IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received 16 March 2023, accepted 30 March 2023, date of publication 6 April 2023, date of current version 12 April 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3265168

TOPICAL REVIEW

Second Life Management From Battery Storage System of Electric Waterborne Transport Applications: Perspectives and Solutions

FABIO MANDRILE[1], **(Member, IEEE), MICHELE PASTORELLI**[1], **(Member, IEEE),**
SALVATORE MUSUMECI[1], **(Member, IEEE), IÑAKI AMILLETA URKIRI**[2],
AND ADRIAN REMIREZ[2]
[1]Dipartimento Energia "Galileo Ferraris," Politecnico di Torino, 10129 Turin, Italy
[2]Ikerlan Technology Research Centre, Basque Research and Technology Alliance (BRTA), 20500 Arrasate-Mondragon, Spain

Corresponding author: Fabio Mandrile (fabio.mandrile@polito.it)

This work was supported by the European Union Horizon 2020 "Solutions for largE bAtteries for waterBorne trAnsporT (SEABAT)" under Grant 963560.

ABSTRACT In electric naval applications, battery storage management plays a key role. The second-life battery use is a fundamental part of the sustainable development of these waterborne transport systems. The article deals with the perspective and solutions of the second-life storage battery systems from the electric ship traction area. This paper presents an overview of the topic of second-life use, application, and future direction with a special focus on battery systems from electric propulsion ships. In particular, a modular converter-battery approach in the storage system structure arrangement is considered. The modular battery storage approach in electric naval propulsion applications is the target of SEABAT project. This proposed solution allows both controls of the electrical quantities of the storage output and monitoring of the battery's electrical parameters to always have its health status available. The advantages of the modular multilevel battery-converter structure developed within the SEABAT project towards second-life use are presented and evaluated, leading to an estimated cost saving of 35% during the whole life time of the batteries. Besides, the integration of multiple battery technology with different degradation state is enabled. Moreover, the power converter features for second-life applications are explored and discussed. Furthermore, the manufacturing and disassembly processes aspects of the SEABAT converter-battery system (CBS) are also investigated to validate the effectiveness of the proposed modular storage solution. The SEABAT project targets a 246 kWh demonstrator with a 1000 V output.

INDEX TERMS Battery storage system (BESS), shipboard power system (SPS), second life, batteries.

I. INTRODUCTION

Electric traction systems are expanding strongly beyond electric vehicles (EVs) applications. It involves all fields of the sustainable development of people's transport. Nowadays, the area of waterborne electric transport applications is of particular interest [1]. In this type of transport, huge volumes of storage systems are required, since the complex electrical system involves different energy sources and actuators [2] (see Fig. 1). The storage units require proper allocation and specific battery management system (BMS) [3], [4]. In the field of electrification of naval propulsion systems, the SEABAT[1] project deals with the development of modular storage systems for pure electric vessels [5]. The modular approach is very attractive and produces remarkable features. Each module is composed of a battery unit with a direct current to direct current (DC/DC) converter that controls the electrical output quantities based on the BMS demand. In the event of degradation or failure, a module can be easily replaced without deteriorating or making the entire

The associate editor coordinating the review of this manuscript and approving it for publication was Vitor Monteiro.

---

[1] Solutions for largE bAtteries for waterBorne trAnsporT.

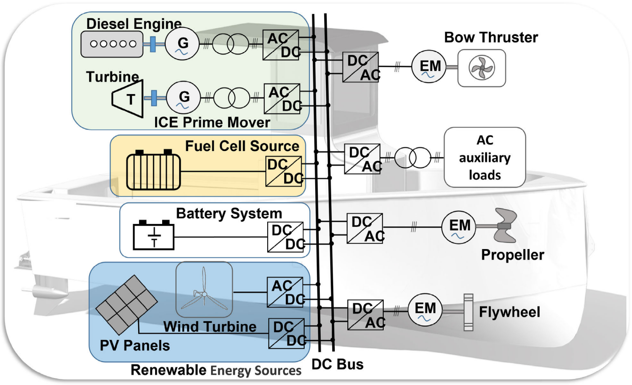


FIGURE 1. Ship electric power system diagram.

storage system unusable. The modular approach arrangement deeper described later in the article has a very positive impact on the second-life use of batteries.[2] The presence of the converter-battery system (CBS) allows adjusting of the output quantities and the contemporary monitoring of the battery status. The objective is to monitor the second-life battery usage from high degradation, optimizing lifetime and cost savings [6]. The monitoring of the battery status through the combined use of the converter regulation characteristics and specific sensor systems leads to the knowledge, in an effective way, of the battery performance. The technical literature does not yet deal with battery systems management for waterborne electric transport applications that also consider their future use in second-life applications. Therefore, the contribution of this paper is to apply a modular battery-converter pack approach for naval systems oriented to their optimal second-life usage. This technological approach is fruitful for a more appropriate and flexible second use of the CBS modules in several applications, as described in the following sections. The article starts with a comprehensive description of second-life battery system applications considering stationary storage (on-grid and off-grid), residential storage, commercial sector, and industrial applications. Furthermore, a brief note on international standards concerning the second use of batteries is reported. For this overview both scientific papers and project reports were considered, dating back to early 2000s. While the scientific papers focus more on the challenges and opportunity of second-life batteries, project reports present actual results of field tests and demonstrators. In total, more than 70 papers were analyzed and among them several previous review works. Then, the modular approach solution of CBS employed in the SEABAT project is presented and critically analyzed concerning both the employment in the vessel and the second life use of the whole CBS module. Moreover, the manufacturing and disassembly processes issues of the battery pack have been evaluated.

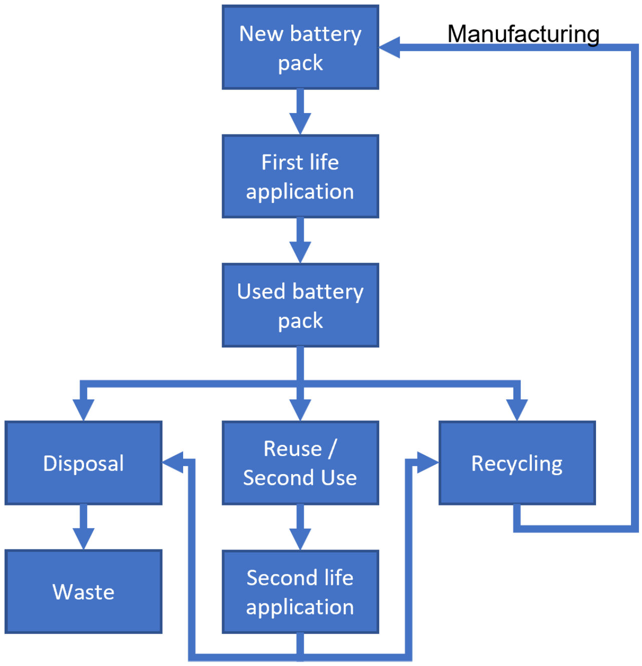


FIGURE 2. Life-cycle of battery packs [11], [12].

II. SECOND LIFE

The significant growth of battery electric vehicles (BEVs) is now posing the question of the future of the batteries currently being installed in such vehicles. It is in fact common practice to consider an EV battery to be at the end of its life (EOL) when its capacity drops 20% with respect to its rated value [7]. This means that EOL batteries from EVs still retain a significant potential for further use, even though not for the same original purpose. Therefore, it is possible and reasonable to consider a battery life cycle as the one depicted in Fig.2. First, the batteries are manufactured and a new battery pack is available. Then, they are employed in their first life application, such as EVs or maritime systems. At the end of first life, they can face one of the following three paths:

1) Disposal: the batteries are not used for any other productive use, but they become a waste product, which must be properly handled [8], [9];
2) Recycling: a second possibility is to dismantle the battery systems and use the raw materials to build new battery systems [9], [10];
3) Reuse/second use: this third option is to take the battery systems and employ them in other context and applications. This opens up to a second life application for such batteries and it will be further discussed in this section

It is worth mentioning that reuse and second use are often used as synonyms and there is no official and clear definition of the difference between them. However, [13] provides a bit more precise definition of these terms as follows:

- Reuse is intended as using the battery system again for the same goal. For example, a traction battery of

---

[2] Second life batteries (SLBs) are ones that have reached the end of their first life (not enough capacity left for their application) but still have a residual capacity of about 70-80%.

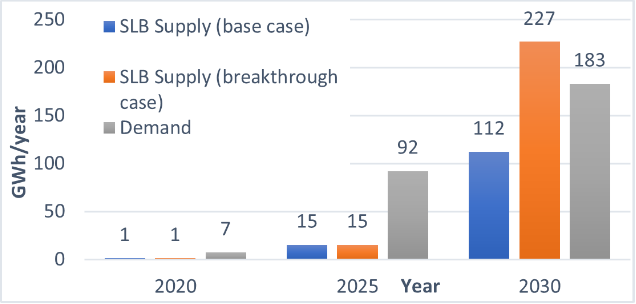


FIGURE 3. Forecast of SLBs availability and demand. Data from [11].

a BEV can be used again in another BEV with lower performance and requirements;

- Second use (or second life) involves employing the battery for a different application than the original one. For example employing a traction battery in a stationary grid application.

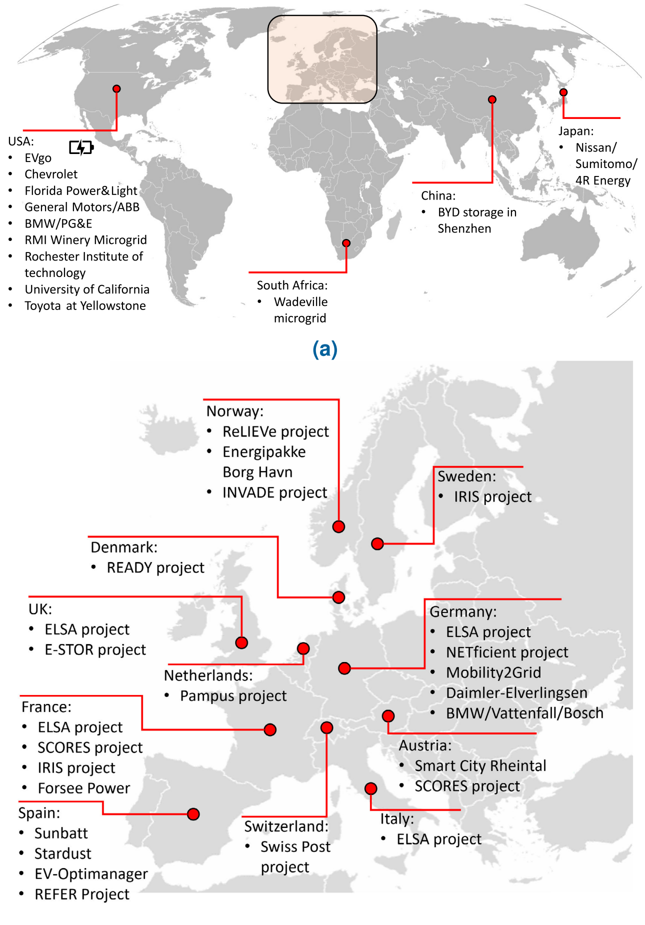
In this section both meanings are considered, and possible applications will be presented for both cases. Despite the definitions, the option of reusing the battery systems has become more and more appealing in the last years thanks to the following advantages:

1) Compared to disposal of batteries, reuse/second use avoids immediate disposal of resources and the consequent pollution;
2) Recycling is currently a cost intensive activity if it targets the recovery of the most precious materials of battery packs (e.g., lithium, aluminum, cobalt...). Therefore, it is often economically not justified compared to the mining of these materials [14].

Moreover, according to the recent forecasts [11] shown in Fig. 3, there will be a large availability of second life batteries (SLBs) from EVs both in the most conservative (base case) and the most optimistic cases (breakthrough case). This increase in the availability would well match the demand of such SLBs, for example in utility-scale storage systems for stationary applications, which will likely increase at a similar pace. However, not only the automotive sector will be a source of potential second-life batteries. It is in fact an ongoing trend to electrify ships [15]. It is therefore expected to have a large battery capacity decommissioned from ships currently being built at the end of their first life. In this outlook, this paper tries to focus and discuss the need of proper design choices for first life battery storage systems with the perspective of their reuse.

To support these considerations and to explore the possibilities of battery reuse, some demonstration projects were conducted in the past 10 years [12], [13], [14] and they are reported in Figs. 4a and 4b. Among the most notable in terms of installed power/energy or technical features, the following can be mentioned:

1) BMW, Vattenfall and Bosch 2 MW, 2800 kWh storage system employing second life batteries for grid frequency support [16].



(a)

(b)

FIGURE 4. Notable second use projects in the world (a) and a focus on Europe (b). Data from [13], [14], [18].

2) Lamar Buffalo Ranch at the Yellowstone National Park stand-alone 85 kWh by Toyota [17]. This system supports a 40 kW photovoltaic system and it uses the original battery containers, just replacing the connections between them. Of particular interest is the fault tolerance of the system, being able to function after a single battery unit failure and the easiness of repair.

A. LIFE TIME ISSUE

The protection of the second-life battery is related to monitoring and controlling its electrical parameters as well as the charging methods allowing for optimization of the life time and cost saving. To achieve the extension of the second-life use of the battery storage system from further degradation the batteries should not be subjected to severe charging and discharging techniques or over-charging conditions. These charge and discharge rules limit the state of charge (SOC) operation as a function of the time t in the following way:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \qquad (1)$$

where SOC_{min} is the minimum acceptable state of charge during the battery discharging phase (e.g., in the range 20%-35%

SOC) and SOC_{max} is the maximum suitable state of charge at battery charging condition (e.g., 90%-95% SOC) [19], [20], [21]. To correctly manage the battery SOC, also alternative methods based on state of available power (SoAP) prediction could be useful. The work in [22] provides and algorithm to estimate the remaining energy for discharge of a battery. The paper [23] introduces a Wavelet-Markov load analysis to predict the SoAP by supervising the working conditions to predict future load. Charging methods allowing for optimization of the life time and cost savings are also of great importance and new techniques are being proposed in the technical literature. Among them, it is worth mentioning [24], which proposes a deep reinforcement learning strategy for fast charging of lithium-ion (Li-ion) batteries and [25], where deep reinforcement learning is exploited to optimize intelligently the power allocation in a hybrid-electric bus. Moreover, [26] proposed fast charging strategies with the goal of minimizing lithium plating. Particular care must be also taken if the batteries are operated in vehicle to grid (V2G) mode during their first life. To this purpose SOC pre-conditioning strategies were proposed [27] to minimize the battery degradation.

The life time of second-life battery expected is a crucial issue in the application use of these storage system [28]. The prediction method is a research key point. Same interesting methodology are described in [29], [30]. In [31], a simplified equation is discussed to achieve a life time considering the actual charge life of a battery cell as a function of the depth of discharge (DoD) and several data parameters related to the battery usage and the capacity C. A simplified equation attained is

$$L_f = \frac{L_{CF} \cdot D_{CF} \cdot C_{RD}}{\sum_{i=1}^{n} d_{eff,i}} \cdot T \tag{2}$$

where L_f is the life time of battery, D_{CF} is the DoD at which rated cycle life was determined, L_{CF} is the cycle life at rated DoD, D_{CF} and at related discharging current $i_{discharge}$, C_{RD} is the rated amp-hour capacity at rated discharge current, T is the time of the estimated system operation and d_{eff} is the effective discharge parameter. The d_{eff} parameter is related to actual capacity at discharge current (C_a), the rated ampere-hour capacity at rated discharge (C_{RD}), and the ampere-hour of the discharge event (d_{act}) as described in (3) [31].

$$d_{eff} = \frac{C_{RD}}{C_a} \cdot d_{act} \tag{3}$$

Unfortunately, the state of degradation of the second life battery is not assured with certainty [6]. Therefore, the monitoring of the battery parameters during the actual use in its "first life" is a fundamental point to estimate the state of health of the battery storage system in the outlook of its second life [32]. To this purpose, the literature presents some examples [33] of advanced smart sensors at cell level for battery monitoring and management. These sensors are able to sense and process the multi-dimensional quantities (electrical, mechanical and thermal), which influence the battery performance and [34] can provide a better estimate of the battery aging during its first life. Moreover, various state of health estimation techniques are available in the literature. Among them, it is worth mentioning model-based methods [35] and data-based methods [36], using artificial neural networks working on health indicators. Furthermore, in [37] is demonstrated how the battery internal impedance can be used to provide predictive information about the battery viability for second-life applications. From this point of view the measurement of the battery electrical quantities are crucial to second life application. Finally, [38] presents a review of artificial intelligence (AI) based solutions to increase the lifetime of the batteries by acting both on their manufacturing and management.

III. SECOND USE APPLICATIONS

As introduced in the previous section, several application examples are currently devised [12], [13], [14], [39]. In general, two main applications are foreseeable:

1) Replacement of Lead-acid batteries;
2) Grid-connected stationary storage.

A. REPLACEMENT OF LEAD-ACID BATTERIES

This first possible application is still in a very early stage, but due to their favorable properties (e.g., energy density), Li-ion batteries could outperform traditional lead-acid batteries. Example relevant applications include automotive starting and lighting, automotive start-stop systems, industrial forklifts and uninterruptible power supplies (UPSs). Given a competitive price for second use batteries, it is possible to open up such market. On the other hand, due to the use profile of lead-acid batteries, it is necessary to study this application more carefully. In fact, lead-acid batteries are often used in low energy ($<$1kWh), pulsed power applications (e.g., starting of a car). Therefore, the large capacity batteries coming from traction systems should need an adaptation process and would be challenged by the power profile demand.

B. STATIONARY STORAGE

The second and more promising application for second use batteries is represented by stationary storage (on-grid and off-grid). In general, such application is very appealing for second life batteries as it requires relatively large storage capacities but with less sever size and weight constraints and lower cycling requirements (both in number of cycles per day and C-rate of charge/discharge). Moreover, the ongoing decarbonization process of the energy sector and the consequent rise in intermittent renewable energy sources will push the demand for grid-connected storage systems to higher levels. More in detail, Table 1 summarizes the various grid-connected options for second life batteries. As it immediately emerges from the table, the cycling of the batteries is much less frequent than in traction application (one cycle per day in the worst cases) and the C-rate at which the battery is subject is much smaller ($\leq$0.5 C) than the one typical of traction applications.

In general, it is possible to define three main operating fields: residential, commercial and industrial.

Moreover, the following types of operation can be devised for second life batteries:

1) Load following: in this operation the storage system supplies the loads when the power source production is not enough. This kind of operation is intended for a short time span ranging from minutes to hours;
2) Load leveling: this involves trying to level and "smooth" the load demand during the day, by leveraging the storage system. Therefore, this can favor cheaper baseload generation.
3) Peak shaving: this is like load following, but it is mostly intended to reduce the overall installed capacity.
4) Back-up systems (UPSs): UPSs are usually supplying critical loads, which cannot be disconnected (e.g., medical, data centers...)
5) Transmission quality and stabilization: this action is mostly intended in the high voltage transmission network and has the goal of improving its quality by providing voltage and frequency support.
6) Spinning reserve and area regulation: again, this is intended at higher power and voltage levels but with the goal of balancing any generation outages or sudden large load demands.
7) Renewable energy sources: in case of high penetration of renewable non-programmable sources, it is important to provide storage capacity to smooth out any sudden production fluctuation (e.g., clouds shading photovoltaic (PV) plants)

In the following sections the presented modes of operation will be discussed for each application field, highlighting which and where they are more feasible.

C. RESIDENTIAL APPLICATIONS

The recent shift towards distributed generation has pushed up the amount of power generation installed in domestic household. The figures, graphed in Fig. 5, show that this sector would demand a significant energy storage to save energy produced during daytime and discharge it in the evening, when there is typically a peak in domestic load curves. Both the energy and power rating of single domestic storage units are well within the achievable performance of second use batteries. Therefore, it can be assumed that the residential applications are a viable market for second use batteries.

D. COMMERCIAL APPLICATIONS

Also in the commercial sector there has been an increment in the installation of PV generation and it is foreseen a rise similar to the residential sector [41]. In this case, differently from the residential load curves, the peak power absorption is usually in the middle of the day, and therefore aligned with the peak production from PV. For the commercial sector too, it would be of interest to invest on load following storage systems, which would represent a compromise between installed energy (number of second life batteries) and performance achieved.

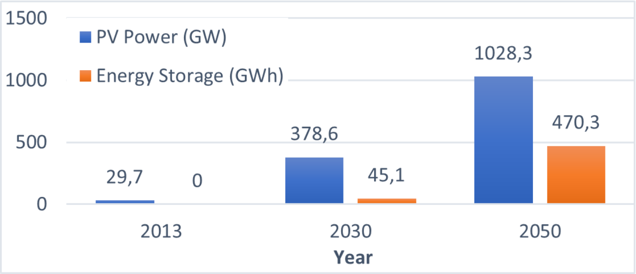


FIGURE 5. Estimated PV and storage installation in domestic households (data source [41]).

E. INDUSTRIAL APPLICATIONS

Industrial applications typically feature load curves with peaks around midday and lower demands in the night. Moreover, the amount of power required by industries is significant and it would probably discourage the use of second life batteries for load leveling applications. On the other hand, renewable energy sources applications for industrial sector would be a more promising opportunity, due to the more reduced power and energy ratings. Finally, it is safe to exclude the use of second life batteries for transmission networks stabilization, as the overall power demand (e.g., peak demand for frequency support) would greatly exceed the capabilities (C-rate) of second life batteries.

The possible applications for second life batteries can be summarized in Table 2 with a qualitative feasibility index [14].

IV. SECOND USE INTERNATIONAL STANDARDS

As for most industrial products, to enable a widespread diffusion of second use application it is useful to standardize the technical implementation of battery systems. This is nowadays a twofold issue:

- Batteries are not completely standardized in their first life (e.g., EV sector) neither in their chemistry aspects nor in their assembly and interfaces;
- There is very limited technical standardization on second life applications.

At present time, only one standard is active (UL 1974) and another one (SAE J2997) is currently under development, as summarized in Table 3. However, the challenges and goals for this standardization process are several. In general, it is thought [14], [42] that the following aspects should go under standardization process:

- Labelling and definition of the battery state of health (SOH) to facilitate the matching of different battery packs for second use. In this sense the ongoing standard SAE J2997 and the European Union steps towards the so called "Battery passport" [43] are well oriented;

TABLE 1. Grid-connected storage opportunities for second use batteries [40], [41].

Application Field	Energy Rating	Power/C Rating	Cycles
Residential load following	3-4 kWh	1 kW (0.3 C)	Daily
Light commercial load following	75-100 kWh	25 kW (0.3 C)	Daily
Load leveling	50 MWh	10 MW	100-200 days/year
Peak shaving	3-4MWh	1MW (0.5 C)	Daily to 6 times a year
Back-up systems	25-50kWh	<5kW (0.2 C)	2 times a year
Transmission quality/stabilization	100MWh	100MW	once a month
Spinning reserve/area regulation	7.5MWh	20MW (0.5 C)	once a month
Renewable firming	1-10MWh	1MW (0.25 C)	10-20 days/month

TABLE 2. Application of first and second life battery to energy storage systems [14].

Application of storage system		Use of first life batteries	Use of second life batteries
On-grid Stationary	Peak reduction	+++	+++
	Load leveling	+++	++
	Frequency regulation	+++	++
	Voltage support	++	+
Off-grid Stationary	Microgrid	+++	+++
	Power quality	+++	+
	Load following	+++	++
Mobility-related applications	EV charging stations	+++	++
	Vehicle to grid for fast charging	+++	+
	EV long trips	+++	Not feasible
	EV short trips	+++	++

- Safety management during transportation, testing and assembly to minimize the occurrence of accidents and reduce the cost of handling battery packs;
- First use application standards. Especially regarding control systems of the first application (e.g., EV), communication protocols and interfaces and base voltages (i.e., multiples of standardized levels, such as 12V, 24V...).

V. SECOND USE TECHNICAL ASPECTS

The actual implementation of a second life battery depends significantly on a series of steps leading from the first use battery up to the repurposed one. This workflow was well described in [12] and it is depicted in Fig. 6. The following key steps are highlighted:

1) Assessment of the batteries after first use using the information on their operation;
2) Disassembly;
3) Performance evaluation: mechanical, electrochemical and from the safety point of view;
4) Sorting and regrouping to match the performance;
5) Adaptation of the control strategy to the second use application;

It is therefore clear that making each of these steps more efficient and economical is a key aspect in the feasibility of second use applications.

TABLE 3. Application of first and second life battery to energy storage systems [14].

Standard	Description
SAE J2997: Standards for Battery secondary use (started 2012)	Testing and definition of batteries for safe reuse. Standard for transportation, labelling and state of health.
UL 1974: Standard for Evaluation for Repurposing Batteries (Active)	General procedure regarding safety management and performance tests on battery packs before second use. No significant details in the required steps.

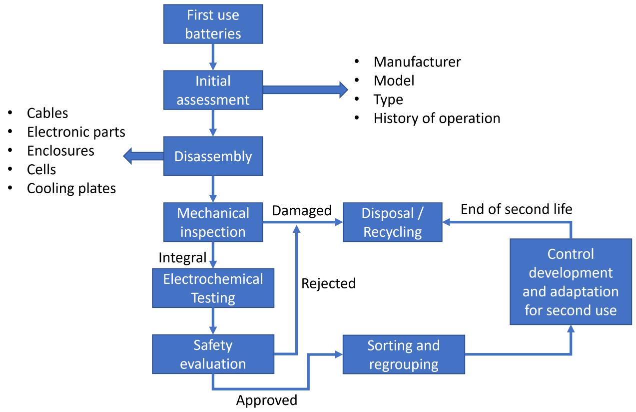


FIGURE 6. **Workflow to produce second life batteries.**

First, when batteries are retired, it is important to evaluate how they were used during their first life. This aspect can represent the ground for a first exclusion of some of them from the following process. This process would be easier if performed by the manufacturers of the battery systems themselves, since they already have potential access to much information about their first use (degradation…). If a third party (reuse company) is in charge of such analysis and sorting, then it is important to develop proper automated testing procedures to perform this first screening in the most efficient and economical way possible. Such procedures include for example data driven estimation of the states of the batteries and diagnosis based on the available information on the first use. As an alternative (in case such input data is not available), it is possible to perform a series of tests on the battery packs at a great cost of time and resources. Very promising techniques are also those based on machine learning, such as presented in [44], [45] and the ones reviewed in [46]. These techniques are well suited to classify cell electrodes according to key indicators, such as the electrode thickness and conductivity. The second phase (disassembly) involves the mechanical steps to separate the battery pack in more fundamental components. Therefore, it is important that the first life manufacturers properly design and built the batteries to facilitate disassembly. Moreover, it is advisable to design the first use battery packs in a more standardize way and already oriented to second use application, therefore reducing the cost of modifications in a later stage. To stress the importance of this disassembly phase, it is worth mentioning an example of today's cost of battery disassembling. As calculated in [47], the disassembling effort for a Smart ForFour battery pack up to module level requires around 71 $/kWh and 800 min/pack. This must be compared with the price of a new first life battery pack, that is expected to be in the range of 100-150 $/kWh in the next 5 years [48]. Therefore, the cost of a second life battery would already be half the price of a new battery only including the disassembly cost, without the further expenses of additional hardware and tests.

After the disassembly step is done, it is necessary to move to a mechanical inspection of the batteries. This phase is a first screening of any safety risk that might derive from the cell and any damaged parts are immediately discarded and sent to disposal or recycling. Nowadays, this process is performed by human operators, who visually inspect the cells or modules [12]. Unfortunately, this is quite an expensive, unreliable and potentially dangerous way of performing this task. Therefore, there is ongoing research on alternative automated techniques to perform this process.

All the cells which passed the mechanical inspection, are then measured for their electrochemical parameters. This phase involves the characterization of their internal open circuit voltage (OCV), resistance and capacity. Depending on the results of these measurements, the cells are discarded (for example if the OCV is too low) or considered for second use. Apart from the basic electrochemical tests, it is important also to perform some estimation of the remaining useful life and the SOH of such batteries. In this sense, it is key to develop automatic prognostic and estimation methods based on the test data and possibly information on their operating history during first life [49].

Once the electrochemical tests have been performed, it has become crucial to carefully evaluate the safety of the batteries for second use. In the past few years, several fires and accidents related to batteries were reported, therefore pushing towards stricter standards even for first life batteries. It is of paramount importance that second use batteries are inspected and checked even for minor defects and flaws to avoid serious safety risks in their following use. This process as well should be as automated as possible leveraging specialized test algorithms and specific safety tests on the batteries that are expected to be most damaged according to their first life history.

The batteries approved after the safety evaluation can then be sorted and regrouped according to their electrochemical performance. The goal of this phase is to match as well as possible the cells and modules together to minimize the variations and differences among them. Being this already important for first life batteries, it is crucial for second life ones, being potentially much more diverse from each other. To perform this process, several grouping criteria are available, such as SOH, SOC and more advanced indicators to quantify their degradation [12].

Finally, the selected batteries are ready for the final step of their repurposing. This involves proper control algorithms to manage the cells differences and detect and tackle any fault that may emerge during second life. Moreover, it is necessary to develop or adapt the internal battery management systems to the interfaces and needs of the second life application in terms of communications, sensors and protections.

A. POWER CONVERTER FEATURES FOR SECOND LIFE APPLICATIONS

An important factor in the last adaptation phase of batteries to second use is represented by the power conversion stage between the batteries and the final application and

TABLE 4. Comparison of the operating conditions and requirements between first and second life [14], [50].

	First Life	Second Life
Nominal voltage rating	400 V	800 V- 1000 V
Operating hours in 10 years	Typ 16800 h	Max 87600 h
Ambient temperature range	-40°C to 60°C	10°C to 35°C
C-rate	2-3 C continuous and >5C peak	<0.5C continuous and 0.5-2C peak
Cooling	Active (air, liquid)	Passive apart from critical use cases
Vibrations	Severe (vehicle)	None
SOH at begin	100%	70-90%
Control	Vehicle battery management	Grid-storage control (frequency control, load following...)
Maintenance	Limited	Frequent
Size	Small (must fit EV)	Can afford larger sizes

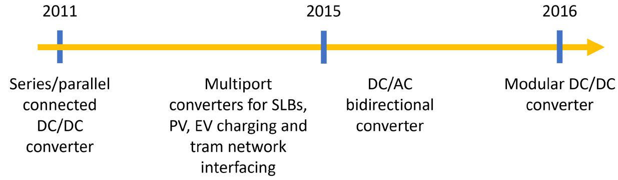


FIGURE 7. Power converters for second life batteries interfacing.

the hardware installation of the battery storage. In general, the batteries are interfaced by either a DC/DC or a direct current to alternating current (DC/AC) converter to the final application and are housed in cabinets and containers. In general, the transition from first to second life involves a series of modifications summarized in Table 4. These modifications include a different operating voltage, as typically the EV powertrains are rated 400 V DC, while grid-connected applications require higher voltages. This can be for example achieved by series connection of multiple packs as in [20] or by using dedicated DC/DC converters. Moreover, the environmental operating conditions and the expecting operating hours are radically different from first to second life. While first life applications (traction) are designed to operate for shorter hours but in very critical thermal and mechanical conditions, the grid-connected application feature a less stressful environment with less critical temperatures and vibrations. However, this comes at the cost of much longer operating hours (virtually 24/7) and therefore putting more stress on the reliability aspects.

As mentioned before, it is important to define the most efficient and economic conversion structure for second life applications. In the literature there have been several proposals of power conversion structures. The most notable have been summarized in Fig. 7.

First in 2011 it was proposed a series/parallel DC/DC conversion structure [51] able to equalize the exploitation of the various batteries, despite the different usable energies. The advantage of this solution lies in the flexibility to modules with different conditions and it enables also the replacement of exhausted ones. Then in 2015 two solutions were proposed. Paper [52] details a specific solution of a multiport DC/DC interface for not only second life batteries, but also for PV generation, EV chargers and the tram DC network. On the other hand, [23] focused on an integrated residential solution for an integrated PV and storage systems with a balancing circuit for batteries to compensate for their inequalities. Finally, a very promising solution was detailed in 2016 [53] where a modular multilevel buck DC/DC converter was proposed to interface several units (depending on the voltage levels involved) to a grid-converter. This solution has several degrees of freedom, being able to charge/discharge the unit batteries and exploit them in a different way, according to their SOC or SOH, ensuring the greatest conversion flexibility.

VI. ADVANTAGES OF SEABAT BATTERY SYSTEM FOR SECOND LIFE APPLICATIONS

Before explaining the features and advantages that the SEABAT concept offers towards second life, it is of interest to mention a few key differences between waterborne transport batteries and automotive. The first important difference lies in the energy and power density of the storage systems: maritime batteries are currently less energy/power dense compared to the automotive counterparts [54], [55]. This is due to more relaxed form constraints on the battery packs. Then, ship batteries are currently designed to be hosted into racks and cabinets [54] for easier installation and maintenance. On the other hand, automotive batteries are highly integrated in the car frame and cannot be disassembled or even accessed easily. Furthermore, automotive applications have a limited DC voltage (e.g., 400 V to 800 V in most recent designs), while 1000 V supplies are quite widespread in the maritime sector. For these reasons, maritime storage systems could be more easily repurposed to second life applications. This trend of modular battery systems is becoming popular in several applications. A power converter system in the module battery pack arrangement is crucial since it permits a controlled, secure, and efficient power exchange with the energy storage system connected [56]. The electrification of different areas, such as transportation systems, industrial applications, and utility sites, has driven the strongest development of modular battery arrangements. For example, Tesla brought forward the Powerpack system, which gave a big boost to the concept of modularity in the use of battery packs [57]. The paper [58] suggests a qualitative comparison among different

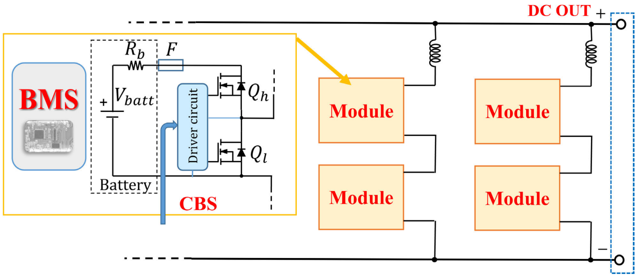


FIGURE 8. General block diagram of the adopted SEABAT solution.

power converter systems for a general approach to a modular solution of a battery storage system connected to a grid. Another point of interest is the storage container layout that contains the battery pack and the power converter to obtain the module arrangement [59]. In the SEABAT project, the modular CBS approach extends and develops the modular battery pack solution for naval applications. The CBS solution permits to optimization of the performance of the battery storage system. With a suitable container layout, the CBS can realize a different modular arrangement based on the requested power rate.

In this outlook, the selected topology for the SEABAT project is a hybrid energy storage system, interfacing two or more battery chemistries to the shipboard system thanks to a modular multilevel structure and it is depicted in Fig. 8. This solution features several advantages [20], [60]. The first advantage is the reduced oversizing in battery capacity. In fact, thanks to the adopted modular approach, the degradation is leveled out between modules and it does not depend on the weakest cell of the system, leading to an overall better utilization of the cells. Moreover, the total cost of the battery system is expected to be reduced. Even though the installation costs are larger compared to a standard monotype battery solution (more complicated structure and more power electronics is needed), the SEABAT concept can lead to a lower cost during the battery system lifetime. This is thanks to the lower maintenance and replacement costs, as single units of the system can be replaced, differently from a standard battery pack. Moreover, the SEABAT solution can exploit cells of different chemistries, integrating them in a modular system. This would allow better tailored storage capacity for the application and benefit from the cost reduction of a larger production of standardized electrical equipment (i.e., same power converters, filter inductors, fuses. . .).

To make second-life possible, the repurposed batteries must feature an advantageous cost vs performance ratio, so that they could become attractive compared to new batteries [46]. The trade-off between cost and performance is a figure of merit directly to the specific sector and reuse of the batteries. Since a limited number of projects are running the evaluations are still on going and partial results are available. In the literature some analysis of specific uses cases of second life batteries are available [61] and the results were accepted from the economic point of view. Reference [62] studied the feasibility of a utility-scale solar plant using second life batteries, demonstrating how second life batteries can be more profitable than new ones, provided a careful management of their SoC. The work by Rallo et al. [63] demonstrated using two real cases how some applications (in that case energy arbitrage) are more profitable when dealing with SLBs and also provided few guidelines to optimize these SLB storage systems. Specific results of SLB in SEABAT project are not yet available, but SLB was taken into account during the design process to reduce the adaptation effort towards second life, thanks to the following aspects. The base unit of the SEABAT battery system will be a converter with a battery voltage around 100 V. Then, several of these units will be connected in series in strings to reach the target output voltage and several strings will be connected in parallel to increase the current capacity. This approach is beneficial for a future reuse of these batteries, as they could be relatively easily reconfigured for different voltage levels and current ratings (e.g., larger output current at lower voltage). Moreover, the adopted structure is very flexible in terms of adopted chemistry. In fact, the chemistry of each module could potentially be different from the others without being a prejudice to the system's functionality. This represents a very strong advantage when sorting and regrouping cells after first use. In fact, such conversion structure (power electronics switches) could be reused with minor changes to match together modules with different degradation levels and then exploiting them according to their SOH. Finally, it is a current trend to look into hybrid energy storage systems for grid applications to reduce the oversizing of the storage systems and extend the lifetime of such battery systems [64], [65]. In this outlook, the SEABAT structure would be immediately ready and reusable in such systems, easily integrating arbitrary battery or storage technologies in the same system. To facilitate this integration, the SEABAT project also carried out a detailed analysis of the possible target ships, defining the most promising ones [66]. Document [15] reports the main sectors where electrification may benefit ship propulsion. Moreover, there is also a focus regarding the robustness of the solution, report [67] clearly states the requirements for the storage system, not only from the performance point of view, but also regarding the safety and risk mitigation. Moreover, the project is currently tackling in detail possible sources of risks and failures. The SEABAT battery system has been designed to operate for 10 years. The estimated size of the storage proposed by SEABAT is reported in [68]. The expected string cabined size is 800 × 800 × 2000 mm, containing either a high energy battery (190 kWh) or a high power battery (56 kWh), each with a 1000 V output. The target cost of this battery system is expected in the range 250-300 €/kWh with production volumes that should settle between 3 and 4 GWh of installations [68]. The results of this analysis will be published in the course of the year 2023.

The SEABAT concept is currently being prototyped and it will result into a 246 kWh system, able to output 200 kW at 1000 Vdc [69].

VII. MANUFACTURING AND DISASSEMBLY PROCESSES

This section analyses the main aspects of the manufacture, assembly and disassembly of batteries, with the aim of obtaining a battery that is easy to assemble, maintain and disassemble for second-life applications and recycling processes. Thus, based on the existing experience derived mainly from the automotive sector, some guidelines and design criteria are provided for the manufacturing of the SEABAT battery, which are also valid for other batteries with similar characteristics. All this, with a clear focus on safety and optimization of the total cost of ownership (TCO) during the manufacturing process. This requires reducing the cost during the production phase of the battery through better assembly design, and, at the same time, reducing the end-of-life cost through better design for disassembly or reuse of the battery.

In order to evaluate the manufacturing and disassembly processes, a focus on the joining technologies used is mandatory. The joining used in cells, modules and battery packs is one of the most critical points in the design of assembly and disassembly in batteries. Accordingly, they may suppose a considerable difference in the total cost of ownership of the manufacturing process. Making the required electrical and structural joints represents several challenges, including, joining of multiple and thin highly conductive/reflective materials of varying thicknesses, potential damage (thermal, mechanical, or vibrational) during joining, a high joint durability requirement, recyclability, cost, and so on. Hence, a comprehensive review of the actual state-of-the-art was done, mainly from the automotive sector, regarding major and emerging joining techniques to support the wide range of requirements during the battery pack manufacturing. Table 5 contains a summary of the main advantages and disadvantages of major joining technologies including ultrasonic, resistance spot welding, micro-Tungsten Inert Gas (TIG) welding/pulsed arc welding, ultrasonic wedge bonding, soldering, magnetic pulse welding, laser welding and mechanical fastening.

Regarding the suitability of available joining methods to build battery packs using prismatic cells, as is the case of the SEABAT project, at cell level, resistance spot welding is used to connect current collector tabs with the case or with the top cap of the case [72]. Typically, prismatic cell positive and negative terminals are based on mechanical nut and bolt assembly. Laser welding is also used for cell level joining and traditionally case sealing. Additionally, as reported by Shannon [73], laser welding has potential for a number of manufacturing applications, such as case sealing and terminal welding. At module and pack level joining, as a result of the stackable form of prismatic cells, battery pack modularity and various design configurations for parallel or series connections are readily achievable. Module and pack level joining is mainly performed with mechanical nut and bolt fasteners or clip fitting. Mechanical nut and bolt assembly has the advantage of easy disassembly and higher joint strength compared with other reported joining techniques. However, there are issues with high contact resistance and maximum torque (to avoid internal damage) that can be sustained by the cell stud. In some cases, laser welding has also been used for connecting cell terminal with bus bar [74]. Moreover, A. Das [70] identifies various of those joining technologies with their corresponding manufacturing readiness levels (MRLs) to indicate options and development status of battery joining from a manufacturing perspective (as illustrated in Fig. 9). Manufacturing readiness levels (MRLs) are used to provide a relative measure of technology maturity, risk level, and extent of application [70].

As stated by the authors, between all the options, ultrasonic welding, ultrasonic wedge bonding, and mechanical assembly are frequently used in battery pack manufacturing and have been demonstrated at the highest level of production (MRLs 8–10). At a lower level, resistance spot welding (RSW), micro-TIG, micro-clinching, and soldering have demonstrated their capability under laboratory conditions (MRL 4) to produce joints for low or batch volume during module manufacture (MRL 6-7). In contrast, laser welding exhibits a broad range of capability from MRL 4 to MRL 10. For example, laser welding applications for module level joining of cylindrical or pouch cells are in MRL 4–6, whereas laser applications for case sealing or module level joining of prismatic cells have been demonstrated at MRL 10. Other joining technologies as magnetic pulse welding (MPW) or electromagnetic pulse technology (EMPT), has only demonstrated limited capability under laboratory conditions to produce tab-to-tab joining [70]. Besides, a Pugh matrix has been employed to evaluate different technologies that are suitable for joining prismatic cell type battery packs (Table 6). It is a scoring matrix used for concept selection in which technology options are assigned scores relative to their fulfillment of explicit criteria, regarding the requirements in the SEABAT project. Each requirement is assigned a relative weight, and for each technology, a score of 5 means that it fully meets the corresponding requirement, and conversely, a score of 1 means that it does not meet the requirement at all.

This decision-matrix shows that considering the specific criteria for the case study discussed, mechanical assembly and laser welding are the most appropriate joining technologies for prismatic cell-based battery pack manufacturing. As seen in [75], [76], [78], [80], [81], [82], another actual tendency and an important aspect when disassembling a battery is the degree of automation of the process. Due to the many product variants, the non-existent standards in battery design and the fact that the detailed designs of the batteries are generally unavailable to the recycler, batteries are currently manually dismantled. However, where labor costs are high, disassembly is one of the most expensive steps in the proposed recycling process. On the other hand, fully automated disassembly is also infeasible to implement at this time, due to the many product variants and relatively small

TABLE 5. Summary of joining technologies [70], [71].

Joining Technology	Advantages	Disadvantages
Ultrasonic welding	• Fast process • High strength and low resistance • Able to join dissimilar materials • Low energy consumption • Self-tooling • Excellent for highly conductive materials	• Only suitable for pouch cells • Needs two sided access • High heat generation can damage batteries • Expensive consumables • Limited joint thickness • Challenging on high strength and hard materials • Sensitive to surface conditions
Resistance spot welding (RSW)	• Fast process • Low cost • Good quality control • Easy automation • Self-tooling	• Difficult for highly conductive and dissimilar materials • Difficult to produce large joints or joining of more than two layers • Risk of expulsion
Micro-TIG/pulsed arc welding	• Low cost • High joint strength and low resistance • Able to join dissimilar materials • Easy automation	• High thermal input and heat affected zone • Porosity • Difficult to join more than two layers
Ultrasonic wedge bonding	• Fast process • Acting as fuses • Able to join dissimilar materials • Low energy consumption • Easy automation	• Only suitable for small wires • Low wire and joint strength • Complex manufacturing
Soldering	• Joining dissimilar materials • Wide spread in electronics industry	• High heat • Labour intensive • Need for solder material • Low joint strength
Laser welding	• High speed • Less thermal input • Non-contact process • Easy automation • High precision	• High initial cost • Need of shielding gas system • Quality control is difficult • Needs good joint alignment • Process monitoring is difficult • Challenges in dissimilar joining
Magnetic pulse welding (MPW)	• Solid state process • Able to join dissimilar materials • High joint strength	• Potential large distortion • Rigid support required • Possibility of eddy current passing through the cells
Mechanical assembly	• Easy dismounting and recycling • Easy repair • Cold process	• Additional weight • High connection resistance • Expensive (not if TCO) • Additional weight

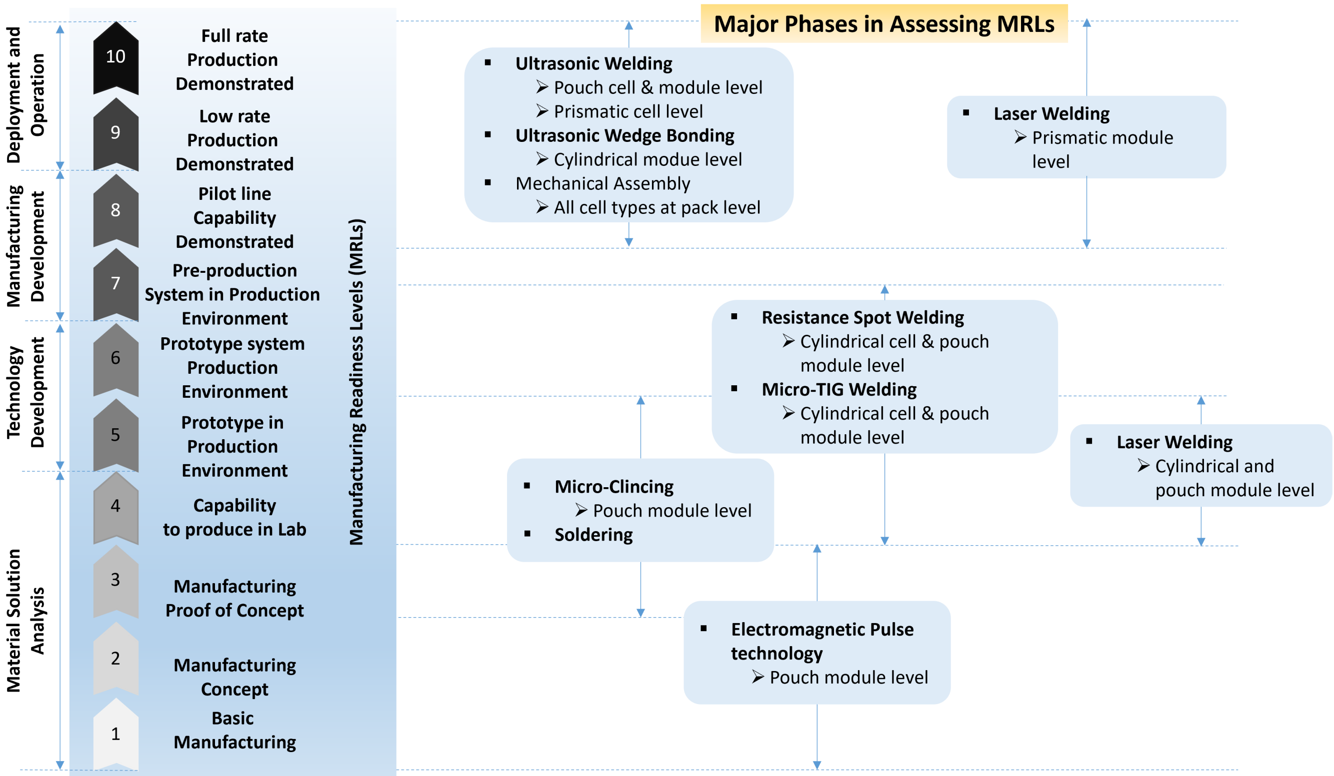


FIGURE 9. MRLs for assessing technology maturity of current joining technologies for module level joining [70].

volume of each variant. Furthermore, at a EOL, components and fasteners may be damaged and therefore more difficult to remove. These challenges are generally not present in assembly processes where automation is commonplace. In order to meet these challenges, an interesting proposition is a hybrid human-robot workstation where the robot executes the simpler, repetitive tasks, alongside a human that handles more complex tasks and is capable of reacting to problems where they occur [81]. One possible task for the robot is the removal of screw and bolt fasteners, which we will refer to as unscrewing. Many variants of EV batteries are held together by a large number of screws and bolts. Unscrewing is a relatively simple task that is repetitive and uninteresting for a human. The potential for robots to take over this task has been previously recognized. Reference [15] describes work on a robotic system for unscrewing, where the inaccurate visual localization of screws was compensated for by using a tool specifically designed for unscrewing. Reference [16] describes a system for unbolting car wheels, whereby an active stereo vision system was used for the detection of screws. A "special unbolting tool" was used, along with a force-torque sensor and task planning module, to perform the physical disassembly. Reference [84] describes a multi-sensorial robotic system capable of unscrewing and removing the compact disk (CD) drive from a PC and the electronic circuit from a toy. This was achieved using a combination of visual sensors and force control. These systems demonstrate that the detection and eventual removal of screws by a robot is an achievable task. [85] describes work on the vision system for the robotic unscrewing of ceiling beams during interior office renovations. For the robot-assisted disassembly of the EV batteries, K. Wegener et al. [81] propose a workstation concept as depicted in Fig. 10. Both the human and the robot require access to the disassembly object, i.e., the battery. To minimize system complexity and the time required to frequently transport the disassembly object between separate workspaces, they propose for the human and the robot to share a common workspace. Furthermore, the human and robot also require access to their own disassembly tools. For the human this may be a variety of tools including pliers, screwdrivers, a hammer and cutting tools. For the robot this consists of different kinds of socket wrench bits for its unscrewing tool (not depicted in the figure). The human carries out more complex tasks such as prying apart components joined with snap fits or (to a limited extent) glue, and pulling out or cutting cables, while the robot unfastens all screws and bolts. The location of the screws and bolts can be either taught manually or detected via a camera (or even a combination of them via learning algorithms). A similar hybrid workstation idea was proposed by the same author in another article [78] for the case study of the Audi Q5 Hybrid battery system (Fig. 11).

In order for a manufacturing line to be able to provide the greatest benefit to manufacturers and a potential aftermarket, having a reconfigurable assembly line that can not

TABLE 6. Pugh matrix for evaluation of joining methods for manufacturing of prismatic cell based module [70], [75], [76], [77], [78], [79], [80], [81], [82], [83].

Joining technologies – Prismatic cells						
Factor	Weight	Ultrasonic wedge bonding	Micro-TIG / Pulsed arc welding	Resistance spot / Projection welding	Laser welding	Mechanical assembly (nut and bolt)
Joint resistance-similar materials	4	5	4	4	5	2
Joint resistance-dissimilar materials	4	5	4	2	3	2
Joint strength-similar materials	4	3	4	4	5	5
Joint strength-dissimilar materials	4	3	3	1	3	5
Heat transfer from process	4	5	3	3	4	5
Potential mechanical damage	4	4	4	4	5	2
Joint current capacity	5	1	2	2	5	5
Joint durability	5	3	4	4	4	3
Potential vibration damage	5	4	5	5	5	5
Joint corrosion resistance	4	5	4	4	4	2
In process quality control	4	5	4	4	2	3
Sensitivity	4	5	4	4	4	5
Repeatability	4	4	4	4	4	5
Cost per battery connection	4	4	5	5	4	3
Investment	3	4	4	4	2	5
Easy recycling	5	2	2	2	2	5
Easy automation	4	5	4	4	5	2
Delivery time	3	4	4	4	3	5
Standard Equipment	4	5	3	4	3	5
Flexibility	5	2	3	3	3	4
Used for similar applications	4	2	1	1	5	5
Safety	5	4	4	4	3	5
Cost of ownership	5	3	5	5	4	5
Technique support	5	4	5	5	4	5
TOTAL		**379**	**378**	**366**	**389**	**419**
Appropriateness		**74.3%**	**74.1%**	**71.8%**	**76.3%**	**82.2%**

only assembly Li-ion components, but disassemble them too, this opens a market far beyond just manufacturing of new batteries. It opens a market for reconditioning, maintenance, recycling and remanufacturing. This follows the belief that, the same tooling and machinery used to assemble the packs can also be used to dismantle the packs to a modular level, which can be sent to recycling centers or reused to manufacture new packs [76]. Accordingly, safety must be considered when speaking about disassembly processes. The main safety risks, i.e. the safety risks with the largest impact, are caused by the high voltage and the chemicals in the battery cells (mainly the electrolyte) even though it is required to fully discharge the batteries before disassembly. Additionally, in the design of the workstations appropriate protective measures for the worker and the environment are required like electrically isolated tools, hand gloves, shoes and floor cover. A further safety risk arises from the electrolyte in the battery cells. In case of the damaging of a cell during the disassembly process the electrolyte may cause fire or toxic gases. In order to protect the worker, the workstations should be equipped with appropriate fire extinguishers (dry chemical or carbon dioxide), emergency kits, gas masks and an extraction unit [78]. Moreover, there are some other interesting design criteria regarding the design for disassembly. In relation to the types of connections between the individual components of the battery, [75], [76] state that a decisive factor is the

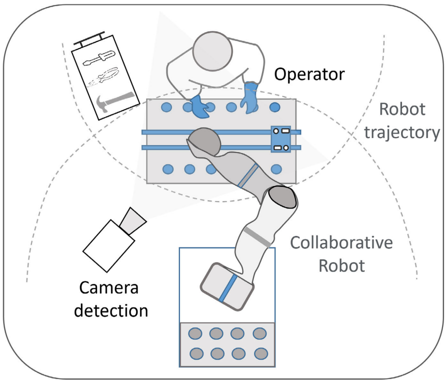


FIGURE 10. **Disassembly workstation [81].**

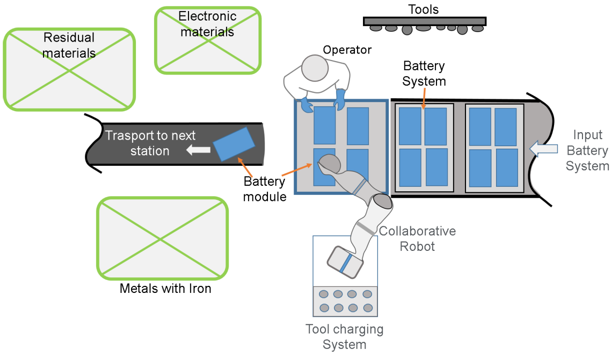


FIGURE 11. **Basic layout of the work station for the disassembly of the Q5 batteries [78].**

non-destructive or destructive separation of the materials, as these must be separated during dismantling. Connections such as welding, are built to be separated again destructively. On the other hand, mechanical connections such as nuts/bolts or wires, can be more easily separated with the appropriate tools and they facilitate maintenance and repair. Similarly, the utilization of adhesive materials should be avoided as far as possible for purposes such as joining or sealing. Nevertheless, it may be challenging not to use this type of materials, especially for thermal management of the battery, for instance in thermal pads located in the interfaces between the cells and the cold plate. The selection of the employed adhesive material must be carefully selected to make the affected components easily separable in disassembly or maintenance processes. In addition, [78], [80], [81] show several aspects that increase the complexity of the disassembly. One difficulty arises from the many different screw types that are usually used for the joints. This means that as many different types of screwdrivers have to be provided for the disassembly, and that during the assembly, a certain amount of time will be spent for changing the tool. Furthermore, it is advisable to reach a standardized design that enables easy access to the connection points and the disassembly direction for all operations (all screws, . . .) to be along the vertical axis, or at least, to be accessible from the same direction. The screw joints are usually at the top, at the side covers and at the bottom of the battery system. This will require several orientation changes of the tool and, due to the screw joints at the bottom of the battery system, even a turnover of the whole battery module (or at least bottom accessibility). By the way, after removing the lid of the battery system, the modules should easily be removed as well as the battery management system, with the presence of as few as possible connections for the module to be opened and cells to be taken out. Additionally, as it is directly related to the degree of automation due to the effort to increase the efficiency of the disassembly systems, the main influencing factor is the number of end-of-life batteries and their standardization (sizes, connections, . . .) as well as the targeted marking and labelling of individual components and entire systems [77], [80]. Another challenge for the disassembly, especially with a focus on automation concepts, are flexible components such as cables and joints that are difficult to access such as the plug-in connectors of the BMS [78]. Moreover, special emphasis should be placed on the way all the wiring, sensorization and so on secondary components related with diverse systems (thermal, electrical. . .) of the battery are rooted in the structure. The outgoing battery design should be well integrated and easy to access and disassemble. All in all, these are some of the most typical designs for assembly (DfA) and design for disassembly (DfD) characteristics. Design for assembly criteria is the part count, the joining techniques, the number of different joining techniques, joining directions, the part dimensions, the part weight, the fragility of parts as well as the stiffness of parts. The design for disassembly criteria are the number of different materials (within product and part), the degree of materials that can be recycled easily, the type and number of fasteners, the number of different fasteners, the overall part number, and as in the DfA, the type and number of joining techniques [79]. In the same way, to achieve the most optimized and efficient manufacturing process, is highly advisable to minimize the number of manufacturing processes, and to integrate them (weld, machining, insulate. . .). With regards to the design for maintenance (DfM), there will be different types of batteries in the hybrid energy storage system (HESS) which will be used in a different way, whose aging will also be different for both battery types. Therefore, it is also important to consider the possibility to replace battery modules at their EOL, while keeping the battery modules which are not at their EOL. This means that battery cells shall be placed so that they are accessible for maintenance and replacement. For instance, it was a requirement for the SEABAT project that the batteries were to be arranged such that each cell or group of cells was accessible from the top and at least one side. Likewise, it would be necessary to replace or repair any component of the battery. Thus, the package must be designed with an adequate spatial layout for that purpose and should consider enough access points such as lids for every main component. This is also related to the system design, where rack-based systems fit better with the accessibility requirements.

VIII. DISCUSSION AND FUTURE OUTLOOK

As it was presented in this paper, there is a great potential for reuse of batteries used in automotive and maritime sector.

In the next few years a great increase of energy storage will be included in ships and this will result in a large number of available batteries for second-life applications. To make second use possible, there are key challenges to be tackled. The most compelling ones can be summarized as:

- Assessment of the battery state;
- Disassembly;
- Sorting and matching of suitable cells;
- Power conversion structure and control adaptation.

For these reasons, there is a significant effort in developing sorting and analysis techniques based on advanced methods, such as machine learning and artificial intelligence. Moreover, a significant help can come from choosing better power conversion topologies, that feature modularity and enable the easy use of different batteries within the same storage system. To this purpose, the solution proposed by the SEABAT project represents a viable solution, by adopting a modular structure where each battery is interfaced to the network by a specific power converter. This modular structure allows easy reconfiguration of the individual modules to tackle second life applications at different voltage and power ratings. Besides, relatively simple modifications to the storage system architecture can equalize the stresses on the various modules and exploit batteries of different chemistry and degradation state at the same time.

The limitations of the SEABAT solution mainly lie in its complexity. As it is clear, the number of power converters, BMSs and control logic is much larger compared to a standard solution with a monotype battery and a single DC/DC converter. On one hand, this would increase the cost and the difficulty of installation of this solution. On the other hand, this modular approach provides several advantages, both in total lifetime cost and performance.

The SEABAT project is currently developing a demonstrator for this concept and it is believed that not only it will benefit the battery first use in terms of cost and performance, but it will also represent an easy way to reuse the batteries in a second-life application, such as grid storage.

IX. CONCLUSION

The use of battery as energy source for naval propulsion systems is a choice that moves towards a more sustainable naval transportation. The batteries, after they are employed for the on board applications, can be suitable for a second life use. This paper first reviewed the main trends and challenges to enable second life of batteries according to the state-of-art, with specific focus on the residual lifetime estimation. Then, possible second life applications were identified, showing how stationary grid applications are a good match for repurposed batteries, both in industrial, energy and domestic applications. It was also shown how proper care must be paid in the manufacturing process with a special focus on the easy disassembly of these batteries after their first life, being this an enabling factor for second use. Finally, starting from the specific design for the first use proposed by the SEABAT project, good practice suggestions are reported in the paper with evaluations of critical points that must be faced for the second life use. The SEABAT solution proposes a modular battery storage composed of stacked integrated battery packs and DC/DC converters. This solution does not only allow a fine tailoring of the storage based on the first life needs, but also an easier reconfiguration of the modules to their second life application. The outcome of this project will demonstrate how this structure can provide a cost reduction in the first life of the storage and also facilitate its repurposing.

ACKNOWLEDGMENT

The present action reflects only the author's view and it does not engage in any way the views of the European Commission.

REFERENCES

[1] D. Paul, "A history of electric ship propulsion systems," *IEEE Ind. Appl. Mag.*, vol. 26, pp. 9–19, Nov. 2020.

[2] B. V. Mathiesen, "Smart energy systems for coherent 100% renewable energy and transport solutions," *Appl. Energy*, vol. 145, pp. 139–154, May 2015.

[3] H. Rahimi-Eichi, U. Ojha, F. Baronti, and M.-Y. Chow, "Battery management system: An overview of its application in the smart grid and electric vehicles," *IEEE Ind. Electron. Mag.*, vol. 7, no. 2, pp. 4–16, Jun. 2013.

[4] M. A. Hannan, M. M. Hoque, A. Hussain, Y. Yusof, and P. J. Ker, "State-of-the-art and energy management system of Lithium-Ion batteries in electric vehicle applications: Issues and recommendations," *IEEE Access*, vol. 6, pp. 19362–19378, 2018.

[5] M. Pastorelli, S. Musumeci, and F. Mandrile, "Battery sources and power converters interface in waterborne transport applications," in *Proc. AEIT Int. Conf. Elect. Electron. Technol. Automot. (AEIT AUTOMOTIVE)*, Nov. 2021, pp. 1–5.

[6] A. Keeli and R. K. Sharma, "Optimal use of second life battery for peak load management and improving the life of the battery," in *Proc. IEEE Int. Electr. Vehicle Conf.*, Mar. 2012, pp. 1–6.

[7] G. Hunt, "US ABC electric vehicle battery test procedures manual, revision 2," Lockheed Idaho Technol. Co., Idaho Falls, ID, USA, Tech. Rep. DOE/ID-10479-Rev.2, Jan. 1996.

[8] M. O. Ramoni and H. C. Zhang, "End-of-life (EOL) issues and options for electric vehicle batteries," *Clean Technol. Environ. Policy*, vol. 15, no. 6, pp. 881–891, Dec. 2013.

[9] Y. Zhao, O. Pohl, A. I. Bhatt, G. E. Collis, P. J. Mahon, T. Rüther, and A. F. Hollenkamp, "A review on battery market trends, second-life reuse, and recycling," *Sustain. Chem.*, vol. 2, pp. 167–205, Mar. 2021.

[10] M. Chen, X. Ma, B. Chen, R. Arsenault, P. Karlson, N. Simon, and Y. Wang, "Recycling end-of-life electric vehicle lithium-ion batteries," *Joule*, vol. 3, pp. 2622–2646, Nov. 2019.

[11] H. Engel, P. Hertzke, and G. Siccardo. (Apr. 2019). *Electric Vehicles, Second Life Batteries, and Their Effect on the Power Sector*. Accessed: Mar. 14, 2023. [Online]. Available: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

[12] J. Zhu, I. Mathews, D. Ren, W. Li, D. Cogswell, B. Xing, T. Sedlatschek, S. N. R. Kantareddy, M. Yi, T. Gao, Y. Xia, Q. Zhou, T. Wierzbicki, and M. Z. Bazant, "End-of-life or second-life options for retired electric vehicle batteries," *Cell Rep. Phys. Sci.*, vol. 2, Aug. 2021, Art. no. 100537.

[13] B. Faessler, "Stationary, second use battery energy storage systems and their applications: A research review," *Energies*, vol. 14, p. 2335, Jan. 2021.

[14] E. Hossain, D. Murtaugh, J. Mody, H. M. R. Faruque, M. S. H. Sunny, and N. Mohammad, "A comprehensive review on second-life batteries: Current state, manufacturing considerations, applications, impacts, barriers & potential solutions, business strategies, and policies," *IEEE Access*, vol. 7, pp. 73215–73252, 2019.

[15] D. Madouch, "SEABAT D1.2—Market evolution and potential within 5, 10, 15 years for different marine applications," SEABAT Project, Eur. Union, Tech. Rep. SEABAT D1.2, May 2021.

[16] *Vattenfall, BMW and Bosch Test Second-Life EV Battery Electricity Storage in Hamburg for Grid Stabilization*. Accessed: Mar. 14, 2023. [Online]. Available: https://www.greencarcongress.com/2016/09/20160923-bmw.html

[17] *Repurposed Camry Hybrid Batteries to Power Yellowstone Campus*. Accessed: Mar. 14, 2023. [Online]. Available: https://www.torquenews.com/1083/repurposed-camry-hybrid-batteries-power-yellowstone-campus

[18] Bloomberg. (Jun. 2018). *Where 3 Million Electric Vehicle Batteries Will Go When They Retire*. Bloomberg.com. Accessed: Mar. 14, 2023. [Online]. Available: https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire

[19] T. M. N. Bui, T. Q. Dinh, J. Marco, and C. Watts, "Development and real-time performance evaluation of energy management strategy for a dynamic positioning hybrid electric marine vessel," *Electronics*, vol. 10, p. 1280, May 2021.

[20] M. Akbarzadeh, J. D. Smet, and J. Stuyts, "Battery hybrid energy storage systems for full-electric marine applications," *Processes*, vol. 10, p. 2418, Nov. 2022.

[21] M. Akbarzadeh, J. D. Smet, and J. Stuyts, "Cost assessment of battery hybrid energy storage system for full-electric marine applications," in *Proc. 22nd Int. Sci. Conf. Electr. Power Eng. (EPE)*, Jun. 2022, pp. 1–6.

[22] M. F. Niri, T. M. Bui, T. Q. Dinh, E. Hosseinzadeh, T. F. Yu, and J. Marco, "Remaining energy estimation for lithium-ion batteries via Gaussian mixture and Markov models for future load prediction," *J. Energy Storage*, vol. 28, Apr. 2020, Art. no. 101271.

[23] M. F. Niri, T. Q. Dinh, T. F. Yu, J. Marco, and T. M. N. Bui, "State of power prediction for lithium-ion batteries in electric vehicles via wavelet-Markov load analysis," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 9, pp. 5833–5848, Sep. 2021.

[24] Z. Wei, Z. Quan, J. Wu, Y. Li, J. Pou, and H. Zhong, "Deep deterministic policy gradient-DRL enabled multiphysics-constrained fast charging of lithium-ion battery," *IEEE Trans. Ind. Electron.*, vol. 69, no. 3, pp. 2588–2598, Mar. 2022.

[25] J. Wu, Z. Wei, W. Li, Y. Wang, Y. Li, and D. U. Sauer, "Battery thermal- and health-constrained energy management for hybrid electric bus based on soft actor-critic DRL algorithm," *IEEE Trans. Ind. Informat.*, vol. 17, no. 6, pp. 3751–3761, Jun. 2021.

[26] U. R. Koleti, T. N. M. Bui, T. Q. Dinh, and J. Marco, "The development of optimal charging protocols for lithium-ion batteries to reduce lithium plating," *J. Energy Storage*, vol. 39, Jul. 2021, Art. no. 102573.

[27] T. M. N. Bui, M. Sheikh, T. Q. Dinh, A. Gupta, D. W. Widanalage, and J. Marco, "A study of reduced battery degradation through state-of-charge pre-conditioning for vehicle-to-grid operations," *IEEE Access*, vol. 9, pp. 155871–155896, 2021.

[28] R. Yudhistira, D. Khatiwada, and F. Sanchez, "A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage," *J. Cleaner Prod.*, vol. 358, Jul. 2022, Art. no. 131999.

[29] R. Hobbs, R. Newnham, D. Karner, and F. Fleming, "Development of predictive techniques for determination of remaining life for lead acid batteries under fast charge," in *Proc. 14th Annu. Battery Conf. Appl. Adv. Conf.*, Jan. 1999, pp. 177–188.

[30] N. Andrenacci, F. Vellucci, and V. Sglavo, "The battery life estimation of a battery under different stress conditions," *Batteries*, vol. 7, no. 4, p. 88, Dec. 2021.

[31] S. A. Pourmousavi, R. K. Sharma, and B. Asghari, "A framework for real-time power management of a grid-tied microgrid to extend battery lifetime and reduce cost of energy," in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Jan. 2012, pp. 1–8.

[32] E. Martinez-Laserna, E. Sarasketa-Zabala, D.-I. Stroe, M. Swierczynski, A. Warnecke, J. M. Timmermans, S. Goutam, and P. Rodriguez, "Evaluation of lithium-ion battery second life performance and degradation," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2016, pp. 1–7.

[33] Z. Wei, J. Zhao, H. He, G. Ding, H. Cui, and L. Liu, "Future smart battery and management: Advanced sensing from external to embedded multi-dimensional measurement," *J. Power Sources*, vol. 489, Mar. 2021, Art. no. 229462.

[34] Z. Wei, J. Hu, H. He, Y. Yu, and J. Marco, "Embedded distributed temperature sensing enabled multistate joint observation of smart lithium-ion battery," *IEEE Trans. Ind. Electron.*, vol. 70, no. 1, pp. 555–565, Jan. 2023.

[35] Z. B. Wei, J. Y. Zhao, D. X. Ji, and K. J. Tseng, "A multi-timescale estimator for battery state of charge and capacity dual estimation based on an online identified model," *Appl. Energy*, vol. 204, pp. 1264–1274, Oct. 2017.

[36] Z. Wei, H. Ruan, Y. Li, J. Li, C. Zhang, and H. He, "Multistage state of health estimation of lithium-ion battery with high tolerance to heavily partial charging," *IEEE Trans. Power Electron.*, vol. 37, no. 6, pp. 7432–7442, Jun. 2022.

[37] M. Tran, T. Messo, R. Luhtala, J. Sihvo, and T. Roinila, "Used lithium-ion batteries in second-life applications: Feasibility study," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Oct. 2022, pp. 1–5.

[38] K. Liu, Z. Wei, C. Zhang, Y. Shang, R. Teodorescu, and Q.-L. Han, "Towards long lifetime battery: AI-based manufacturing and management," *IEEE/CAA J. Autom. Sinica*, vol. 9, no. 7, pp. 1139–1165, Jul. 2022.

[39] J. Neubauer, K. Smith, E. Wood, and A. Pesaran, "Identifying and overcoming critical barriers to widespread second use of PEV Batteries," Nat. Renew. Energy Lab. (NREL), Golden, CO, USA, Tech. Rep. NREL/TP-5400-63332, 1171780, Feb. 2015.

[40] E. Cready, J. Lippert, J. Pihl, I. Weinstock, and P. Symons, "Technical and economic feasibility of applying used EV batteries in stationary applications," Sandia Nat. Lab. (SNL-NM), Albuquerque, NM, USA, Sandia Nat. Lab. (SNL-CA), Livermore, CA, USA, Tech. Rep. SAND2002-4084, Mar. 2003.

[41] F. McLoughlin and M. Conlon, "Secondary re-use of batteries from electric vehicles for building integrated photo-voltaic (BIPV) applications," Technol. Univ. Dublin, Dublin, Ireland, Tech. Rep. 2015-4, Apr. 2015.

[42] M. Bowler, "Battery second use: A framework for evaluating the combination of two value chains," Ph.D. thesis, Dept. Automot. Eng., Clemson Univ., Clemson, SC, USA, May 2014.

[43] *Batteries and Accumulators*. Accessed: Mar. 14, 2023. [Online]. Available: https://ec.europa.eu/environment/topics/waste-and-recycling/batteries-and-accumulators_en

[44] K. Liu, M. F. Niri, G. Apachitei, M. Lain, D. Greenwood, and J. Marco, "Interpretable machine learning for battery capacities prediction and coating parameters analysis," *Control Eng. Pract.*, vol. 124, Jul. 2022, Art. no. 105202.

[45] K. Liu, X. Hu, J. Meng, J. M. Guerrero, and R. Teodorescu, "RUBoost-based ensemble machine learning for electrode quality classification in Li-ion battery manufacturing," *IEEE/ASME Trans. Mechatronics*, vol. 27, no. 5, pp. 2474–2483, Oct. 2022.

[46] M. Shahjalal, P. K. Roy, T. Shams, A. Fly, J. I. Chowdhury, M. R. Ahmed, and K. Liu, "A review on second-life of Li-ion batteries: Prospects, challenges, and issues," *Energy*, vol. 241, Feb. 2022, Art. no. 122881.

[47] H. Rallo, G. Benveniste, I. Gestoso, and B. Amante, "Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries," *Resour., Conservation Recycling*, vol. 159, Aug. 2020, Art. no. 104785.

[48] "Global EV outlook 2020 analysis," Int. Energy Agency (IEA), Paris, France, Tech. Rep. IEA 2020, 2020.

[49] X. Hu, L. Xu, X. Lin, and M. Pecht, "Battery lifetime prognostics," *Joule*, vol. 4, no. 2, pp. 310–346, Feb. 2020.

[50] B. Gohla-Neudecker, M. Bowler, and S. Mohr, "Battery 2nd life: Leveraging the sustainability potential of EVs and renewable energy grid integration," in *Proc. Int. Conf. Clean Electr. Power (ICCEP)*, Jun. 2015, pp. 311–318.

[51] M. Einhorn, R. Permann, C. Kral, F. V. Conte, W. Guertlschmid, T. Blochberger, R. Kumpusch, and J. Fleig, "Current equalization of serially connected battery cells for a possible second life application," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Sep. 2011, pp. 1–5.

[52] O. Hegazy, M. A. Monem, P. Lataire, and J. Van Mierlo, "Modeling and analysis of a hybrid PV/second-life battery topology based fast DC-charging systems for electric vehicles," in *Proc. 17th Eur. Conf. Power Electron. Appl. (EPE ECCE-Eur.)*, Sep. 2015, pp. 1–11.

[53] N. Mukherjee and D. Strickland, "Analysis and comparative study of different converter modes in modular second-life hybrid battery energy storage systems," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 4, no. 2, pp. 547–563, Jun. 2016.

[54] C. S. Chin, J. Xiao, A. M. Y. M. Ghias, M. Venkateshkumar, and D. U. Sauer, "Customizable battery power system for marine and offshore applications: Trends, configurations, and challenges," *IEEE Electrific. Mag.*, vol. 7, no. 4, pp. 46–55, Dec. 2019.

[55] F. Cherchi, M. Porru, and A. Serpi, "Electrification of commercial vessels: Pilot projects and open issues," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Oct. 2021, pp. 1–5.

[56] T. P. Corrêa, T. A. C. Maia, and B. J. C. Filho, "High-performance power electronic battery pack based on a back-to-back converter," *Energies*, vol. 16, no. 1, p. 375, Dec. 2022.

[57] M. Ozbek, B. Pierquet, and A. D. Baglino, "Scalable and flexible cell-based energy storage system," U.S. Patent US20 170 093 156 A1, Mar. 30, 2017.

[58] F. Diaz-Gonzalez, D. Heredero-Peris, M. Pages-Gimenez, E. Prieto-Araujo, and A. Sumper, "A comparison of power conversion systems for modular battery-based energy storage systems," *IEEE Access*, vol. 8, pp. 29557–29574, 2020.

[59] S. Rothgang, T. Baumhöfer, H. van Hoek, T. Lange, R. W. D. Doncker, and D. U. Sauer, "Modular battery design for reliable, flexible and multi-technology energy storage systems," *Appl. Energy*, vol. 137, pp. 931–937, Jan. 2015.

[60] J. D. Smet, M. Akbarzadeh, R. Barrera-Cardenas, O. Mo, J. Anzola, A. A. Loiti, E. G. Perez, J. U. Arocena, and D. Süzen, "SEABAT D3.1—Evaluation and selection of architectural concept," SEABAT Project, Eur. Union, Tech. Rep. SEABAT D3.1, Dec. 2021.

[61] M. H. S. M. Haram, J. W. Lee, G. Ramasamy, E. E. Ngu, S. P. Thiagarajah, and Y. H. Lee, "Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges," *Alexandria Eng. J.*, vol. 60, no. 5, pp. 4517–4536, Oct. 2021.

[62] I. Mathews, B. Xu, W. He, V. Barreto, T. Buonassisi, and I. M. Peters, "Technoeconomic model of second-life batteries for utility-scale solar considering calendar and cycle aging," *Appl. Energy*, vol. 269, Jul. 2020, Art. no. 115127.

[63] H. Rallo, L. C. Casals, D. D. L. Torre, R. Reinhardt, C. Marchante, and B. Amante, "Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases," *J. Cleaner Prod.*, vol. 272, Nov. 2020, Art. no. 122584.

[64] J. Malavatu, R. O'Born, P. Kepplinger, and B. Faessler, "Hybrid energy storage systems of energy- and power-dense batteries: A survey on modelling techniques and control methods," *Proc. CIRP*, vol. 105, pp. 794–798, Jan. 2022.

[65] J. I. Leon, E. Dominguez, L. Wu, A. M. Alcaide, M. Reyes, and J. Liu, "Hybrid energy storage systems: Concepts, advantages, and applications," *IEEE Ind. Electron. Mag.*, vol. 15, no. 1, pp. 74–88, Mar. 2021.

[66] *SEABAT D2.1—Application Matrix*, SEABAT Project, Eur. Union, Aug. 2021.

[67] C. Mosteiro and C. Hoyos, "SEABAT D2.3—Detailed requirements document," SEABAT Project, Eur. Union, Tech. Rep. SEABAT D2.3, Aug. 2021.

[68] J. D. Smet, M. Akbarzadeh, J. Baake, T. Vandenhove, S. K. Venkatesan, M. Morshed, E.-M. Stelter, T. Pfeiffer, I. Amilleta, F. Mandrile, and M. Pastorelli, "SEABAT D3.2—Integrated safe, modular & flexible battery system architecture," Dec. 2021.

[69] J. De Smet, M. Akbarzadeh, R. Barrera-Cardenas, O. Mo, J. Anzola, A. A. Loiti, E. G. Perez, J. U. Arocena, D. Süzen, J. Baake, T. Vandenhove, S. K. Venkatesan, M. Morshed, E.-M. Stelter, T. Pfeiffer, A. L. de Heredia, D. Marcos, M. Alzuri, F. Mandrile, and M. Pastorelli, "SEABAT D3.3—Preliminary design of a 300 kWh battery for waterborne applications," SEABAT Project, Eur. Union, Tech. Rep. SEABAT D3.3, Sep. 2022.

[70] A. Das, D. Li, D. Williams, and D. Greenwood, "Joining technologies for automotive battery systems manufacturing," *World Electr. Veh. J.*, vol. 9, no. 2, p. 22, 2018.

[71] M. F. R. Zwicker, M. Moghadam, W. Zhang, and C. V. Nielsen, "Automotive battery pack manufacturing—A review of battery to tab joining," *J. Adv. Joining Processes*, vol. 1, Mar. 2020, Art. no. 100017.

[72] K. Tagawa and R. J. Brodd, "Production processes for fabrication of lithium-ion batteries," in *Lithium-Ion Batteries*, M. Yoshio, R. J. Brodd, and A. Kozawa, Eds. New York, NY, USA: Springer, 2009, pp. 1–14.

[73] G. Shannon, "Improve tab to terminal connections in battery pack manufacturing," Amada Miyachi Amer., Monrovia, CA, USA, Tech. Rep., 2016.

[74] *Automotive Battery-Battery Module Samsung Sdi*. Accessed: Mar. 14, 2023. [Online]. Available: http://www.samsungsdi.com/automotive-battery/products/battery-module.html

[75] S. Blankemeyer, D. Wiens, T. Wiese, A. Raatz, and S. Kara, "Investigation of the potential for an automated disassembly process of BEV batteries," *Proc. CIRP*, vol. 98, pp. 559–564, Jan. 2021.

[76] R. D'Souza, J. Patsavellas, and K. Salonitis, "Automated assembly of Li-ion vehicle batteries: A feasibility study," *Proc. CIRP*, vol. 93, pp. 131–136, Jan. 2020.

[77] T. E. Schwarz, W. Rübenbauer, B. Rutrecht, and R. Pomberger, "Forecasting real disassembly time of industrial batteries based on virtual MTM-UAS data," *Proce. CIRP*, vol. 69, pp. 927–931, Jan. 2018.

[78] K. Wegener, S. Andrew, A. Raatz, K. Dröder, and C. Herrmann, "Disassembly of electric vehicle batteries using the example of the Audi Q5 hybrid system," *Proc. CIRP*, vol. 23, pp. 155–160, Jan. 2014.

[79] A. Tornow, S. Andrew, F. Dietrich, and K. Dröder, "Impact of multi-material components on the assembly and disassembly of traction batteries," *Proc. CIRP*, vol. 29, pp. 792–797, Jan. 2015.

[80] C. Herrmann, A. Raatz, S. Andrew, and J. Schmitt, "Scenario-based development of disassembly systems for automotive lithium ion battery systems," *Adv. Mater. Res.*, vol. 907, pp. 391–401, Apr. 2014.

[81] K. Wegener, W. H. Chen, F. Dietrich, K. Dröder, and S. Kara, "Robot assisted disassembly for the recycling of electric vehicle batteries," *Proc. CIRP*, vol. 29, pp. 716–721, Apr. 2015.

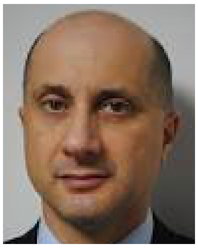
[82] C. Herrmann, A. Raatz, M. Mennenga, J. Schmitt, and S. Andrew, "Assessment of automation potentials for the disassembly of automotive lithium ion battery systems," in *Leveraging Technology for a Sustainable World*, D. A. Dornfeld and B. S. Linke, Eds. Berlin, Germany: Springer, 2012, pp. 149–154.

[83] D. L. Thompson, J. M. Hartley, S. M. Lambert, M. Shiref, G. D. J. Harper, E. Kendrick, P. Anderson, K. S. Ryder, L. Gaines, and A. P. Abbott, "The importance of design in lithium ion battery recycling—A critical review," *Green Chem.*, vol. 22, no. 22, pp. 7585–7603, 2020.

[84] P. Gil, J. Pomares, S. V. P. C. Diaz, F. Candelas, and F. Torres, "Flexible multi-sensorial system for automatic disassembly using cooperative robots," *Int. J. Comput. Integr. Manuf.*, vol. 20, no. 8, pp. 757–772, Dec. 2007.

[85] S. R. Cruz-Ramírez, Y. Mae, T. Arai, T. Takubo, and K. Ohara, "Vision-based hierarchical recognition for dismantling robot applied to interior renewal of buildings: Vision-based hierarchical recognition for dismantling robot," *Comput.-Aided Civil Infrastruct. Eng.*, vol. 26, no. 5, pp. 336–355, Jul. 2011.

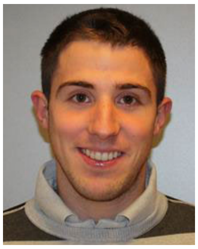
FABIO MANDRILE (Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical engineering from Politecnico di Torino, Italy, in 2017 and 2021, respectively. He is currently an Assistant Professor with Dipartimento Energia "Galileo Ferraris," Politecnico di Torino. His main research interests include virtual synchronous machines and power electronics for grid-connected applications, on which he focused his Ph.D. degree and current research activity.



MICHELE PASTORELLI (Member, IEEE) received the Laurea and Ph.D. degrees in electrical engineering from Politecnico di Torino, Turin, Italy, in 1987 and 1992, respectively. He is currently a Full Professor of electrical machines with Politecnico di Torino. He has been involved as a Consultant in research contracts with foreign and Italian companies. He has authored more than 140 papers published in technical journals and conference proceedings. He was responsible for research programs funded by the Italian Research Ministry and European Bodies. His research interests include power electronics, high-performance servo drives (synchronous drives for both industrial, commercial, and residential applications), and the energetic behavior of electrical machines.

SALVATORE MUSUMECI (Member, IEEE) was born in Giarre, Italy. He received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Catania, Catania, Italy, in 1991 and 1995, respectively. From 1996 to 2001, he was with the Research and Development Department, STMicroelectronics, Catania, as an Application Engineer on power device applications. From 2001 to 2017, he was involved in several research collaborations with the Department of Electrical Electronic and Systems Engineering, University of Catania. Since 2018, he has been an Associate Professor of power electronics, electrical machines, and drives with Dipartimento Energia "Galileo Ferraris," Politecnico di Torino, Turin, Italy. He is involved with the Power Electronics Innovation Center (PEIC), a new competence center of Politecnico di Torino focused on power electronics. He has authored more than 130 papers in scientific journals and international conferences on topics related to the fields of interest described. His research interests include advanced power devices, switching power converter applications, high-efficiency industrial motors, magnetic materials and their applications, battery management systems, and automotive power electronic applications.

IÑAKI AMILLETA URKIRI received the M.Sc. degree in industrial engineering (mechanical engineering) from the University of the Basque Country, Bilbao, Spain, in 2021. He is currently a Researcher with the Mechanical Systems Design Team, Ikerlan, where his activity has been mainly focused on structural engineering for the wind energy sector, fracture mechanics, and energy storage systems design. His main research interests include the design of mechatronic systems and energy storage systems.



ADRIAN REMIREZ received the M.Sc. degree in mechanical engineering from Mondragon University, Spain, in 2012. Since 2013, he has been a Researcher with the Mechanical Design Team, Ikerlan, where he has been focused on the transportation and energy sectors. With his team, he holds three patents and four utility models in different engineering domains. His main research interests include the design of mechatronic systems and energy storage systems.

• • •

Open Access funding provided by 'Politecnico di Torino' within the CRUI CARE Agreement