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Topical Review

Manufacturing of lithium battery toward deep-sea environment

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Abstract

The operation of deep-sea underwater vehicles relies entirely on onboard batteries. However, the extreme deep-sea conditions, characterized by ultrahigh hydraulic pressure, low temperature, and seawater conductivity, pose significant challenges for battery development. These conditions drive the need for specialized designs in deep-sea batteries, incorporating critical aspects of power generation, protection, distribution, and management. Over time, deep-sea battery technology has evolved through multiple generations, with lithium (Li) batteries emerging in recent decades as the preferred power source due to their high energy and reduced operational risks. Although the rapid progress of Li batteries has notably advanced the capabilities of underwater vehicles, critical technical issues remain unresolved. This review first systematically presents the whole picture of deep-sea battery manufacturing, focusing on Li batteries as the current mainstream solution for underwater power. It examines the key aspects of deep-sea Li battery development, including materials selection informed by electro-chemo-mechanics models, component modification and testing, and battery management systems specialized in software and hardware. Finally, it discusses the main challenges limiting the utilization of deep-sea batteries and outlines promising directions for future development. Based on the systematic reflection on deep-sea batteries and discussion on deep-sea Li batteries, this review aims to provide a research foundation for developing underwater power tailored for extreme environmental exploration.

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1. Introduction

The oceans cover over 70% of Earth's surface, representing an immense, largely uncharted frontier rich in natural resources [1, 2]. Although there has been diversified exploration in shallower oceans, the distribution of exploration decreases along the oceanic depth, especially showing rapid under the Hadal zone (deep, sea region ranging below 6000 m down). Deep-sea is considered the largest but least-explored biome [3, 4], primarily due to its extreme environmental conditions. Solar radiation diminishes with depth, resulting in a dark and cold environment in deep-sea [5]. Moreover, a great body of seawater generates intense hydraulic pressure, rising by approximately one atmosphere every ten meters, which exceeds 100 MPa at the Mariana Trench as the deepest seafloor [6]. It demands driving underwater vehicles to access the deep-sea region, while the operation of underwater vehicles in such extreme environments is critically dependent on robust and reliable power sources [6–8].

As the primary power source for underwater vehicles, including submersibles and underwater robots, electrical power is supplied through tethered cables or onboard batteries [9–12]. Submersibles connected to sea-surface facilities via cables receive a continuous and efficient power supply. However, their maneuverability is constrained by the tether length. This limitation intensifies with depth, where extended tethers face increased risks of entanglement from ocean currents. To address these restrictions, onboard batteries have been introduced to enable untethered operation and greater maneuverability. In the 1960s, the bathyscaphe 'Trieste' became the first submersible to reach the seafloor of the Mariana Trench [8], equipped with onboard lead–acid (Pb–acid) and silver-zinc (Ag-Zn) batteries to operate untethered from cables. While onboard batteries remove the spatial constraints of tethers, their power capacity restricts mission duration and range, requiring regular returns to the sea surface for recharging, which is a major disadvantage for prolonged deep-sea missions. Additionally, operating at extreme depth requires onboard batteries with strong resilience to harsh conditions, including high pressure, low temperature, and seawater attack [13, 14]. As the lifeblood of underwater vehicle fleets, deep-sea batteries must be developed with greater power capacity as well as stronger adaptability for deeper ocean operations.

Designing onboard batteries for deep-sea applications demands meticulous consideration of the extreme challenges presented by the harsh underwater environment. To maintain functionality, deep-sea batteries should be intact and undamaged to prevent seawater intrusion and failure due to the extremely high hydraulic pressure at depth. To address these risks, the batteries are typically housed in specially designed, sealed containers that can resist deep-sea environments [15–18], including seawater corrosion, conductivity, hydraulic pressure, and temperature variations. Besides, the improvement in onboard batteries is supportive for upgrading underwater vehicles. For example, increased battery capacity extends the vehicle's endurance, while higher power output enhances cruising speed [19–21]. Hence, onboard batteries can be constantly improved by increasing the available energy density, similar to strategies used in aircraft design, through two main methods: optimizing electrochemical systems and reducing weight to maintain buoyance. It shapes the development stage of deep-sea batteries based on applying diversified electrochemical systems, each offering distinct operational characteristics [22–24]. Important factors in battery design include electrochemical performance like energy density and cyclic aging [25], safety and reliability (e.g., preventing side reactions), and maintenance. Practically, the deep-sea environment poses specific challenges: the enclosed protection structure can impede heat dissipation during battery discharge, and high pressure can affect both electrochemical processes and structural stability [26–28]. Consequently, effective battery management systems (BMS) are crucial for optimizing performance, though they may partially reduce energy density due to the added components. After decades of research, Li batteries have proven to be the most promising power source for deep-sea applications due to their high energy density, safety, and reliability [29–31].

Li batteries are currently the leading power source for deep-sea applications, with the industry evolving rapidly toward modularization and advanced electrochemical systems to support the growing fleet of underwater vehicles [32–34]. Modular Li battery systems offer flexible configurations and customizable electrical performance to suit various underwater vehicle requirements. This modular approach not only facilitates tuning of power distribution but also lowers cost by allowing partial swapping of degraded modules rather than the entire system [35]. Besides this, there are two deep-sea Li electrochemical systems developed, including liquid Li-ion batteries and solid Li-ion batteries applying liquid and solid electrolytes, respectively. Both systems have been validated for application at full-sea-depth [36, 37], yet performance degradation remains a concern due to electrode materials deterioration, which is exacerbated by external pressure [38]. While direct explanations of electrochemical transformation in the deep-sea environment are scarce, the greatest feature of electrode materials evolution is based on the coupling between electrochemistry and mechanics. Therefore, it requires introducing electro-chemo-mechanical models to clarify the change in deep-sea battery electrode

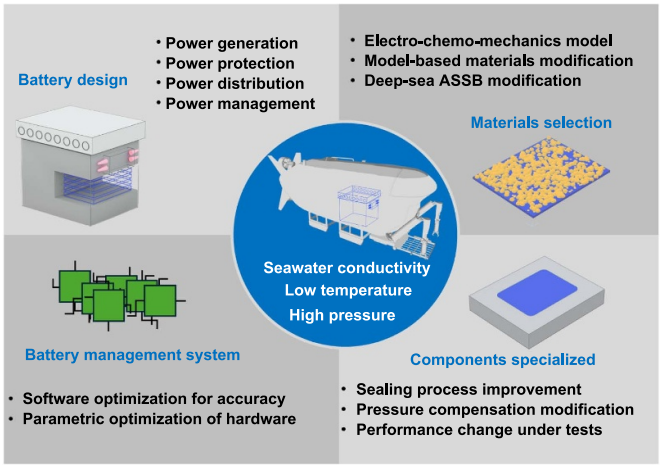

Figure 1. The manufacturing of deep-sea lithium batteries involves the systematic design of deep-sea power and multilevel consideration, including materials selection, components, and the specialized battery management system.

materials and provide targeted strategies for optimizing electrode materials. Moreover, deep-sea Li batteries function as multilevel systems, which are integrated by diversified components, incorporating specialized cells and other essential functional components like BMS. The deep-sea environment requires additional modifications to maintain battery performance reliability and support sustained deep-sea operations, notably in component sealing as well as thermal management to bolster resistance to high pressure and temperature variations.

Over recent decades, there has been extensive research in deep-sea batteries, involving different technological progress like improving electrochemical systems, strengthening power protection, and optimizing BMS. However, previous reviews have largely focused on the practice of deep-sea batteries in different underwater vehicles or specific technological aspects [24, 29, 39]. This review first introduces the systematic design of deep-sea battery manufacturing technology, covering key aspects of power generation, protection, distribution and management (figure 1). Moreover, it highlights the recent progress in deep-sea Li batteries, outlining their major technological features and broader developmental trends. Then, this review delves into the selection of materials for deep-sea Li batteries, emphasizing the application of electro-chemo-mechanics models. It discusses component modifications tailored to the extreme underwater environment and the relevant testing. Additionally, this paper addresses critical aspects of BMS specialized for deep-sea Li batteries, including both software design and hardware optimization, to enhance performance and safety in challenging underwater conditions. Finally, it proceeds with an analysis of the current challenges and future directions in deep-sea Li battery development. This review is devoted to presenting the full picture of deep-sea batteries, especially the promising deep-sea Li batteries, to provide a fundamental insight into the development of deep-sea power.

2. Design of deep-sea battery

As the principal power source for underwater vehicles, onboard batteries are increasingly favored for deeper ocean operations, valued for their enhanced power performance, low vibration, and low noise, which minimize interference with other onboard instruments. This growing demand has driven the development of deep-sea batteries with diverse technical specifications tailored to the specific mission profiles of different underwater vehicles. Over decades of development, the manufacturing of deep-sea batteries has progressively become more principled. The design of deep-sea batteries emphasizes critical aspects, including power generation, protection, distribution and management, alongside continuous improvements in energy density, reliability, and safety. Consequently, diverse technologies for deep-sea batteries have emerged to meet the rigorous demands of deep-sea exploration.

2.1. Power generation

The operation of underwater vehicles relies on the onboard power source to drive propulsion and support diverse submerged functions, such as illumination, communication, and other instrumentation. It indicates the direct enhancement of missions and endurance submerged through improving onboard power sources. Various types of electrochemical systems have been developed as power sources for running underwater vehicles [24], broadly categorized into primary batteries and secondary batteries, with secondary batteries preferred for deep-sea underwater vehicles due to their ability to be recharged without the retrieval to the sea surface for costly replacement. Both primary and secondary batteries are basically composed of an anode, cathode, and electrolyte [30], while the greatest difference lies in rechargeability, as primary batteries are non-rechargeable. Despite this limitation, primary batteries, such as Li/$SOCl_2$, Li/CF_x, and alkaline batteries [17, 40–42], are still utilized because of their significantly higher energy density compared to secondary batteries, albeit at the cost of irreversible performance degradation during discharge. This limits the reusability of primary batteries, necessitating the swap for the next launch, which increases turnaround time greatly. Hence, primary batteries are applied more in unmanned underwater devices for long-endurance missions or auxiliary power sources for onboard instruments specialized to reduce failure risks submerged.

Comparatively, secondary batteries are the optimal power source for reusable underwater operations, greatly reducing both costs and the technical complexity associated with replacing primary batteries after each dive. However, secondary batteries require a ‘breathing’ period for recharging, where the battery discharges while submerged to power onboard instruments and then charges at the sea surface to enable the next dive [43]. Various secondary batteries have been developed for underwater applications, mainly including Pb–acid [44], Ni–Cd [45], Ag–Zn [46], and Li batteries. These batteries have successively supported generations of underwater vehicles, enhancing their diving depth capabilities and

Table 1. The practice of various electrochemical system types as underwater power generation.

Types	Energy Density ($W{\cdot}h{\cdot}kg^{-1}$)	Power (kW·h)	Depth (m)	Submersibles	References
Pb–acid	33–45	35	4500	Alvin	[13]
Pb–acid		44	6000	Nautile	[56]
Ag–Zn	40–110	86	6527	Shinkai 6500	[57]
Ag–Zn		110	7062	Jiaolong	[52]
Li-ion	150–600	96	10 898	Deepsea Challenger	[58]
Li-ion		110	10 909	Fendouzhe	Our team

submerged operational endurance (table 1), with Li batteries presently leading in underwater power applications. The early manned submersible 'Alvin' set the stage with Pb–acid batteries, establishing this technology as global popularity for its maturity and reliability [47]. However, the limited capacity of Pb–acid batteries constrained the advancement of underwater vehicles. Hence, Ag–Zn batteries are employed due to larger energy density, contributing to deeper dives and allowing the increase of onboard instruments. Despite these benefits, both Pb–acid and Ag–Zn batteries raise significant safety concerns about gas emissions [48–50], especially hydrogen gas, which is highly explosive, along with other toxic gases. These batteries require venting mechanisms to process gases produced safely, which further compromises energy density. Recently, Li batteries have become increasingly preferred, offering markedly higher energy density and resolving many of the risks associated with conventional battery chemistries, thus significantly lowering operational hazards [50, 51]. Herein, the technical attributes of the main types of secondary batteries are summarized comparatively to explain the shift from conventional onboard batteries to Li batteries.

Pb–Acid Battery The origin of deep-sea industry lies with the Pb–acid battery, first employed in the 1960s by the pioneering research submersible 'Alvin', which was powered by a Pb–acid battery (35 kW·h) that supported key operations such as photography and acoustic scanning. This early application established the Pb–acid battery industry with mature manufacturing techniques as well as lower cost. Pb–acid batteries are structurally composed of cathode (PbO_2), anode (Pb), and electrolyte (H_2SO_4), and it is rechargeable based on a reversible electrochemical reaction. However, this electrochemical configuration is heavy and limits energy density. Besides, huge capacity loss occurs irreversibly resulting from $PbSO_4$ buildup during high-rate discharge, which drastically shortens service life. Additionally, hydrogen generation during recharging poses a serious explosion risk as hydrogen accumulates. These inherent limitations underscore the challenges of Pb–acid battery technology in deep-sea contexts and highlight the ongoing need for better solutions.

Ag–Zn Battery Given the limitations of Pb–acid batteries, Ag–Zn batteries were developed with higher energy density and high-rate discharge capability, which allowed submersibles to reach unprecedented depths. The submersible 'Shinkai 6500' powered by an Ag–Zn battery (86 kW·h), set a depth record of 6527 m [34]. This record was later broken by the submersible 'Jiaolong', which achieved a 7000 m descent, and was also powered by an onboard Ag–Zn battery (110 kW·h) [52, 53]. Ag–Zn batteries mainly consist of cathode (silver oxides), anode (Zn), and electrolyte (KOH), and it is rechargeable through a reversible electrochemical reaction. However, they are costly due to their reliance on silver as a noble metal component. Despite their advantages over Pb–acid batteries, Ag–Zn batteries are challenged by inherent issues, notably hydrogen gas release during zinc corrosion by the alkaline electrolyte, which poses explosion risks when mixed with oxygen decomposed from cathode oxides. Moreover, mercury alloyed in Zn anode may be vaporized due to heat accumulated while abusing an Ag–Zn battery, highlighting significant safety concerns for deep-sea applications.

In addition to these batteries, various electrochemical systems have been successfully adapted for deep-sea power applications. For example, an alkaline aluminum hydrogen peroxide semi-fuel cell was developed to power an autonomous underwater vehicle (HUGIN 3000), offering a high energy density without the weight penalty under ambient pressure. However, the need for constant chemical replenishment limits its operational scope and raises concerns over safe chemical handling [54]. Fuel cells, with superior energy density, offer additional promise but remain constrained by unresolved challenges in fuel storage and transport [18, 55]. The high-pressure storage of reactive gases like hydrogen and oxygen imposes strict sealing requirements while refueling logistics are costly and complex. Consequently, fuel cells currently find use in smaller-scale power applications like unmanned underwater vehicles (UUVs), where safety concerns are more manageable.

2.2. Power protection

Although the design of power protection with additional weight reduces the energy density of deep-sea batteries, the protection specialized for deep-sea batteries is essential for ensuring reliable operation at extreme depths. There are two main popular configurations of power protection referred to as

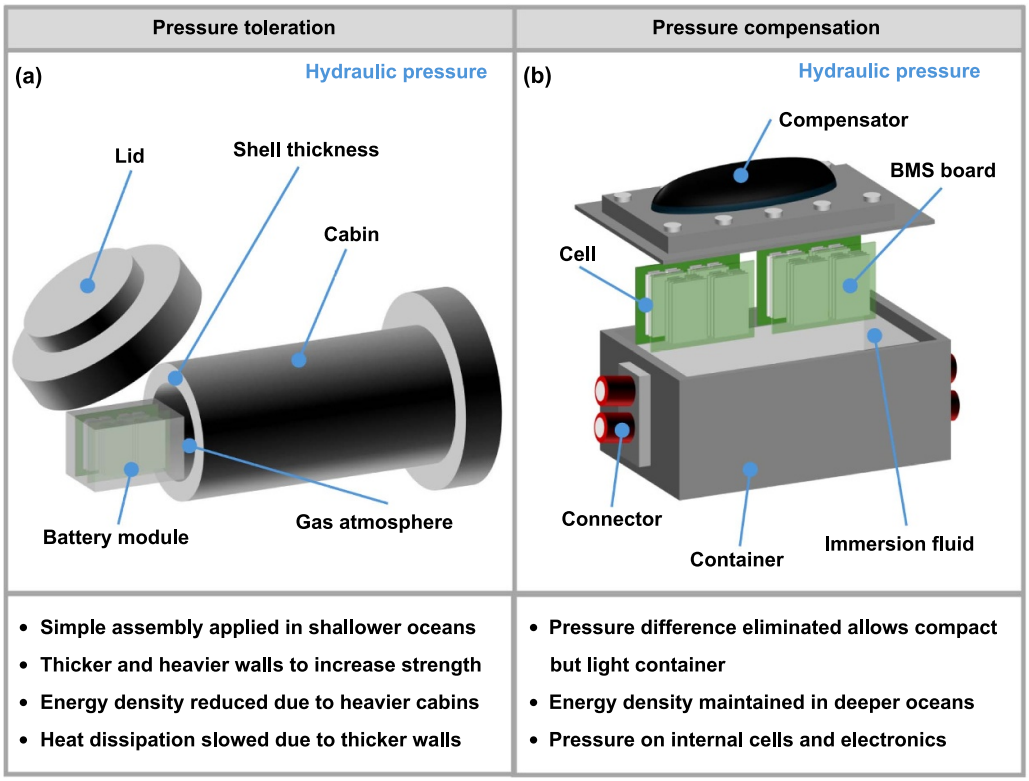

Figure 2. The scheme of designing two power protection configurations specialized for deep-sea batteries, including (a) pressure toleration and (b) pressure compensation configurations.

pressure toleration and pressure compensation. Pressure toleration is more commonly applied in shallower oceans, while pressure compensation is preferred in deeper oceans.

In the pressure toleration configuration, deep-sea battery cells are enclosed within sealed, pressure-resistant cabins that shield them from seawater, maintaining a dry internal environment [17, 18]. These cabins are mostly streamlined to fit the structural design of underwater vehicles, optimizing spatial efficiency (figure 2(a)). Cylindrical housings, for example, are common in torpedo-shaped autonomous underwater vehicles [59]. This simple configuration is widely applied to isolate the batteries from deep-sea conditions but fairly demands highly resilient, watertight casings. To achieve this, various materials with high mechanical strength, such as aluminum, magnesium, titanium alloys, and ceramics, are processed for the casings. It features the higher strength of cabins resulting from shells of larger thickness [30], while the selection is ruled by the trade-off between mechanical stability and density to maximize the energy density of deep-sea batteries [60]. For shallower dives, lighter aluminum alloys are often preferred, whereas deep-sea missions favor titanium to avoid less available volume due to the thickening shells of aluminum alloys. However, the heavier shells raise the buoyancy load, causing additional electrical power consumption [61]. Thus, as descending into deeper waters, the pressure toleration configuration reduces the energy density of deep-sea batteries obviously, ultimately limiting the depth and duration of underwater exploration.

To address the limitations of the pressure toleration configuration, a pressure compensation configuration has been developed. This design equalizes pressure inside and outside the battery housing, requiring only sealed, intact enclosures instead of heavily reinforced and thicker shells. In this configuration, deep-sea cells are immersed in an insulating fluid of incompressibility, typically oil, within a container that connects to a pressure compensator, such as a flexible membrane or piston, which maintains equilibrium between internal and external pressure (figure 2(b)) [54, 62]. Notably, the seawater battery has been proposed as a promising alternative thanks to its environmental benefits by applying seawater directly [63, 64], which eliminates the need for insulating media that compromise the energy density of batteries. However, the low concentration of dissolved oxygen in seawater limits its support to underwater vehicle operations, and corrosive side reactions can damage battery components, raising operational risks significantly [65]. Therefore, oil-immersed battery designs remain the primary choice for powering underwater vehicles in the deep-sea. In a pressure compensation configuration, as external pressure increases with depth, the compensator deforms inward, transmitting this pressure to the insulating oil and balancing the internal and external conditions. This design optimizes internal space for placing onboard cells, reduces structural weight load, and allows for greater power capacity at extreme depths, as demonstrated by full-sea-depth batteries deployed on missions to the Mariana Trench. However, unlike the constant atmosphere in pressure toleration configuration,

pressure transmission also subjects internal cells to varying depths, which may alter the performance of deep-sea cells, necessitating specialized manufacturing to withstand these conditions. Although it discards heavy cabins, the metallic shells must be compact structurally and corrosion-resistant to both seawater and internal fluids. Similarly, the compensator, often the flexible membrane, is susceptible to deterioration under repeated deformation due to varying ambient pressure, with normal nitrile butadiene rubber (NBR) prone to rapid aging with instant cracking growth, which therefore requires specialized modification on hydrogenated NBR base. The fluid-filled in the container is required with incompressibility to avoid internal void space that could deform and destroy the structure. Additionally, it is designed to be insulated to prevent short-circuit owing to seawater invasion [66, 67], and it also shows the advantage of oil bathing in accelerating thermal transfer to prevent local heat concentration happening commonly in pressure-tolerant cabins [68]. In some cases, solid potting is used as pressure transfer media, but this option requires more on the manufacturing process to eliminate voids, as even minor imperfections can severely impair pressure compensation [62].

2.3. Power distribution and management

Onboard power consumption for underwater vehicles is primarily split between propulsion and instrumentation [69], both of which typically operate on alternative current (AC), while deep-sea batteries generate direct current (DC). To bridge this gap, specialized converters are essential for AC–DC transformation, alongside connection devices such as cables and penetrators to facilitate secure power transport [70–72]. These components are designed with unique specifications according to the protection configurations in use. In a pressure toleration configuration, they are shielded from conductive seawater through waterproof, insulated enclosures, as pressure resistance is not a concern. Conversely, in a pressure compensation configuration, these components are housed in enclosures that additionally withstand ambient pressure. The distribution of onboard power relies on these components to meet the diverse electrical demands of different instruments, which often require precise, controlled power output. It not only depends on designing the circuit diagram but also on the further arrangement of the power sources.

The onboard power of underwater vehicles is allocated to support various instruments, making the power consumption spectrum essential in determining the specifications of deep-sea batteries, such as available capacity and nominal voltage. These parameters are achieved through constructing modular power systems, where battery modules can be arranged to tailor voltage and capacity. There are two basic modes including in-series and in-parallel, which are primely applied for adjusting voltage and capacity, respectively. Specifically, each battery module is constructed from cells arranged in series and in parallel [23, 73], allowing for precise tuning of power output. This modular design enables customization based on the unique power demands of different underwater vehicles. A standardized mechanical design across modules for a given underwater vehicle class enables easy replacement of individual modules without the removal of the entire battery system. This modular approach not only simplifies power-swapping processes but also reduces operational risks by enabling targeted management of local failing modules [33, 74]. Besides this, the use of smaller cells enhances safety, although the greater number of cells may marginally raise the probability of incidents, any resulting issues are more localized with less severity.

Effective power management in underwater vehicles is critical for meeting diverse operational requirements and addressing safety and reliability challenges inherent to deep-sea batteries [75, 76]. On one hand, the varied mission profiles of underwater vehicles such as sampling, varying-speed cruising, and tilting at different depths [77, 78], demand power management strategies that optimize power distribution across all onboard systems rather than focusing solely on the battery. This approach maximizes power utilization and reduces the load on the power system [79]. On the other hand, robust safety management is crucial to mitigate potential battery failures, including risks such as thermal runaway, seawater infiltration, and mechanical destruction. Therefore, various tailored subsystems are required for resolving the safety issues emerging in different underwater vehicles, for instance, balancing subsystems that equalize charge across cells can prevent localized failure, improving overall battery stability and operational safety [80]. By increasing the output from cells with more capacity retention and reducing the participation of abused cells, the overall utilization of batteries arises, thereby avoiding the risk of local cell failure and improving safety as well. Additionally, it is necessary to implement a disconnection to handle uncontrollable events, exampled as isolating a malfunctioning battery module to prevent the escalation of potential danger while minimizing power loss. Despite the numerous safety and reliability issues, operational failure primarily originates from abnormal status in individual units. These anomalies can be effectively detected through real-time monitoring to analyze the instant state, with common issues including over (dis)charge, under voltage, short-circuit, and imbalanced SOC (state of charge) [35, 81]. The detection of these basic parameters is crucial for devising efficient intervention strategies, requiring the application of robust monitoring systems specialized for deep-sea batteries. Considering numerous cells assembled together, the implementation of a battery management system is essential to strengthen the reliability, safety, and service life of deep-sea batteries. These deep-sea battery systems are typically organized in a multilayered architecture, comprising an array of cells within a module [82], ultimately forming the sophisticated multilayered structure that defines the BMS.

2.4. Deep-sea Li battery

The rapid growth of deep-sea Li batteries occupies increasingly in the deep-sea power industry, while it has boosted the technological transformation of underwater vehicles

over recent decades. This shift is largely attributed to the unique virtues of Li batteries, including their compact structure, adaptable configurations, and exceptional power performance, alongside heightened safety and reliability. These attributes have enabled the development of diverse deep-sea Li battery types, now deployed in a wide array of underwater vehicle models. According to rechargeability, deep-sea Li batteries are classified into primary and secondary types. Although primary deep-sea Li batteries have a much larger capacity and higher potential, secondary deep-sea Li batteries are adopted as onboard power preferentially due to the practical demand of underwater vehicles. For most primary Li batteries, despite their high energy density, they pose significant thermal runaway risks while submerged [62], and the need for replacement between dives adds both time and expense. In contrast, secondary Li batteries are highly regarded for their sustainability and safety profile, though continued optimization is needed to enhance power performance. While Li batteries in pressure toleration configuration are widely used in shallower oceans, increasing demand for full-sea-depth Li batteries presents new challenges. The extreme conditions at full-sea-depth such as low temperatures, particularly intense hydraulic pressure, significantly require mechanics as a main factor in designing deep-sea Li batteries, for example, electrochemical reactions altered by external pressure and component resistance to mechanical force. Moreover, thermal management is always unignorable for the systematic manufacturing of deep-sea Li batteries. Given deep-sea Li batteries enclosed in cabins, heat generation during discharging brings unexpected damage to batteries, such as poor heat transfer and nonuniform thermal distribution. Thus, effective manufacturing of deep-sea Li batteries is determined by the trade-off among multiple factors including power performance, safety, cost, and additional considerations to the specific needs of various underwater vehicles.

The evolution of deep-sea Li batteries employed for underwater vehicles highlights two main trends. On one hand, underwater vehicles equipped with conventional power sources have transitioned to Li batteries, which offer a larger capacity to improve operation submerged substantially. For example, as introduced before, the 'Shinkai 6500' submersible initially ran on Ag–Zn batteries but switched to Li-ion batteries in 2004 [34], improving overall performance by extending service life, lowering weight, and reducing maintenance. Even the earliest research submersible 'Alvin' submersible, has plans for a Li battery upgrade based on the comprehensive evaluation of diversified underwater battery candidates [13]. Recently, Li batteries have been the preferred power source in newly developed submersibles, especially for the most manned submersibles such as 'Deepsea Challenger' and 'Limiting factor' submersibles, attesting to their suitability for deep-sea exploration. On the other hand, there are constant efforts to improve deep-sea Li batteries, focusing on materials selection, component modifications, and functional system optimization. Till now, the popularity of developing deep-sea Li batteries has been raised significantly for constructing the fleet of underwater vehicles, which has achieved serial development of various underwater vehicles. It is worth noting that the high modularity and flexibility of manufacturing deep-sea Li batteries have shaped the genealogical development of full-sea-depth Li batteries [32], which get validated by the successive development in 'Haidou', 'Haidou I', 'Fendouzhe', and 'Siyuan' submersibles successively (figure 3). In June 2016, the diving of 'Haidou' submersible reached 10 767 m down with the onboard pressure-resistant Li-ion battery with cells of 45 Ah and 2.5 kW·h capacity developed by our team. By April 2020, with the support of the upgraded pressure-resistant deep-sea Li-ion battery with cells of 45 Ah and 25 kW·h capacity developed by our team, 'Haidou I' completed the first 10 000 m-level sea trial and experimental application mission successfully. Since October 2020, 'Fendouzhe' has successfully bottomed at the Mariana Trench in 10 909 m down, which renewed the former record once more. 'Fendouzhe' HOV has still adopted our team-developed deep-sea Li battery with 110 kW·h capacity as well as 12 700 m-level pressure resistance. Additionally, another type of deep-sea Li battery with cells of 35 kW·h capacity has been equipped in the China-developed 'Siyuan' unmanned underwater vehicle, which completed a series of deep-sea experiments in the high seas of the Western Pacific Ocean in August 2021. This submersible with the outstanding performance of the maximum 8072 m diving depth and the longest work period of over 8 h is capable of various research instanced as seabed detection and sampling.

3. Materials for deep-sea Li battery

Deep-sea Li batteries encompass a range of electrochemical systems, primarily categorized into liquid and solid Li-ion batteries based on the type of electrolyte. For liquid Li-ion batteries, the liquid electrolyte flows easily to infiltrate the interface between electrode and electrolyte to allow efficient ion exchange. This fluidity accommodates SOC-induced electrode deformation, thereby reducing mechanical conflict and ensuring stable contact among cell components to maintain long cyclic performance. However, the inflammability of many liquid electrolytes makes them particularly susceptible to thermal runaway [83], especially in enclosed spaces with limited heat dissipation capabilities. Comparatively, solid Li-ion batteries exhibit higher energy density and enhanced safety owing to the thermal stability of solid electrolytes (polymer-based typically), while which is (quasi)solid-state with inferior rheological performance to conform to electrode surfaces poorly, hence, it requires the modifications of altering electrolyte deformability to maintain solid contact between electrolyte and electrode [84]. Although solid Li-ion batteries offer the competent potential as liquid counterparts for deep-sea applications, their manufacturing demands sophisticated technology as well as higher costs. Consequently, liquid Li-ion batteries are currently favored for large-scale power needs, especially in manned submersibles with extremely high requirements.

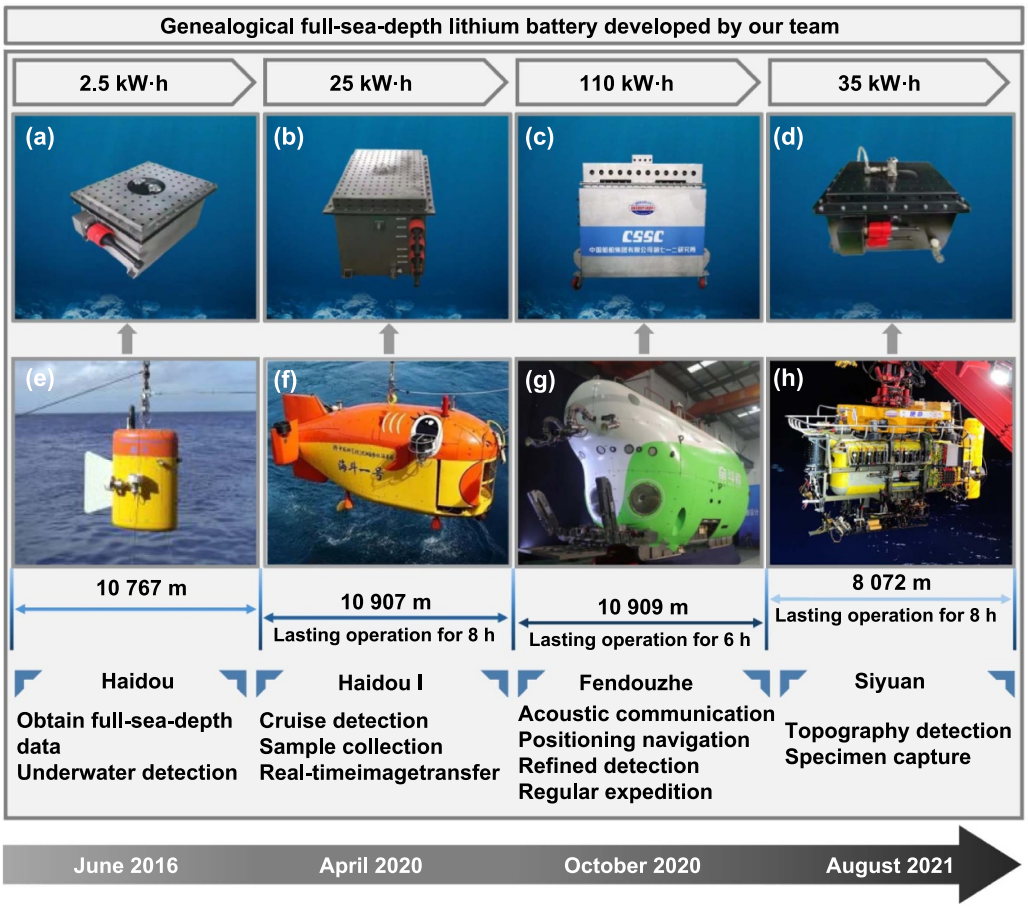

Figure 3. Genealogical development of the serial underwater vehicles based on deep-sea lithium batteries developed by our team systematically. (a) Deep-sea Li battery of 2.5 kW·h equipped in (e) 'Haidou' submersible. (b) Deep-sea Li battery of 25 kW·h equipped in (f) 'Haidou I' submersible. (c) Deep-sea Li battery of 110 kW·h equipped in (g) 'Fendouzhe' submersible. (d) Deep-sea Li battery of 35 kW·h equipped in (h) 'Siyuan' submersible. Among them, 'Haidou', 'Haidou I' and 'Siyuan' submersibles are categorized into unmanned underwater vehicles (UUVs), while 'Fendouzhe' submersible is categorized into human occupied vehicles (HOVs). Normally, HOVs are more complicated than UUVs technically with higher power requirements for exclusive onboard instruments like survival systems.

Additionally, deep-sea Li batteries are mainly protected through either pressure toleration or pressure compensation designs. In the pressure toleration configuration, deep-sea cells housed within a constant cabin atmosphere, are shielded from direct exposure to the high-pressure deep-sea environment. As a result, thermal management receives concerns majorly instead of external environmental influence on electrochemical reactions. Comparatively, the pressure compensation designs expose Li cells directly to ambient external pressure. This configuration introduces numerous unexpected issues, especially electro-chemo-mechanical challenges as high external pressure can impact electrochemical behavior, altering reaction processes and interactions within cells. Accordingly, hydraulic pressure encountered at extreme depths poses the greatest challenge for constructing deep-sea batteries, requiring the selection of suitable materials for deep-sea Li batteries based on the coupling between electrochemistry and mechanics.

The mechanical stability of electrode materials sustains consistent electrochemical reactions, yet electrochemical reactions will gradually degrade electrode materials structurally in turn, such as capacity fading due to active particle crack growth during recharge cycles [85]. It suggests electro-chemo-mechanical couple can be influenced by external hydraulic pressure as a mechanical parameter, which is fundamental to designing electrode materials specialized for deep-sea Li batteries. There are mainly two types of deep-sea Li electrochemical systems applying liquid and solid electrolyte materials in deep-sea Li batteries. Hence, there are different considerations for applying materials to improve deep-sea Li batteries performance.

3.1. Deep-sea liquid Li-ion battery

In deep-sea Li-ion batteries with liquid electrolytes, the flowability of liquid electrolytes minimizes mechanical conflicts between electrolytes, but structural degradation of electrode materials still leads to electrochemical failure during repeated cycles, even electrode materials applied in deep-sea show much larger mechanical strength than the maximum hydraulic pressure encountered [86, 87]. There are quite a few research having tried various electrode materials to improve power

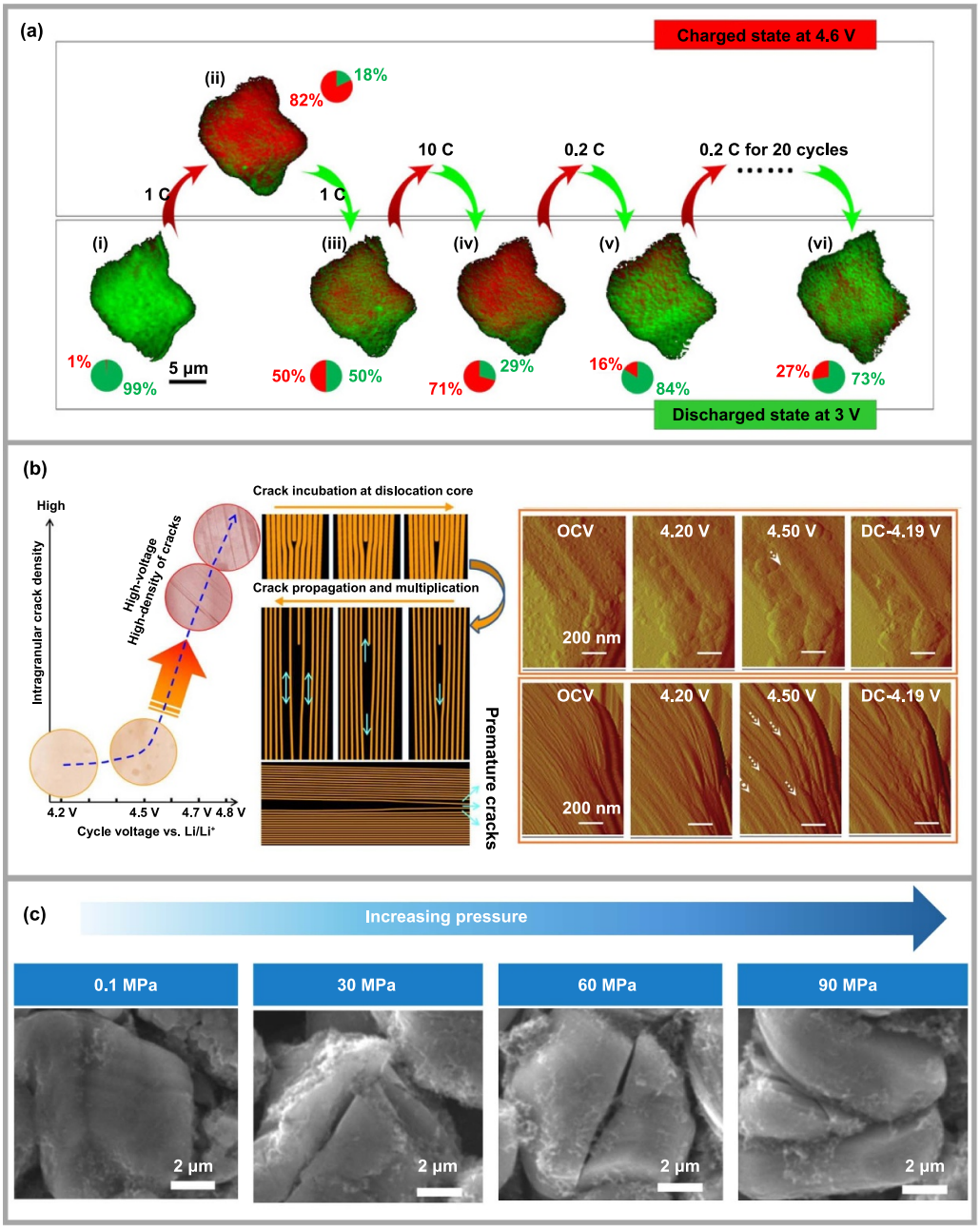

Figure 4. The electro-chemo-mechanical evolution of electrode materials considering the application of deep-sea Li battery in different conditions, including (a) larger current. Reprinted with permission from [89]. Copyright (2017) American Chemical Society. (b) High voltage. Reproduced from [93]. CC BY 4.0. From [94]. Reprinted with permission from AAAS. and (c) ambient pressure. Reprinted from [38],© 2022 Elsevier Ltd All rights reserved.

performance. For example, according to comparing a series of carbon materials, graphite anode offering a larger capacity, has a lower current density than hard carbon, which suffers from rapid capacity drop. Besides this, cathode materials present their specific limitations as well, for instance, $LiCoO_2$ delivers large capacity as well as high working potential but is unstable structurally under cycling, whereas $LiMn_2O_4$ shows safety in high-voltage conditions but has limited capacity, blocking its broader application [88]. These issues reflect inherent mechanical degradation in electrode materials during electrochemical reactions, even at normal atmospheres, suggesting that deeper submersion further exacerbates these challenges. In the pressure toleration configuration, a stable atmosphere cannot keep active particles intact under electrical shock. In the pressure compensation configuration, high external hydraulic pressure (∼90 MPa) will accelerate electro-chemo-mechanical stress generation in cathode materials ($LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$) during cycles [38], inducing fast capacity decay with more fracture distribution (figure 4(c)). Therefore, it is fundamental to figuring out the electro-chemo-mechanical evolution of

electrode materials in different electrical conditions, especially the constant requirements on deep-sea Li batteries, including large-current and high-voltage.

Large-Current For deep-sea Li batteries, large-current (high-rate) performance is consistently sought to maximize power capacity for onboard instrumentation and shorten turnaround time through faster charging after submersible recovery. However, large-current cycling exerts intense mechanical stress on electrode materials, usually leading to particle pulverization [89–91], rapid capacity fade, and reduced service life (figure 4(a)). During low-rate cycles, sufficient time for ionic transfer allows complete phase change throughout the particle, resulting in a uniform single-phase distribution that prevents internal mechanical differences. In contrast, during high-rate cycles, the slower ionic transfer relative to electronic transfer causes incomplete (dis)charge states within the particles. This discrepancy establishes a steep concentration slope, generating mechanical stress to destroy particles structurally [92]. Moreover, high-rate (dis)charge intensifies side reactions, further compromising the integrity of electrode materials. For instance, the thickening of the solid-electrolyte interphase (SEI) can lead to atomic layer exfoliation, weakening the electrode as well as accelerating performance degradation.

High-Voltage For underwater vehicle propulsion, high-voltage is essential for boosting maneuverability and allows for additional onboard instrumentation, enhancing operational versatility. However, the high-voltage intensifies defect growth within electrode particles, further inducing irreversible particle deformation. Yan *et al* validated that higher applied voltage significantly increases dislocation density, including intergranular and intragranular dislocation [93]. Moreover, Bi *et al* concluded that the diffusion of edge dislocation driven by high-voltage generates stress to force planar gliding, which leaves sliding steps exposed on monocrystal electrode particle surfaces irreversibly (figure 4(b)) [94]. This grain deformation intensifies mechanical conflicts among primary grains, accelerating secondary particle breakdown, moreover, the exposed sliding steps on particle surfaces increase susceptibility to side reactions with the liquid electrolyte.

Based on depicting electro-chemo-mechanical evolution in electrode materials under electrical shock, a range of modification strategies have been developed to improve the performance of deep-sea Li batteries. Despite the diversity of these approaches, each targets a specific stage within the electro-chemo-mechanical process to strike an optimal balance between mechanical stability and electrochemical reactions during cycling. Herein, design strategies specialized for improving electrode materials for deep-sea Li batteries are presented.

Size To alleviate stress generated from sluggish ionic diffusion in monocrystal particles, two main strategies have emerged: prolonging diffusion time under low-rate (dis)charge or minimizing diffusion distance during high-rate (dis)charge. Jiang *et al* compared the rate-performance of small and large particles, concluding that smaller particles show more uncertainty of detachment from the electrode matrix [95]. Moreover, sluggish diffusion happened across larger particles inducing phase separation of two-phase reactions, while one-phase reactions persisted within the particles of a small scale leading to a solid solution process [96]. This implies two fundamentally different models for mechanical analysis of the (de)lithiation of solids, while also establishing lattice strain at the interface between the inner and outer phases. It indicates downscaling particle size to achieve fast ionic diffusion, which contributes to large-current performance significantly. Of note, there is a lower tap density of active particles with smaller size compromising energy density [97], which consequently sets a practical limit to the degree of downscaling particle size based on onboard power requirements.

Morphology In practical applications, most electrode materials consist of polycrystalline particles (secondary particles) formed by aggregating monocrystalline particles (primary particles). This aggregation brings about mechanical conflict at interfaces between primary particles, inducing the crushing of secondary particles as primary particles deform [98, 99]. There is a strategy to mitigate this internal mechanical stress by adjusting the contact configuration between particles appropriately. For example, by tuning grain alignment along the radial direction with more active facets exposed instead of disordered stacking, Xu *et al* obtained grains with radial deformation, where mechanical conflicts are diminished to maintain structural integrity [100]. There are plenty of morphology modification methods to optimize electro-chemo-mechanical properties to improve electrode performance, however, implementing these modifications incurs additional manufacturing costs and technological complexity.

Composition For intercalation-type electrode materials, their elasticity is derived from lattice breathing during the reversible migration of Li ions migration, while it decays obviously due to irreversible structural degradation under electrical shock. For example, cobalt-based cathode materials were early selected for deep-sea Li batteries due to their superior energy density (150 $Wh{\cdot}kg^{-1}$) compared to conventional batteries, while it is further replaced by nickel-based materials, which exhibit even higher energy density (190 $Wh{\cdot}kg^{-1}$) [101]. $LiCoO_2$, favored for its relatively higher potential and large capacity, experiences a significant capacity drop under high-voltage-induced stress due to mechanical strain from irreversible phase transitions [102, 103], which damages structural stability as well as increases power maintenance costs. Beyond selecting different base materials, tuning composition offers another strategy to improve electrode performance [104, 105]. According to the introduction of different dopants, the intrinsic structural collapse is diminished by the dopants pillar, as well as hinders detrimental ions diffusion.

Deep-sea Li batteries commonly use various carbon materials for their anodes, such as graphite, hard carbon, mesocarbon microbeads, favored for their robustness under extreme hydraulic pressures (up to 115 MPa) which maintains effective Li ion diffusion. In contrast, it shows greater influence at the electrode scale resulting from structural deformation under pressure. Despite this, carbon materials are limited by comparatively low capacity, prompting research into alloy-type

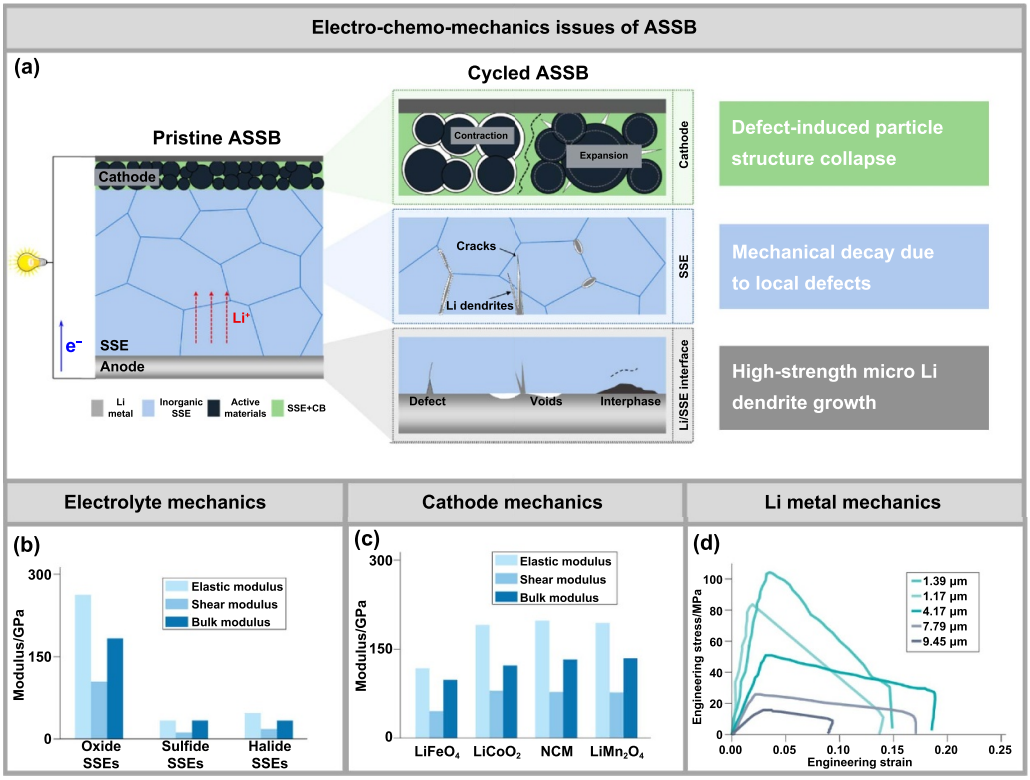

Figure 5. The distribution of electro-chemo-mechanical issues in ASSB, and the related mechanics of different constituents of ASSB. (a) The main issues of ASSB are based on electro-chemo-mechanics, blocking the development of deep-sea solid Li-ion batteries. Reprinted with permission from [116]. Copyright (2022) American Chemical Society. It involves with basic mechanics of different constituents of ASSB.. Including (b) electrolyte. Reproduced from [86], with permission from Springer Nature. (c) Cathode. Reproduced from [86], with permission from Springer Nature. And (d) Li metal. Reproduced from [86], with permission from Springer Nature.

electrode materials with higher theoretical capacities. Yoshida *et al* investigated alloy-type materials of Sn to increase the capacity of single cells under 110 MPa, while a poor capacity is delivered by applying pure Sn composite metal. As applying Sn composite consisting of few carbon black, it obtains an initial charge capacity of 553 mAh·g^{-1} as paired with Li metal, and a lower capacity of 126 mAh·g^{-1} as paired with nickel-containing cathode [88]. This is concluded as the result of structural destruction of anode materials in the early stage. It suggests the mixture of composite metal and carbon is a better choice for alloy-type anode than pure metal.

3.2. Deep-sea solid Li-ion battery

Li polymer batteries, as an alternative to liquid Li-ion batteries, offer higher energy density in light and compact design by incorporating solid-state electrolytes in place of liquid electrolytes. This improvement is made possible by replacing liquid electrolytes with solid-state counterparts, eliminating the need for thermally unstable separators and flammable carbonate liquids. Solid-state electrolytes are categorized into polymer and inorganic substances (e.g., oxides, and sulfides). While polymer electrolytes currently dominate deep-sea solid Li-ion batteries, the development of deep-sea power will increasingly depend on the electro-chemo-mechanical analysis of all-solid-state batteries (ASSBs). This is especially significant as ASSBs show great potential for incorporating Li metal electrodes to provide higher energy density for deep-sea power. Solid-state electrolytes offer several advantages over liquid systems in the deep-sea environment. Their inherent rigidity ensures a compact and uniform configuration, avoiding inhomogeneities caused by liquid electrolytes being compressed into localized defects under external pressure. The bulk robustness of solid-state electrolytes provides exceptional resistance to hydraulic pressure, preserving the structural integrity, unlike the deformability associated with ductile liquid electrolytes. They also exhibit higher mechanical strength to suppress Li dendrite growth at a high current density, preventing penetration into liquid electrolytes, which typically have low shear strength. However, a few technical barriers are hindering the widespread adoption of solid-state electrolytes for deep-sea power (figure 5(a)).

For ASSBs deployed in extreme deep-sea conditions, external pressure may deform ASSBs structurally once voids exist within the battery components. This requires compact assembly and dense, robust components capable of withstanding external pressure [54]. Ideally, the mechanical strength of these components must surpass the external pressure encountered in deep-sea to keep stability structurally. For most cathode and inorganic electrolyte materials, their intrinsic strength significantly exceeds hydraulic pressure in the deep-sea (figures 5(b) and (c)), providing

a theoretical foundation for structural resilience at full-sea-depth. Considering varying hydraulic pressure at different sea depths, it selects various solid components by comparing solid mechanical strength and external pressure maximum. However, the electrochemical reactions introduce irreversible mechanical deformations, such as phase transitions and atomic mixing, which gradually erode their mechanical integrity. These internal defects lower the threshold for crack initiation and propagation, rendering the materials with weakened strength increasingly susceptible to failure under hydraulic pressure. This coupling of electrochemical-induced mechanical instability and external pressure complicates the design of ASSBs, as such deformations are largely irreversible without active intervention. Although ASSBs are often manufactured densely using techniques like thermal sintering or cold compression, the initial intimate contact between the electrode and solid electrolyte tends to degrade over time. During the subsequent cycling, interfacial voids form, disrupting ionic transport pathways and increasing impedance [106–108]. Unlike liquid electrolytes, which are highly deformable and can fill gaps and restore contact, compensating for deformation energy to remove interfacial mechanical conflict, both solid electrolytes and electrodes are stiff and lack self-healing capability. This rigidity intensifies mechanical conflict at the electrode–electrolyte interface, causing localized stress accumulation [109]. It suggests that the likelihood of crack propagation increases if stress concentrations exceed solid strength, further accelerating structural degradation. Applying external pressure has been proposed as a strategy to mitigate interfacial contact loss by forcing solid components into closer contact, thereby reducing void formation [86, 107]. However, excessive external pressure risks damaging battery components, such as fracturing electrodes or deforming current collectors, potentially resulting in catastrophic failure. Importantly, determining the optimal external pressure requires evaluating the dynamic electro-chemo-mechanical behaviors of ASSBs. The static mechanical strength of solid components is insufficient for evaluation, as their structure and composition evolve during electrochemical reactions. Conclusively, performance fluctuations caused by the pressure changes experienced during underwater vehicle ascent and descent underscore the need for solid electrolytes with greater toughness to tolerate electrode deformation while keeping effective contact to complete stable ionic transport.

Although Li metal presents significant risks due to uncontrollable dendrite growth, the rigid nature of solid electrolytes provides a compressive constraint to inhibit axial dendrite penetration into other components. According to Monroe-Newman model, Li dendrite growth can theoretically be suppressed when the shear modulus of polymer exceeds twice that of Li metal [110]. Of note, Xu *et al* demonstrated that the mechanics of Li metal vary at different scales (figure 5(d)), revealing larger strength at a smaller scale, which underscores the importance of scale-specific design for Li metal batteries [111]. While high deep-sea pressure may hinder dendrite growth macroscopically, local penetration remains a risk in regions where Li dendrites exhibit higher rigidity than solid electrolytes [112, 113]. Although inorganic solid electrolytes generally possess higher shear strength than their polymeric counterparts, they are not impervious to dendrite growth, primarily due to inherent mechanical imperfections. Unlike polymer electrolytes, which are characterized by nearly perfect structure, inorganic solid electrolytes are susceptible to defect-driven degradation. According to Griffith's theories, structural imperfections like cracks and grain boundaries act as stress concentrators, greatly lowering the threshold for crack propagation while serving as nucleation sites for dendrite growth owing to higher surface energy [114, 115]. These defects preferentially trap guest ions due to the relatively wide energy gap to escape, concentrating Li deposition at these sites and facilitating dendrite formation. Then it bridges the cathode and anode by directing Li deposition growing along grain boundaries to penetrate through solid electrolytes, causing the hazard of short-circuit. The infiltration of Li into crack-like flaws creates extremely high local stress at crack tips, accelerating crack propagation due to lowered fracture toughness at the tip. This process exposes fresh open areas, further intensifying Li deposition and perpetuating a destructive cycle of structural degradation. Consequently, as cracks proliferate, the mechanical strength of solid electrolytes diminishes, ultimately leading to structural collapse. In deep-sea environments, extreme pressure exacerbates this degradation by accelerating defect growth and amplifying dendritic penetration, especially under larger current density that drives rapid Li deposition. Therefore, minimizing the density and size of defects within solid electrolytes is essential to strengthen their structural integrity and resist high external deep-sea pressure.

4. Components for deep-sea Li battery

For deep-sea battery assembly, the components of a deep-sea Li battery can be broadly categorized into two groups, including power cells, which are the primary energy source, and functional components, which serve for power distribution, management, and other operations. These components must be specifically engineered to withstand extreme environmental challenges. However, the design considerations differ significantly depending on the chosen protection configuration. In the pressure toleration configuration, the components are majorly housed within pressure-resistant cabins, it accordingly shifts the focus to thermal management, as the external pressure is effectively isolated. In contrast, the pressure compensation configuration directly exposes components to the surrounding high-pressure environment by filling with a pressure-transmitting fluid, introducing two significant technical challenges: efficient external pressure transfer and compatibility between components and the filling fluid. Given its advantages for extreme-depth applications, herein, the component design in the pressure compensation configuration is emphasized, and the relative technical challenges are presented as well.

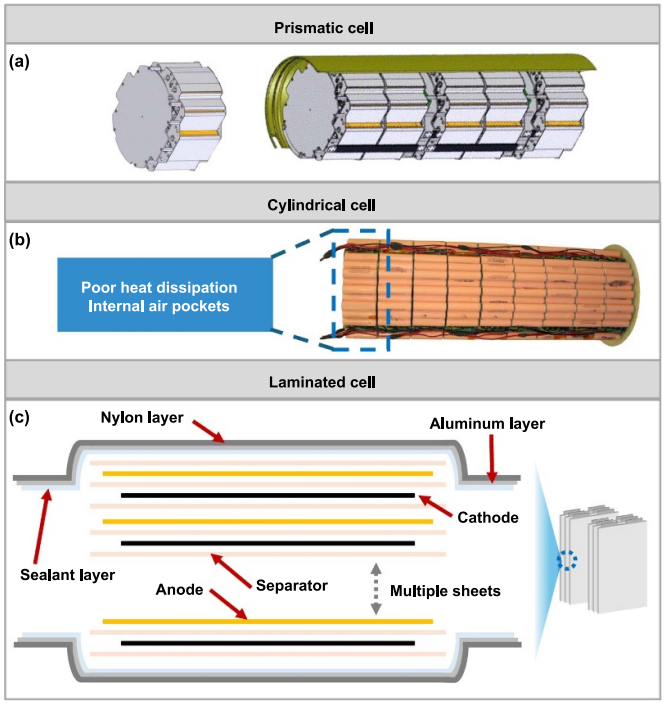

Figure 6. Different deep-sea Li battery formations, including (a) prismatic. Reprinted from [117],Copyright © 2004 Elsevier B.V. All rights reserved. (b) cylindrical. Reproduced with permission from [32]. CC BY-NC-ND 4.0 and (c) laminated cells.

4.1. Component modifications

Deep-sea Li power cells are engineered in various formations, including prismatic, cylindrical, and laminated cells (figure 6), which are then arranged in specific configurations to tailor module shapes. The choice of cell formation prioritizes structural compatibility and practical performance under deep-sea environments. For instance, prismatic cells are normally preferred in torpedo systems to maximize the utilization of available volume [117]. Cell spacing is another critical consideration due to the challenges of heat dissipation and the nonuniform thermal, particularly in relatively narrow arrays. When exposed directly to ambient pressure, laminated cells are generally favored over cylindrical cells. Cylindrical cells, with their inherent air pockets, are more susceptible to deformation under high external pressure and are prone to storing excessive heat during discharge [32]. Laminated cells, on the other hand, are advantageous thanks to their superior thermal dissipation, compact and dense vacuum sealing, and lightweight packaging. However, the adoption of laminated cells under deep-sea pressure requires additional manufacturing techniques to address their weakness. Under high external pressure, burrs in the laminated structure are forced to penetrate electrode sheets or separators, increasing short-circuit risk heavily. To counter this, electrode sheets must be flawlessly smooth and uniformly even. Specifically, the machining of electrode sheets is enclosed in space with 10 000-level cleanliness to avoid environmental contamination, and it demands elevated-temperature rolling to remove the uneven distribution of composite coatings on base sheets. In addition, the formation process for deep-sea Li cells differs markedly from Li cells applied in the normal environment, involving higher formation temperature and formation pressure, approximately double those used in the normal formation. The elevated conditions facilitate to complete interfacial reactions of SEI as well as minimize the internal voids ratio of deep-sea Li cells. Besides internal elements of cells, a robust and impermeable enclosure is critical to protect internal cell elements from soaking fluid. This demands two key considerations: first, ensuring good compatibility between the pressure-transfer fluid and the cell packaging materials to prevent corrosive destruction; second, employing highly stringent sealing to block the invasion of soaking fluid under extreme conditions. Notably, even seals by thermal fusion bonding have shown vulnerability, with soaking fluid (oil) penetrating the cell interiors under pressure. To mitigate these issues, a multilayer packaging structure is adopted, for instance, an aluminum layer sandwiched between an outer polymer and an inner sealant layer (figure 6(c)). Yoshida *et al* suggested that filling oil invasion is avoidable by folding up the edges of laminated cells and sealing them with a bond [88]. Besides, the sealing quality is critically influenced by the heat sealing process. Packaging failures under extreme external pressure often originate from localized structural defects, needing enhanced sealing quality of deep-sea Li cells, especially uniform sealing to minimize stress concentration as well as eliminate weak points. During hydraulic pressure tests at 115 MPa, bubbling along sealing edges was observed within the first three times, which is blamed on the existing local defects. Hence, precise control of the heat sealing process is imperative, for example, the temperature accuracy of the heat sealing knife must be limited within 5 °C empirically to ensure the consistency of peeling strength along sealed edges. Equally important is the precise calibration of heat sealing time and pressure during repeated sealing manipulation.

Mechanical challenges are equally essential for functional components, as both cells and functional components are immersed in dielectric fluid within containers. These functional components must not only be compatible with the filling fluid but also demonstrate resilience to ambient external pressure [118–120]. Improper packaging can lead to dissolution in the surrounding liquid, resulting in device failure due to liquid penetration. As hydraulic pressure increases at greater depth, components risk structural damage if the external pressure surpasses their mechanical strength (figure 7(c)). Functional components, typically integrating diverse electronics such as chips, capacitors, and transistors, are normally not designed for extreme high-pressure environments. Conventional packaging methods fall into two categories: (1) the electronics are protected by filling gel and hard shell housing (figure 7(a)); (2) the hard shell is substituted by top coating (figure 7(b)) [121]. For normal packaging (1), the applied hard shell enlarges the overall size, reducing available space. The air space and external soaking fluid generate huge pressure differences on hard shells, which are readily destroyed [118]. Additionally, the air pocket hinders efficient

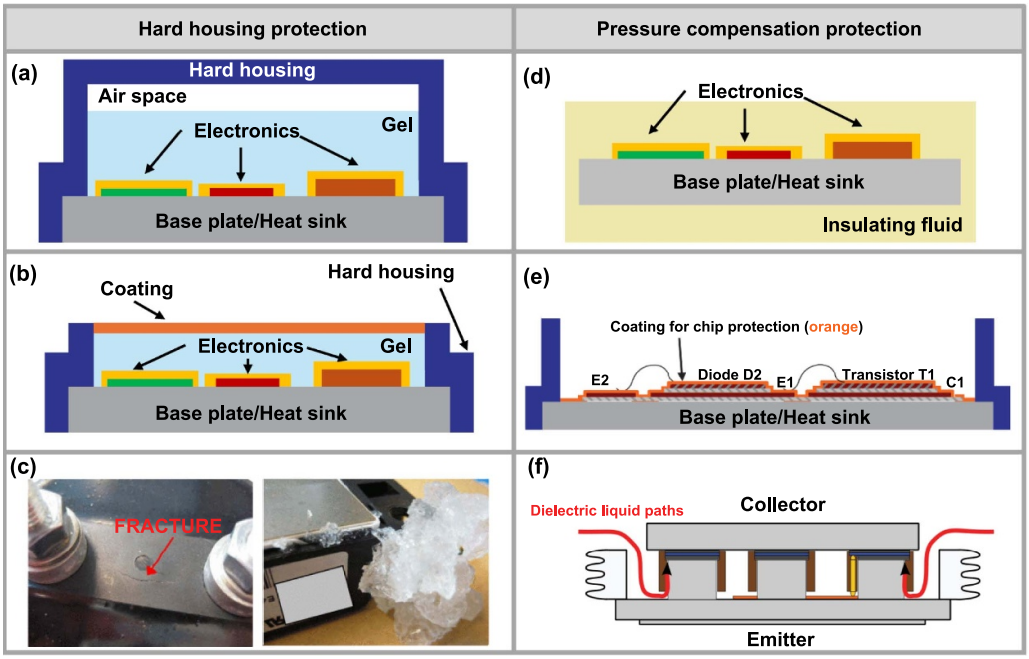

Figure 7. The incompatibility of normal functional components for deep-sea application, and component modifications for strengthening resistance to deep-sea environment. (a) Hard housing and (b) coating protection for normal components and (c) structural instability under pressure. © [2019] IEEE. Reprinted, with permission, from [118]. (d) Modification of pressure compensation method to components, manifested as the open-design modification for (e) bonded. Used with permission of Society of Petroleum Engineers (SPE), from [124]; permission conveyed through Copyright Clearance Center, Inc. and (f) press-pack IGBTs. Used with permission of Society of Petroleum Engineers (SPE), from [124]; permission conveyed through Copyright Clearance Center, Inc.

heat dissipation. For packaging (2), this approach reduces component size through the substitution by top coating, but the gel with voids inside is prone to deformation under external pressure, while thick gel layers impede heat dissipation. To address these limitations, functional components require specialized mechanical modifications tailored for deep-sea. For example, as widely applied in underwater power systems, the types of insulated gate bipolar transistors (IGBTs) are categorized as press-pack and bonded IGBTs structurally [122]. For normal press-pack IGBTs, the filled gaseous SF_6 is used to protect internal chips within sealed housings; for normal bonded IGBTs, the chips are enclosed within gel layers (often containing hole defects) and hard housing. However, at pressure as 10 MPa, these designs show mechanical vulnerabilities such as base plate deformation, housing cracks, and gel extrusion. Increasing the thickness of housing walls to enhance strength is not a feasible solution, as it compromises heat dissipation and reduces energy density. Instead, introducing dielectric and incompressible fluids to equalize pressure is a preferred solution (figure 7(d)), while mechanical modifications are implemented differently for the two IGBT types. For the press-pack, Petterteig *et al* designed a pre-clamped phase leg as well as a slot around the collector plate for dielectric fluid flow (figure 7(f)), and the oil applied can fill in all cavities in this module [123]. For the bonded, Pittini and Hernes removed the housing and gel layers to avoid mechanical defects, instead adding the substantial coating to shield chips from environmental contaminations (figure 7(e)), and the passivation with dielectric fluid filled was required [124]. This mechanical modification has adapted pressure successfully, it has tested up to 30 MPa without performance deviation.

4.2. Component tests

In addition to designing components tailored for deep-sea applications, rigorous testing is necessary before their equipment to underwater vehicles to avoid unexpected risks. Unlike normal battery tests, testing for deep-sea batteries demands special consideration of extreme conditions, like diving depth and practical power output. This necessitates performance evaluation under simulated deep-sea environments, typically conducted in hyperbaric chambers capable of precisely controlling pressure, temperature, and electrical loads (figure 8(b)) [88, 101]. A defining feature of hyperbaric chamber testing is its replication of authentic deep-sea conditions, characterized by three-dimensional (3D) compression, as different from the uniaxial pressure popularly applied in normal Li battery tests, and uniform heat distribution facilitated by immersion in a soaking fluid. Various tests have examined the effects of pressure on Li cells' performance, with results generally indicating marginal pressure impact on deep-sea Li-ion cells during moderate discharge. For example, in a test conducted at 20 °C, the pressure was increased incrementally to the maximum of 30 MPa first and maintained for one hour before being decreased at the same rate (1 MPa per minute). During this test, with the discharging load set at 0.5 A, both the

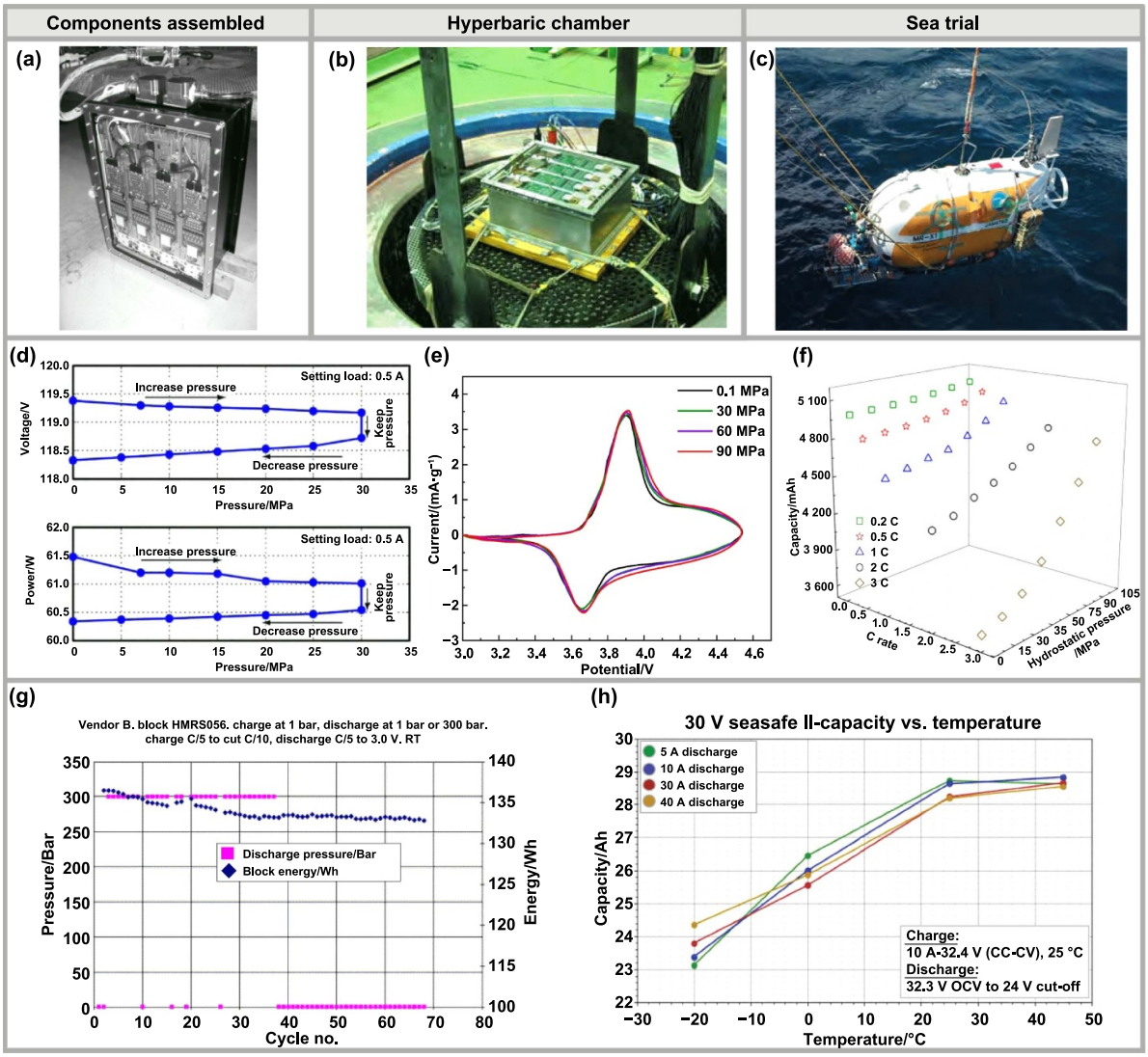

Figure 8. The tests for components integrated into the deep-sea battery. (a) Deep-sea Li battery module assembled by diversified components. © [2011] IEEE. Reprinted, with permission, from [101]. (b) Hyperbaric chamber specialized for tests to simulate the deep-sea environment. © [2011] IEEE. Reprinted, with permission, from [101]. (c) Sea trial after component tests. © [2011] IEEE. Reprinted, with permission, from [101]. (d) The performance change of deep-sea liquid Li-ion battery compressed under moderate discharging. © [2011] IEEE. Reprinted, with permission, from [101].(e) CV .Reprinted with permission from [101] and (f) discharge plots of the liquid Li-ion battery at different rates and hydrostatic pressure. Reprinted from [38],© 2022 Elsevier Ltd All rights reserved. Reprinted from [38],© 2022 Elsevier Ltd All rights reserved. (g) The performance change of deep-sea Li polymer battery compressed under moderate discharging. Reprinted from [62],Copyright © 2005 Elsevier B.V. All rights reserved. (h) The thermal and discharging conditions affect the performance of deep-sea Li polymer batteries. Reproduced with permission from [126].

battery's voltage and power remained stable under pressure (figure 8(d)) [101]. Further investigations confirm the minimal impact of pressure on the electrochemical performance of liquid Li-ion batteries, there is no obvious change in discharge characteristics of cells at 0.1, 30, 60, and 90 MPa. Likewise, no significant difference in redox reaction under varying pressure was observed (figure 8(e)), suggesting the stability of electron transfer [38]. Interestingly, higher external pressure has been found to reduce overpotential at large discharging current, thereby facilitating improved Li ion diffusion and mitigating capacity loss (figure 8(f)). Another study thoroughly examined the impact of full-sea-depth hydraulic pressure (115 MPa) on mesocarbon microbead anodes, revealing substantial structural and performance variation. Under this extreme pressure, electrode thickness decreased significantly from 150 μm to 115 μm, while porosity was markedly reduced from 47.8% to 35.1%. Those changes severely reduced discharge capacity, which dropped to 33 Ah at 1.0 C (about 21.5% serious loss), together with larger overpotential at a high discharge rate. Such findings bring worry about ionic transport being blocked by enclosing internal open pores under high pressure, including micropores in separators [125]. However, the pressure impact on Li polymer cells is less significant than that of discharge rate and temperature. For instance, at 100 Bar, Li

polymer batteries showed a voltage drop during 0.2 C discharging, while pressure influence is still ignorable. As external pressure increases to 300 Bar, the cyclic performance change remained largely unchanged (figure 8(g)) [54]. This robustness is attributed to their compact and dense configuration to resist compressing deformation. At a constant temperature, higher discharge rates generally result in reduced capacity. Ambient temperature influences capacity delivery as well, with a positive correlation between capacity and temperature ranging from 0°C–25 °C (figure 8(h)) [74, 126]. Collectively, the performance of deep-sea Li batteries exhibits notable fluctuations as powering various onboard instruments under varying deep-sea environments, especially in the extreme conditions of the Hadal zone. To ensure reliability and safety, sea trials are exclusively essential following hyperbaric chamber tests. These trials involve installing all components into underwater vehicles, allowing for comprehensive validation of their practical performance under real-world deep-sea conditions (figure 8(c)).

5. Battery management system for deep-sea Li battery

As previously discussed, the deep-sea battery system features a multilayer architecture comprising modular units formed by the integration of individual cells. This structure requires a BMS specialized for deep-sea Li batteries. To ensure the safety and reliability of the system, various BMS designs have been developed, addressing key issues such as over (dis)charge, short-circuit, and imbalanced SOC distribution, which are common sources of power failure. To avoid these potential risks, the BMS must monitor and analyze the status of battery systems, enabling practical, real-time intervention strategies. The primary role of the BMS is thus defined as the detection of unhealthy battery states and the execution of corrective measures to prevent system failures. This capability is underpinned by the specialized design and implementation of BMS. The detection of BMS normally involves monitoring critical cell states such as voltage, current, and SOC. Accurate reflection of these states forms the foundation for timely and effective intervention, empowering the BMS to address potential issues proactively. Given the unpredictable nature of cell state evolution, continual improvement in data processing is essential for enhancing the responsiveness and efficacy of BMS operation. To achieve these objectives, both BMS hardware and software must be meticulously designed for deep-sea Li batteries to cater to the unique challenges of onboard power in extreme conditions of deep-sea.

5.1. BMS software design

Although the multifunctionality of a BMS is achieved by integrating different subsystems, its practical effectiveness hinges on thoughtful layout design and efficient data processing. Consequently, the topological architecture of a BMS determines management performance significantly, involving key aspects like maintenance, sensitivity, and accuracy. Considering the BMS is typically co-installed with battery modules, its architecture design follows the multilayer layout of the battery system. Broadly, there are two basic architectural designs for battery management: centralized and distributed architectures [82]. While both architectures can support multifunctionality, their management performance varies due to inherent differences in their structural characteristics.

In the centralized architecture, a single BMS board oversees the entire battery system, requiring a number of communication channels between the central BMS board and the distributed cells. This design simplifies the overall structure by consolidating management onto a single BMS board, thereby reducing structural complexity. However, it also concentrates on potential risks. For example, the failure of the central BMS board due to external pressure can induce the collapse of the entire battery system. Moreover, this centralized design decreases management flexibility, as partial functions are confined solely to the central BMS board, reducing the system's adaptability in responding to localized issues.

In the distributed architecture, the battery system is divided into independently managed units, typically defined as battery modules. Each unit is equipped with its own multifunctional BMS, such as disconnection control at the module level rather than the whole system. This approach ensures that a malfunctioning module can be isolated to maintain the power supply, a significant advantage over centralized architectures, where a single failure could incapacitate the entire power system. As a result, the distributed architecture offers unparalleled flexibility and resilience. Communication within a distributed architecture occurs between individual units, reducing the complexity of the BMS circuit and enhancing reliability. Moreover, its modular design makes the distributed BMS highly replaceable and scalable, allowing for adjustments by adding or removing BMS units of varying specifications to meet specific requirements. Notably, each unit can be reduced to the individual cell level, enhancing the precision and functionality of the BMS. However, this refinement comes with increased complexity and costs.

The operation of a BMS heavily relies on accurate battery parameters to effectively manage various subsystems, particularly electrical and environmental parameters. Improving the precision of parameter processing directly enhances the reliability of BMS. Despite numerous parameters, SOC is regarded as a critical index of the available capacity, guiding power allocation for running underwater vehicles [127]. A lot of efforts thus have been dedicated to refining SOC estimation [128, 129], especially those based on battery models. One widely adopted method is the equivalent circuit model, which balances circuit complexity with estimation accuracy. This method is based on circuit structure and parameter identification, enabling the derivation of customized equivalent circuit models tailored for deep-sea batteries. In view of this, the popular parameter identification methods based on equivalent circuit models were compared under three conditions by Chen *et al*, including offline methods based on mechanism and least squared (LS), as well as online methods based

on recursive least square (RLS) with forget factor RLS and extended Kalman filter (EKF) [130]. Their study revealed that SOC estimations based on all four methods fit well with the reference without disturbance. However, in the case of disturbing measurement and initial SOC deviated, there were much lower SOC estimation errors based on the EKF method than the others, indicating the robustness of EKF parameter identification during the external disturbance. However, EKF is also proposed as incompetent for SOC estimation because the discharging curve of Li batteries changes with temperature lowering during the dives. Hence, Zhang *et al* modified the EKF method with the regularized extreme learning machine to revise the SOC estimation value, and the modified SOC estimation is less than 1.67% finally [131]. Besides this, Chen *et al* proposed other accurate SOC estimators applied at low temperatures [132]. On one hand, it newly built a radial basis function neural network (RBFNN) battery model to substitute equivalent circuit models to estimate SOC value. On the other hand, a temperature compensation strategy was developed by correlating SOC with terminal voltage at a different temperature, without increasing computational burden. Finally, both two efforts were incorporated with an unscented Kalman filter (UKF) to obtain the RBFNN-UKF-based SOC estimator. SOC estimation errors at low temperatures have been significantly reduced compared with equivalent circuit methods.

5.2. BMS hardware modification

The deep-sea Li battery's enclosed design, intended to shield it from external environmental influences, introduces specific challenges to safety and reliability, depending on the adopted protection configuration. In the pressure toleration configuration, external pressure is neutralized by maintaining a constant internal atmosphere, attained through a pressure-resistant shell that structurally encloses the cells. This shell must be intact mechanically with strong resistance to seawater invasion, especially external hydraulic pressure and saline liquid corrosion. However, any compromise in its structural integrity can lead to increased humidity within the sealed compartment, adversely impacting onboard electronics by inducing performance instability or even catastrophic short-circuit. A critical challenge in these designs is thermal management, exacerbated by the fully enclosed nature of the protective shell. Heat and gaseous byproducts generated during the operation of cells and electronics accumulate within the confined space, as the design inherently prevents their release. Despite the cooling effect of the surrounding deep-sea environment, the low thermal conductivity of air trapped within the cabin impedes heat dissipation, particularly during high-rate discharge. This issue becomes more pronounced at greater depths, where thicker shell walls, necessitated by higher pressure, further restrict heat transfer. The resulting thermal gradients, characterized by significantly elevated temperature at the central part relative to the battery edges near cold seawater, create internal thermal fluctuations [133]. Such conditions accelerate performance degradation, compromise battery consistency, and increase the likelihood of thermal runaway triggered by flammable discharge byproducts. Notably, these risks correlate strongly with the varying states of cells. Based on analyzing vent gas composition, Somandepalli and Marr concluded a positive correlation between the total volume of hydrogen gas released and SOC of the cells, which induces different combustion characteristics [134]. These findings underscore that thermal issues are highly risky for deep-sea batteries, especially for those in the pressure toleration configuration, thus requiring hardware modifications to enhance thermal management for deep-sea batteries.

Thermal management in batteries faces two critical challenges: the accumulation of heat within enclosed cabins and nonuniform thermal distribution, both of which cause inconsistency in battery performance. These issues predominantly stem from insufficient thermal transfer. Thermal management employs three kinds of heat transfer media, namely air, liquid, and solid coolants, each with distinct thermal dissipation characteristics. These media are usually applied in active (e.g., air cooling, liquid cooling), passive, or hybrid thermal management systems, tailored to specific operational needs. The inherent flowability of air and liquid media requires forced ventilation to accelerate thermal conduction and diminish internal temperature differences. This is typically achieved by installing additional cooling fans and pumps within the battery cabins. However, these additions come with prominent shortcomings: they reduce the available space for battery cells, increase the overall system weight, and impose additional power consumption demands. Moreover, their inclusion complicates the structural design of battery systems. Hence, solid media, especially phase change materials (PCMs), have gained increasing favor for thermal management in deep-sea Li batteries. PCMs are uniquely advantageous due to their passive heat dissipation capabilities, requiring no additional energy input. Despite this benefit, their practical application is hindered by their intrinsic low thermal conductivity. Furthermore, the integration of PCM will also increase the weight of the onboard power system, thereby compromising the energy density of the battery. To overcome these limitations, substantial endeavors are directed toward improving thermal management systems.

Active thermal management systems utilizing liquid coolants are superior to air-based systems due to their higher thermal conductivity, making them more suitable for effective heat dissipation. Li *et al* built a liquid cooling system incorporating essential components such as a pump, heat exchanger, and valve (figure 9(a)) [135]. The system features bionic wave-shaped channels designed for individual cells (figure 9(b)), with water chosen as liquid coolant. It has systematically examined this liquid cooling system based on cooling system parameters as well as underwater vehicle operation, including channel shapes, coolant mass flow rate, coolant inlet direction, and dynamic operational strategies. On one hand, optimization of the cooling system was achieved by altering different parameters. For example, (1) bionic wave channels were preferred to straight channels because the periodic convex and concave structures of bionic wave shape provided a larger heat exchange area to enhance heat dissipation (figure 9(c)). (2) The

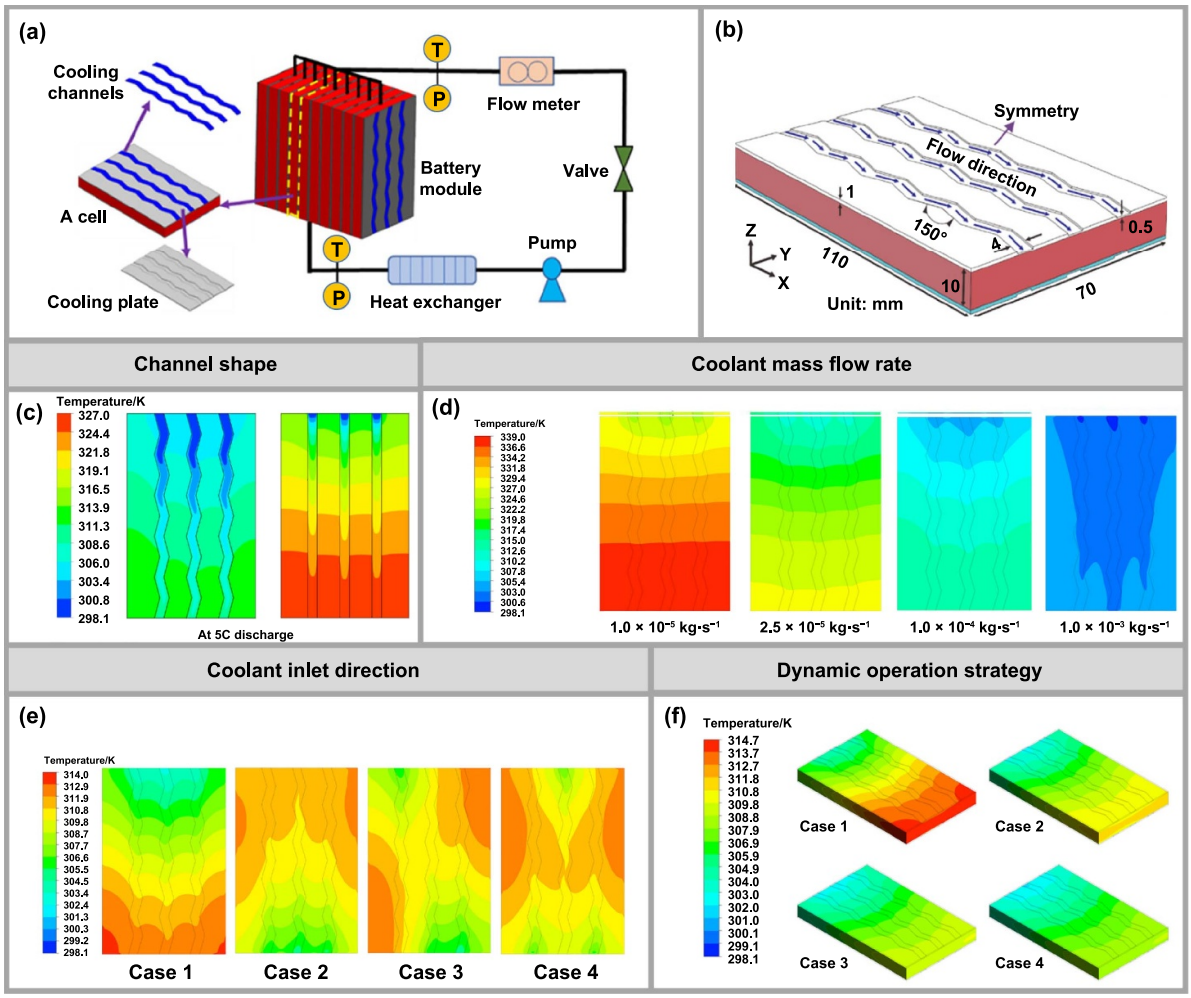

Figure 9. The active cooling system for thermal management on deep-sea batteries. (a) The scheme of designing the liquid cooling system. [135] John Wiley & Sons.© 2021 John Wiley & Sons Ltd. (b) The scheme of designing bionic channels of the liquid cooling system. The effect of (c) channel shape, (d) coolant mass flow rate, (e) coolant inlet direction, and (f) dynamic operation strategy on thermal management for deep-sea batteries.

effect of coolant mass flow rate was different for obtaining optimal temperature maximum and difference (figure 9(d)). (3) It has compared the cooling effects of four coolant inlet directions, suggesting the lowest temperature at the inlet and the highest temperature at the edge of the battery (figure 9(e)). Moreover, the change of inlet direction had a marginal effect on the maximum temperature, but it was obvious to improve the uniformity of thermal distribution. On the other hand, the effect of the cooling system was different for varying usage of power batteries. Considering underwater vehicles run at varying cruising speeds, it compared the thermal results of different dynamic operational strategies (figure 9(f)). Besides this, there are further explorations on improving liquid cooling systems, exampled as parametric optimization of cooling microchannels based on the genetic algorithm, and machine learning surrogate models to predict thermal parameters. While significant enhancements have been made in active cooling systems for onboard thermal management, their limitations persist, particularly in terms of additional energy consumption and the complicated circuit distribution within the narrow cabins. Consequently, there is a growing preference for passive cooling systems, especially the types of PCMs, as they maintain effective thermal management without imposing additional energy loads on the onboard power system.

PCMs are commonly applied to wrap batteries, absorbing the heat generated during discharge due to their high latent heat storage capacity (figure 10(a)) [136]. PCMs require a substantial amount of heat to initiate the phase change, even more required for melting, but the melted PCMs will solidify as the heat generation subsides. This makes PCMs invaluable for thermal monitoring and protection of batteries. For instance, PCMs maintain a constant cabin temperature at their melting point by absorbing excessive heat, with the temperature controllable by selecting PCMs with different melting points. To improve the thermal conductivity of PCMs, various modifications have been made, mainly especially in the structure and composition of the PCM wrapping. In cylindrical battery formations, Li *et al* deliberately designed a battery module into a honeycomb structure to save materials as well as increase spatial utilization thanks to the hexagonal shape (figure 10(b))

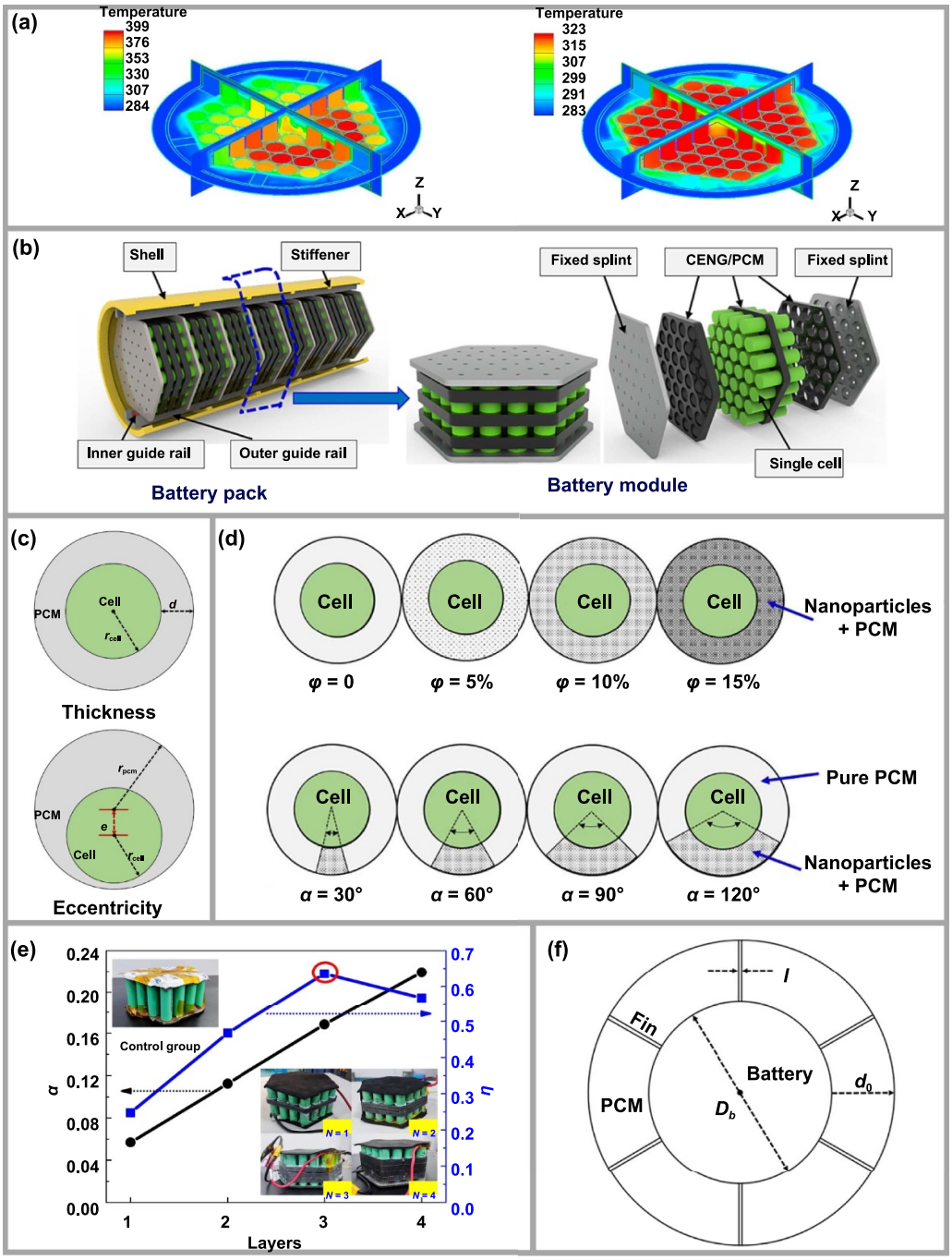

Figure 10. The passive cooling system of thermal management on deep-sea battery. (a) The acceleration of heat dissipation through applying PCMs. Reprinted from [136], © 2018 Elsevier Ltd All rights reserved. (b) The scheme of designing the passive cooling system of applying PCMs for managing cylindrical cells thermally. Reprinted from [137], © 2024 Elsevier Ltd All rights reserved. The parametric optimization of (c) PCM thickness and eccentricity. Reprinted from [138], © 2022 Elsevier Ltd All rights reserved. (d) Compositional addition percentage and filling angle. Reprinted from [139], © 2022 Elsevier Ltd All rights reserved. (e) PCM layers (α is the ratio between mass of PCM layers and battery, and η is defined as a dimensionless factor to evaluate comprehensive thermal management performance of PCM). Reprinted from [137], © 2024 Elsevier Ltd All rights reserved. And (f) fin to improve thermal management of PCM cooling effect [140]. John Wiley & Sons. © 2022 John Wiley & Sons Ltd.

[137]. Considering battery cells wrapped by PCMs, Li *et al* revealed the heat transfer mechanism of PCMs by investigating the parameters of wrapping thickness and eccentricity between battery and PCMs (figure 10(c)) [138]. According to thickening PCM layers, the rise of battery temperature was delayed and it was effectively controlled when the thickness exceeded 16 mm. The eccentricity had influences on the melting behaviors of PCMs as well, resulting from the top region of PCMs melting faster than the bottom due to buoyancy-induced natural convection. It demonstrated that the

rate of PCMs melting accelerated nonlinearly as eccentricity increased, with an optimal value of 10 mm. Moreover, thermal conduction behaviors can be modified by tuning the composition of the PCM layers, particularly by adding materials of high thermal conductivity such as metal-based and carbon-based materials. Li *et al* added Al_2O_3 nanoparticles into PCMs to enhance battery heat dissipation with improved thermal conductivity of PCM layers, while the latent heat storage of PCM layers is reduced due to the less volume portion of PCMs (figure 10(d)) [139]. Besides this, the distribution of nanoparticles influenced the thermal behaviors of wrapping layers as well, which showed an optimal melting rate at the bottom when the nanoparticle filling range was 60°. Carbon-based additives are often preferred due to their lower density comparatively. It has been validated that thermal management improves by combining compressed expanded natural graphite with PCMs, effectively preventing battery temperature rise at different ambient temperatures. Of note, Li *et al* proposed the trade-off between thermal management and energy density reduced by installing PCM layers (figure 10(e)). Although the maximum temperature of the battery module decreased along with increasing the number of PCM layers, it simultaneously increased the mass ratio of PCMs [137]. Therefore, the optimal number (three) of PCM layers is concluded from the evaluation based on the comprehensive thermal management performance. Another strategy to accelerate the heat dissipation of battery modules is the use of fin/PCM composites (figure 10(f)). Li *et al* examined the effects of different parameters of fins thoroughly, including the number and length ratio of fins, as well as the angle between fins [140].

Conclusively, the installation of a thermal management system is indispensable for BMS. However, it inevitably increases the load on the onboard power. Therefore, it is necessary to optimize different thermal management systems by minimizing their mass, volume, and impact on energy consumption for deep-sea batteries. Comparatively, the pressure transfer media utilized in a pressure compensation configuration also serves as the heat transfer media, which diminishes thermal impact, but the enclosed container cannot be overlooked. Moreover, mechanical issues are unavoidable for BMS electronics soaked in dielectric oil within containers. As such, all related BMS components are required with modification of pressure resistance, as introduced before. Undoubtedly, the practical implementation of a BMS in the pressure compensation configuration necessitates a more sophisticated design.

6. Conclusion and outlook

As platforms for exploring deep-sea, underwater vehicles require safe and reliable electrical power to support their operation while submerged. With the development of deeper ocean exploration, tethered cables for electricity transportation have been abandoned in favor of onboard batteries, supporting greater maneuverability without dimensional constraints. As a result, the operation of these vehicles is entirely dependent on the performance of the onboard battery. Over the past several decades, substantial efforts have been made to improve the performance of deep-sea batteries, resulting in technological advancements across various aspects of deep-sea battery systems. These systems are designed with consideration for several main factors: (1) power generation, (2) protection, and (3) distribution and management. (1) For power generation, it has developed electrochemical systems of generations to raise energy density, such as early Pb–acid and Ag–Zn batteries, while it favors Li batteries at present because of their higher available energy density and conventional technological issues resolved. Although other electrochemical systems have been explored, they remain limited by lower energy density and higher operational risks, for example, despite their higher energy density, fuel cells are constrained by the challenges of fuel storage and transportation. (2) The protection for deep-sea batteries is necessitated by the extreme conditions of deep-sea, including ultra-high hydraulic pressure and seawater conductivity. Accordingly, these batteries are typically encapsulated to separate from seawater, while the inner situation is different in the respective two configurations. In shallower depths, deep-sea batteries are placed in a dry atmosphere without external pressure. In deeper oceans, deep-sea batteries are bathed in insulating fluid (wet) to eliminate pressure differences across the container shells, thus increasing the energy density of the battery. (3) The power distribution is dictated by the energy consumption spectrum of the onboard instrument, while power management systems are employed to avoid potential risks by monitoring and processing battery status. Recently, deep-sea batteries have evolved into more advanced Li batteries, with trends toward modularity and continued upgrades in their electrochemical systems. This development trend contributes significantly to shaping the genealogical development of underwater vehicles.

Li batteries hold great promise for developing deep-sea power systems, but deepening improvements across different aspects are required to fully realize their potential. (1) For materials of Li batteries, electro-chemo-mechanics models are specially introduced to resolve the pressure effect on the electrochemical reactions of Li batteries. These electro-chemo-mechanical models differ between liquid and solid Li-ion batteries. For liquid Li-ion batteries, external pressure intensifies structural degradation, requiring modifications to electrode materials to alter electro-chemo-mechanical evolution under high-pressure conditions. For solid Li-ion batteries, liquid electrolytes are substituted by solid-state electrolytes, forming Li polymer batteries. This transition provides more opportunities for developing deep-sea solid Li-ion batteries based on this model, while presenting key issues to be tackled. (2) The normal deep-sea Li cells are greatly unsuitable for deep-sea applications due to their incapability to withstand high external pressure. Therefore, cell modifications are required to enhance the resilience of cells, such as the thermal sealing process. Besides this, the structural collapse of normal electronics under high external pressure weakens the operation of BMS. To counteract this, hardware components must be reinforced using strategies similar to power protection

methods, filling electronic interiors with insulating, incompressible fluids. Component testing is necessary to ensure safety and reliability, while liquid and solid Li-ion batteries show distinct performance characteristics during such evaluations. (3) The BMS specialized for deep-sea Li batteries, mainly encompassing both software design as well as thermal management within enclosed containers. There are various attempts to improve BMS efficiency, with tailored software required to address the specific issues of deep-sea Li battery operation under different conditions. Given the sluggish heat radiation, thermal management requires effective heat transfer media. As a result, solid media such as PCMs are preferred for underwater BMS applications because of their stable performance and absence of additional power consumption. However, there remain plenty of challenges to developing deep-sea battery systems further.

Considering the incompatibility of normal batteries with the extreme conditions of deep-sea, emerging requirements have driven the development of new manufacturing approaches for smaller, lighter batteries with higher capacities. As discussed previously, deep-sea cells with reduced scales are favored owing to the minimized operational misfunction while increasing systematic control. Additionally, lighter battery designs contribute to alleviating the load to maintain buoyance during submersion, a requirement that is further supported by increased battery capacity. This has brought energy density as a critical index in developing deep-sea batteries. However, improving the performance of deep-sea batteries within the constraints of normal battery manufacturing presents formidable challenges. For example, while increasing electrode thickness enhances battery capacity, it often results in sluggish ionic transport. Besides this, the space occupied by onboard batteries inevitably restricts the design and installation of other instruments. This limitation is exacerbated by the rigidity of deep-sea cells, which cannot deform to save onboard space. Fortunately, alternative manufacturing methods offer promising solutions to these issues [141, 142]. Flexible batteries, designed to withstand external forces, are constructed using deformable components. For example, normal rigid current collectors can be replaced with stretchable substrates [143, 144], which effectively absorb deformation energy to mitigate uncontrollable structural degradation. The active layers can also be customized with varying structural specifications, exampled as metallic micromesh embedded [145, 146]. Although these structures are developed to enhance electrode transparency mainly, they are also beneficial for mechanical conduction, enabling greater resistance to external forces. Zhang *et al* utilized photolithography to obtain customizable grooves, which are prepared for regulating subsequent electrochemical deposition of metals [147]. This as-produced metallic micromesh is composed of dense pores without large junction resistance structurally, which is transparent as well as highly flexible. Moreover, another cutting-edge method to modify electrode architecture lies in 3D printing, an additive manufacturing technique capable of fabricating devices ranging from nanoscale to macroscale [148, 149]. This approach holds particular promise for the fabrication of small-scale batteries, enabling the customization of electrode architectures with intricate internal channels, supporting the construction of thick electrodes [150]. Although challenges such as low output, high cost, and sophisticated processes remain, these newly developed manufacturing technologies represent transformative opportunities for further development of deep-sea batteries.

Despite the energy density of onboard power has greatly increased, it remains limited, demanding frequent returns to the sea surface for charging. This mandatory requirement severely constrains the operation of underwater vehicles, reducing the time available for executing submerged missions. A transformative solution to this limitation lies in enabling underwater recharging systems. Underwater docking stations, analogous to terrestrial gas stations, not only provide a platform for recharging underwater vehicles but also enable effective informational communication while the vehicles remain submerged [151–153]. These seabed stations can harvest environmental energy to maintain a stational energy reserve, transferring power to onboard batteries as needed. And deep-sea batteries can be integrated into underwater docking stations to serve as electricity reservoirs. The energy used for recharging stational batteries is derived from abundant and renewable sources, like solar, wind, and wave energy. However, most current energy-harvesting technologies are designed as surface-based applications, rendering them impractical for direct deployment in deep-sea due to the far spatial distance [154–157]. The installation of energy transmission cables from surface sources to underwater stations is prohibitively expensive and operationally complicated. Therefore, it is proposed to harvest underwater energy, such as ocean thermal and tidal energy, which offer localized and sustainable power generation. Another critical challenge is the charging technology applied for the power transfer between docking stations and onboard batteries. Similar to aerial refueling, underwater charging can be attained through wired systems utilizing wet plugs. However, wet plugs demand exceptional precision, sealing, and the robustness of connection, while the application of plug docking is prone to corrode due to the great pull force and seawater sinking. Wireless power transfer emerges as a superior alternative [151]. The separation of charging components from seawater eliminates the risk of wire exposure to the conductive marine environment, significantly reducing maintenance costs by preventing corrosion-related damage. Additionally, increasing the wireless induction space minimizes docking time, accelerates navigation, and greatly enhances the coordination of underwater transportation.

Despite the immense challenges of applying batteries in extreme deep-sea, the development of deep-sea Li batteries holds tremendous significance in promoting underwater vehicles as well as enlarging subsea exploration. It is also valuable to serve as the prototype for future electrochemical energy facilities, the derived electro-chemo-mechanical models are inspiring to understand novel phenomena in coupled fields, providing research fundamental for designing safe and reliable power applied in extreme conditions. This field, still largely uncharted, expects continued efforts to unlock its full potential.

Data availability statement

Data will be made available on request.

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Conflict of interest

The authors declare no competing interests.

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