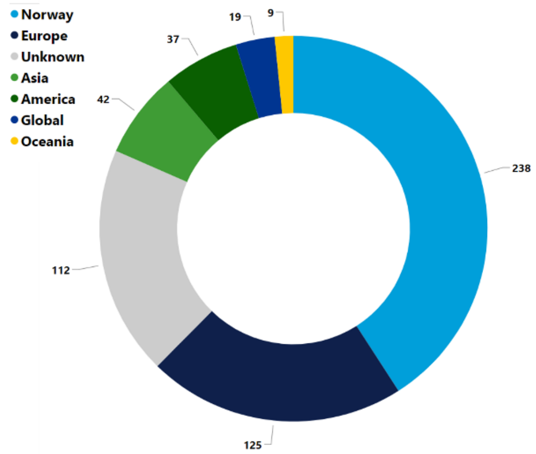

Figure 15: Area of operation [20].

At the moment, batteries are most common in the car and passenger ferry segment, approaching 250 vessels in operation or under construction. Batteries are also taking up a larger share in offshore vessels, cruise ships, fishing vessels and tugs, and is expected to continue to expand across ship segments in the coming years. Besides short-sea segments, hybrid solutions are also emerging in deep-sea vessels and larger ships to optimize power management [21]. The distribution of ships with batteries by ship type is given in Figure 16.

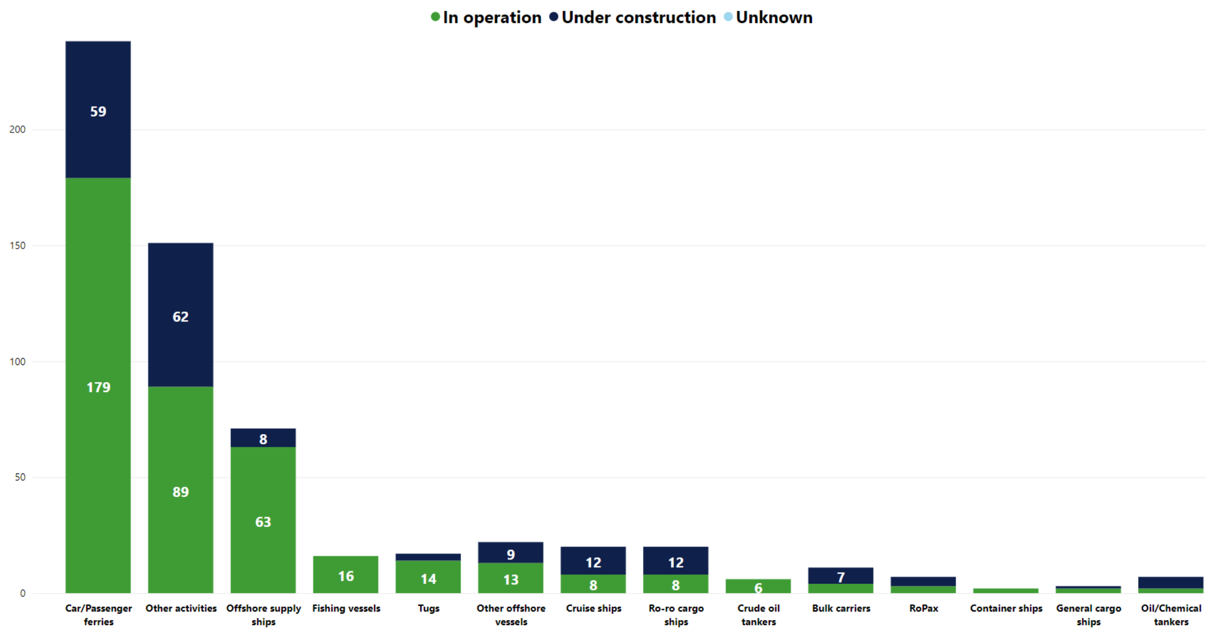

Figure 16: Number of ships with batteries by ship type [20].

In terms of second life potential, most battery driven ships were commissioned in the period 2015-2020. Assuming a lifetime of 10 years, the capacity available for 2nd life purposes will first reach considerable amounts around 2025-2030. To give an estimate on the expected available capacity for 2nd life applications from the maritime sector, historical data has been provided by Corvus [22]. The data contain information about battery size and year of operation for 213 ships operating in European sea waters. Figure 17 presents the accumulated capacity per ship segment that will be potentially available for 2nd life purposes, assuming a 70% state of health (SoH) at end-of-life (EoL) (10 years). The largest share derives from the car and passenger ferries, which is also the dominating segment in terms of number of ships. Battery capacity from cruise ships is also considerable due to the larger batteries required for these ships.

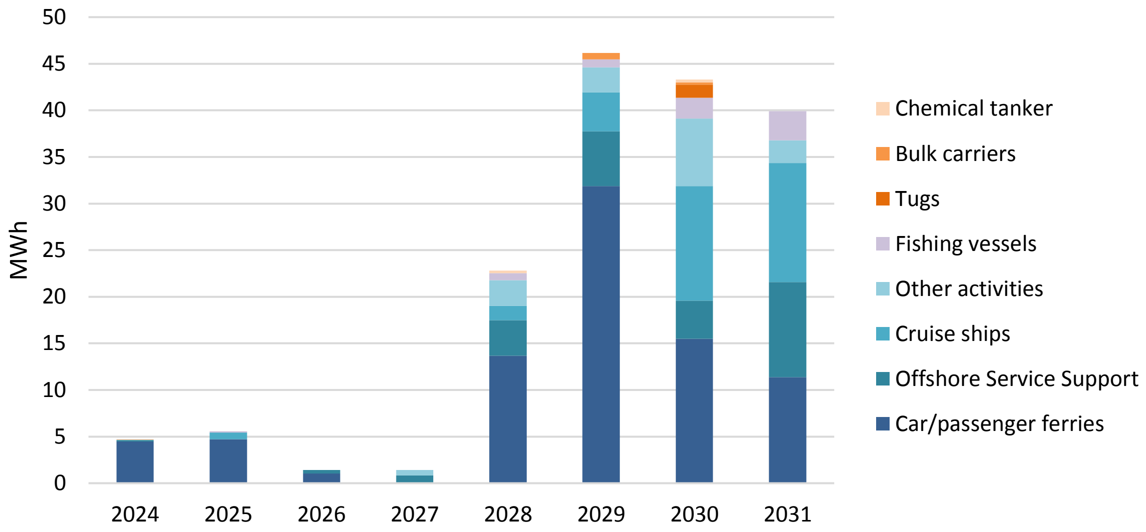

Figure 17: EoL capacity in maritime batteries assuming a lifetime of 10 years and SoH of 70%.

Noteworthy, the assumption that the ship battery has a remaining capacity of 70% after 10 years lifetime is highly case specific and depends largely on the operational profile and the cell characteristics. In the maritime sector, many contracts are time dependent (typically 10 years), meaning that the battery is taken out of operation regardless of its SoH. The battery's EoL is therefore normally a commercial decision and not a technical one. In addition, some batteries are replaced due to other considerations. As maritime batteries have higher standard requirements than EVs in terms of tolerance, batteries can sometimes be replaced due to one bad cell, making the module inoperable for the initial maritime application. Moreover, some batteries are withdrawn due to technology improvements that allow for a higher energy density. Consequently, second life batteries from the maritime sector can have a SoH above 70% when reaching end of first life [22].

5 Comparison of EV and maritime batteries

There are some structural and operational differences which can make the batteries from the two sectors suitable for different 2nd life applications. While maritime batteries are often taking out of operation due to "end-of-contract", EV batteries remain in operation until the vehicles are scrapped. Even though EV manufacturers guarantee a lifetime of about 8 years, many vehicles are in operation much longer. A hypothesis can therefore be that 2nd life batteries from the maritime sector might have a better SoH compared to EV batteries, as their EoL is often reasoned by other factors than its technical performance. Another important difference is the structural aspects. Maritime batteries require a higher degree of safety, being more protected against incidents compared to conventional land-based batteries. They are developed to withstand tougher stresses, vibrations, storms, humidity etc. These batteries should therefore be suitable for more demanding second life applications. Moreover, larger batteries are used in the maritime sector. To contextualize, a typical EV battery consists of about 20-50 modules, while a 10 MWh cruise ship battery contain 1800 modules. Going towards a zero-emission society in 2050, with worldwide commercialization of maritime batteries, the accumulated capacity has the potential to increase exponentially.

Lastly, the chemical characteristics of EV and maritime batteries differ and has also changed in recent years. Lithium manganese oxide (LMO) batteries were among the first to be used in the early EVs but has later been substituted by NCA and NMC batteries due to superior energy performance and lower cost [23]. Like EV batteries, NMC is also the dominant cell chemistry for maritime batteries, holding a market share of 61%. A higher deployment of LFP and LTO batteries exists in ships as these are intrinsically safer than other chemistries. The future share of battery chemistry in the maritime and EV market will be influenced by energy density and safety, but also on the availability and price of raw materials. This is particularly relevant for cobalt-based chemistries, in which the cobalt shortage will likely move the market towards low-cobalt batteries. The cobalt-free LMOs and LFPs might therefore see a resurgence also in the EV market, despite being less favorable due to lower performance [23].

6 The window of opportunities for second life purposes

6.1 Market potential for batteries (in Norway/Europe/World)

The market potential for batteries is expected to grow substantially towards 2050, driven mainly by large cost reductions and electric mobility. From today's capacity of 200 GWh, the battery demand in 2050 is estimated to be 25 times as large, reaching approximately 5 000 GWh. The largest demand is anticipated in China, while Europe make up about 15% of the share (775 GWh) [24].

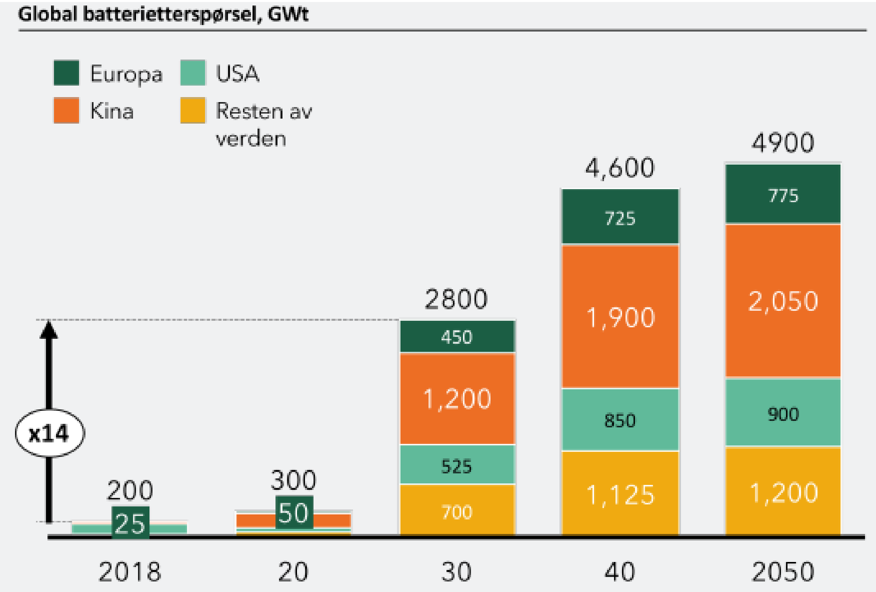

Figure 18: Global battery demand projections towards 2050 (GWh) [24].

Electrifying the transport sector will likely constitute a large part of the battery demand in the coming decades, however, an increasing need for batteries is also identified in other applications. With the expected growth in electricity demand from electric vehicles, and the rate of which variable renewable energy is displacing fossil fuels, the need to relieve and stabilize the transmission grid is increasing. In fact, stationary batteries are already operating worldwide in grid connected installations for these purposes. Moreover, Bloomberg New Energy Finance estimate stationary battery capacity to be 122 times greater in 2040 compared to 2018 [25].

However, the rising demand for Li-ion batteries bring challenges to the battery value chain. Most critical is the dependency on certain raw and refined materials such as cobalt, nickel and lithium, in which both long-term and temporary shortages are expected. In light of the Ukrainian invasion, the importance of geopolitical factors on the availability of raw materials has also been evident. Moreover, battery manufacturing has a significant environmental and social impact, in terms of water utilization and CO_2 emissions [26]. One means to address these concerns, is to consider reuse of EV (and other) batteries in new applications, to enhance the circular battery economy.

The strong uptake of electric vehicles and maritime batteries during the next decades will result in the availability of several terawatt-hours of batteries that no longer meet the required specifications for first-life usage. These batteries can, however, perform sufficiently to serve less-demanding applications, including stationary energy-storage services, and therefore play an important role in meeting the growing battery demand. Based on analysis made by McKinsey, second-life batteries can provide substantial economic benefits as they can become 30-70% less expensive compared to using new batteries in stationary applications in 2025 [27].

6.2 Second-life battery applications today

Second-life batteries are already widely used in various applications across Europe and is increasingly gaining interest by electric automakers, as well as sustainable businesses. As more and more companies define ambitious targets towards increased sustainability and even CO2-neutrality, the use of local produced renewable energy to cover self-consumption is becoming increasingly common. In particular, solar rooftop installations have escalated in recent years, both in the residential and commercial sector. By creating combined solar-plus-battery systems, consumers can gain on reduced electricity bill, and at the same time provide demand side flexibility that can further unlock the integration of higher shares of variable renewables in the grid. Stationary battery energy storage for buildings is one of the common second-life applications today, having less-demanding requirements on the cycle and rate performance. These batteries often deliver more than one function, such as providing back-up power, increasing renewable energy generation, reducing peak demand and stabilizing the grid through frequency regulation.

The authors of [28] performed a comprehensive survey of industrial projects using second-life batteries and listed them in a timeline from 2010 to 2020. Some of the most typical applications found in the study included low-speed electric bicycles and motor cars, small scale distributed ESSs for homes and street lighting, large-scale stationary ESSs, and portable charging devices. They found four main trends: 1) number of projects have increased dramatically the last 3 years leading up to 2021, 2) almost all major automotive original equipment manufacturers (OEMs) have, or are planning to, launch second-life projects, 3) large-scale stationary ESS are becoming more popular, and 4) types of applications are diversifying. In the following, some of the larger and more recent projects in Norway and Europe has been presented.

6.2.1 Commercial applications for second-life batteries

<u>Harbor/industry area – Borg Havn in Norway [29]</u>

Description: Pilot project for implementing energy storage solution. An industry area where second-life batteries are used as a battery bank for storing electricity produced by local solar panels. Solar panels supply shore power to vessels, port cranes, warehouses, refrigeration etc. Battery bank is placed in a 10-foot container.

Aim: Reduce reinvestments in larger infrastructure for energy production and distribution, reduce peak demands and provide increased flexibility.

Capacity: 90 kW/ 195 kWh

System provider: Batteriretur, Pixii

Johan Cruyff Arena in Amsterdam [30]

Description: Stadium in Amsterdam where batteries are used to store energy produced by solar rooftop panels. The system combines 148 used (Nissan leaf) and new batteries, whereof 40% is 2ND life. They aimed at accepting second-life battery cells with a SoH of <82%.

Aim: Deliver backup power during highly attended events, reduce the use of diesel generators, provide frequency reserve, peak shaving and optimization of PV integration. 14 EV chargers and one V2G unit is also installed.

Capacity: 3 MW/ 2.8 MWh.

System provider: Eaton, The Mobility House

Bislett stadium Norway (xStorage buildings) [31]

Description: Sports stadium in Norway where used Nissan Leaf battery modules have been repurposed to 3x30 battery packs, which are used to store energy produced by solar rooftop panels.

Aim: Deliver backup power, peak shaving, optimize PV integration and reduce emissions.

Capacity: 100 kW, 109 kWh.

System provider: Eaton

Jærhagen shopping mall (xStorage buildings) [32]

Description: The first commercial building in Norway that produces electricity for customers' electric vehicles through solar panels and a separate battery bank. The battery bank consists of three xStorage Home units, based on used Nissan Leaf batteries.

Aim: first and foremost, cover electricity demand from customers' electric vehicles and demand from other parts of the mall (mainly Coop Mega) in the case of superfluous power. In addition, enable peak shaving and reduced electricity bill.

Capacity: 3 x 5 kWh.

System provider: Eaton, Smartly

6.2.2 Residential applications for second-life batteries

xStorage Home (e.g., Skjold Stall and Solvang condominium) [33]

Description: Recycled battery cells from Nissan Leaf vehicles are integrated in the electrical facility of the residence. The idea is for the battery to charge at night and discharge at day in hours of high demand. In many projects, residences are also equipped with solar panels. Project pilots exist in Norway, Spain, Germany, the Netherlands and Bulgaria. Effect based tariffs makes solution more attractive in Norway.

Aim: Reduce electricity bill, defer investments in transmission and distribution grid, peak shaving, optimize PV integration.

Capacity: 3.6-6 kW, 4.2-10.08 kWh.

System provider: Eaton, Smartly

Powervault 3eco smart home battery [34]

Description: Partnership between Powervault and Renault, re-using EV batteries in home energy storage units. 50 trial units have been placed in homes in the UK who already have solar panels installed, with the purpose to explore the technical performance of 2nd life batteries and the customer reaction.

Aim: Reduce energy bills by storing solar energy or electricity from the grid, provide grid services.

Capacity: 3.9, 5.9 and 7.9 kWh.

System provider: Powervault

6.2.3 Stationary batteries for grid stabilization

Energy storage at Umicore [35]

Description: Industrial battery system implemented at Umicore's Olen site, consisting of 48 used Renault EV batteries, forming one large stationary storage. In the second life application, each battery has available capacity of 15-17 kWh (from nominal capacity of 22 kWh).
Aim: Support the electricity grid by providing primary reserve. Umicore aim to learn and identify opportunities in the balancing market, frequency containment market or smart energy management, as well as achieving a healthy internal rate of return (IRR).
Capacity: 1.2 MW, 720 kWh.
System provider: Connected Energy (E-STOR)

Stationary storage Audi & EnBW [36]

Description: Joint pilot storage facility in Heilbronn between EnBW and Audi, using EV batteries from Audi cars. The site function as a reference storage facility to test various use scenarios of the combined heat and power plant. Eventually, EnBW would develop similar tools for sale to industrial power customers, local utilities, or decentralized generation plants.
Aim: Store surplus renewable energy and support the grid.
Capacity: 5 MW [37].
System provider: EnBW

BMW Battery storage farm [38]

Description: Battery storage farm in Leipzig which connect 500 BMW i3 high-capacity batteries (out of total 700). The batteries are used to temporarily store electricity produced by local wind turbines and have also been integrated into the public power grid to provide primary balancing power.
Aim: Optimize local energy management, balance peak loads and stabilize the power grid.
Capacity: 15 MWh, 10 MW.
System provider: BMW Group

6.2.4 Charging stations with second-life batteries

Renault off-grid [39]:

Renault's Zoe program involves leasing the battery pack for a monthly fee. Some of these used battery packs are used in a second life to power electric vehicle charging stations. They currently exist on highways in Belgium and Germany, locations where constructing a high power connection to the power grid is very costly. The battery packs are powered using onsite solar arrays or micro wind turbines.
System provider: Connected Energy (E-STOR)

Volkswagen mobile charging [40]:

Mobile quick charging stations which work according to the principle of a power bank. It can be implemented without a power supply, meaning that the charging station is exchanged for a new charged one when the energy content goes below 20%. Alternatively, it can permanently be connected to a power supply with up to 30 kW, in which the battery recharges itself. It has a charging capacity of 340 kWh, enabling 15 e-vehicles (Volkswagen ID) to be charged in stand-alone operation. Up to 4 vehicles can be charged simultaneously. Charging station also offer the possibility of temporarily storing power (if connected to grid). Flexible location can be found via apps.
System provider: Volkswagen Group Components.

7 Conclusion

With increased market share of EV's, the total battery capacity for the passenger vehicle fleet in Norway is expected to be approximately 81 GWh in 2030 and increase to an estimated range of 200-370 GWh in 2050. Including also other vehicle segments, the Norwegian vehicle fleet can potentially exceed battery volumes of 600 GWh in 2050. For the capacity available for 2nd life applications, TØI estimate approximately 1.5 GWh from used EVs by 2030, considering the scrapping rate and the state of health of the batteries when reaching end-of-life. In terms of maritime batteries, a rough estimate based on historical data indicate that, by 2030, approximately 43 MWh can be available from ships operating in European sea waters. The largest share derives from the car and passenger ferries. The amounts are small compared to that of EVs, however, with worldwide targets of zero-emission socities, the battery volumes in the maritime sector is expected to increase substantialy by 2050.

The most common battery chemistry for both EV and maritime batteries is NMC. While electric vehicle also uses NCA and LMO batteries, maritime ships tend more towards LFP and LTO batteries due to higher safety. When considering the development at longer time scales, there is large uncertainty in terms of which battery chemistries will be dominating, dependent on energy density, safety, and the availability of raw materials. Given both the cobalt scarcity and the superior life cycle of LFP batteries, there is a potential for this battery chemistry to rise both in the automotive and maritime industry.

The quality of 2nd life batteries will be dependent on conditions during which the battery has been operated in, such as the state of charge, depth of discharge, C-rate and temperature. Also, the calendar lifetime is of importance. This large variation of parameters makes it challenging to predict battery degradation speed, imposing significant uncertainty about battery turn-over rate in vehicle fleets and expected battery state of health when the vehicles are scrapped. Results from degradation models show, however, a general tendency of lower capacity loss when battery is cycled within lower SoC and DoD levels. Studies also indicate that operating the battery at very high or low temperatures largely accelerates degradation.

There is no doubt that the market for 2nd life batteries is substantial, with global battery demand estimated to grow by 25 times to 2050. Suitable applications for 2nd life batteries, on a national and international scale, depends largely on the operation of the battery at 1st life and the safety requirements at the respective application. Some of the most common use cases in Europe today are small scale distributed energy storage for residential buildings, large-scale stationary energy storage for commercial buildings, grid stabilization, and powering EV charging stations. In many cases, battery storage is combined with transient, renewable energy sources in a hybrid system. Moreover, the batteries are often used to serve multiple applications simultaneously, such as increasing self-consumption, reducing the demand charge, and delivering back-up power.

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