Toward the next-generation energy systems for unmanned underwater vehicles: Status, challenges, and solutions

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Received: February 24, 2025; Accepted: July 8, 2025; Published Online: September 16, 2025; https://doi.org/10.59717/j.xinn-energy.2025.100106

Citation: Li J., Hu Y., Luo S., et al. (2025). Toward the next-generation energy systems for unmanned underwater vehicles: Status, challenges, and solutions. *The Innovation Energy* **2**:100106.

Dear Editor,

Unmanned underwater vehicles (UUVs) have emerged as indispensable tools across diverse fields, from oceanographic research to military surveillance. However, their energy systems pose significant challenges that limit endurance and operational capabilities. This perspective delves into the current status of thermal and electric energy-based UUVs, and clarifies the faced challenges of the energy systems. To surmount these, we propose the innovative solutions of the next-generation energy systems for UUVs. Hybrid energy systems combining batteries and fuel cells offer enhanced endurance and redundancy. Marine energy capture from temperature gradients, waves, and currents provides supplementary power. Underwater wireless charging and intelligent battery management systems optimize energy utilization and prolong battery life. These advancements are pivotal in revolutionizing UUV applications, enabling longer, more efficient underwater missions and unlocking the full potential of ocean exploration.

BACKGROUND

An unmanned underwater vehicle (UUV) is an unmanned, untethered robotic system designed to operate independently in underwater environments. These vehicles are equipped with their own propulsion systems and onboard computers, which allow them to navigate and make decisions without direct human intervention.[1] UUVs are utilized in a variety of applications, including oceanographic research, underwater mapping, environmental monitoring, search and rescue operations, and military surveillance. They can reach depths and locations that are inaccessible or too dangerous for humans, making them invaluable tools for exploring the world's oceans. The primary modules of an UUV include navigation and control system, communication system, payload module, propulsion system, and energy system,[2] as shown in Figure 1A. As UUVs are deployed in remote and challenging underwater environments, a robust and efficient energy system is essential to support their diverse functions, including propulsion, navigation, sensing, and communication.

STATUS AND CHALLENGES

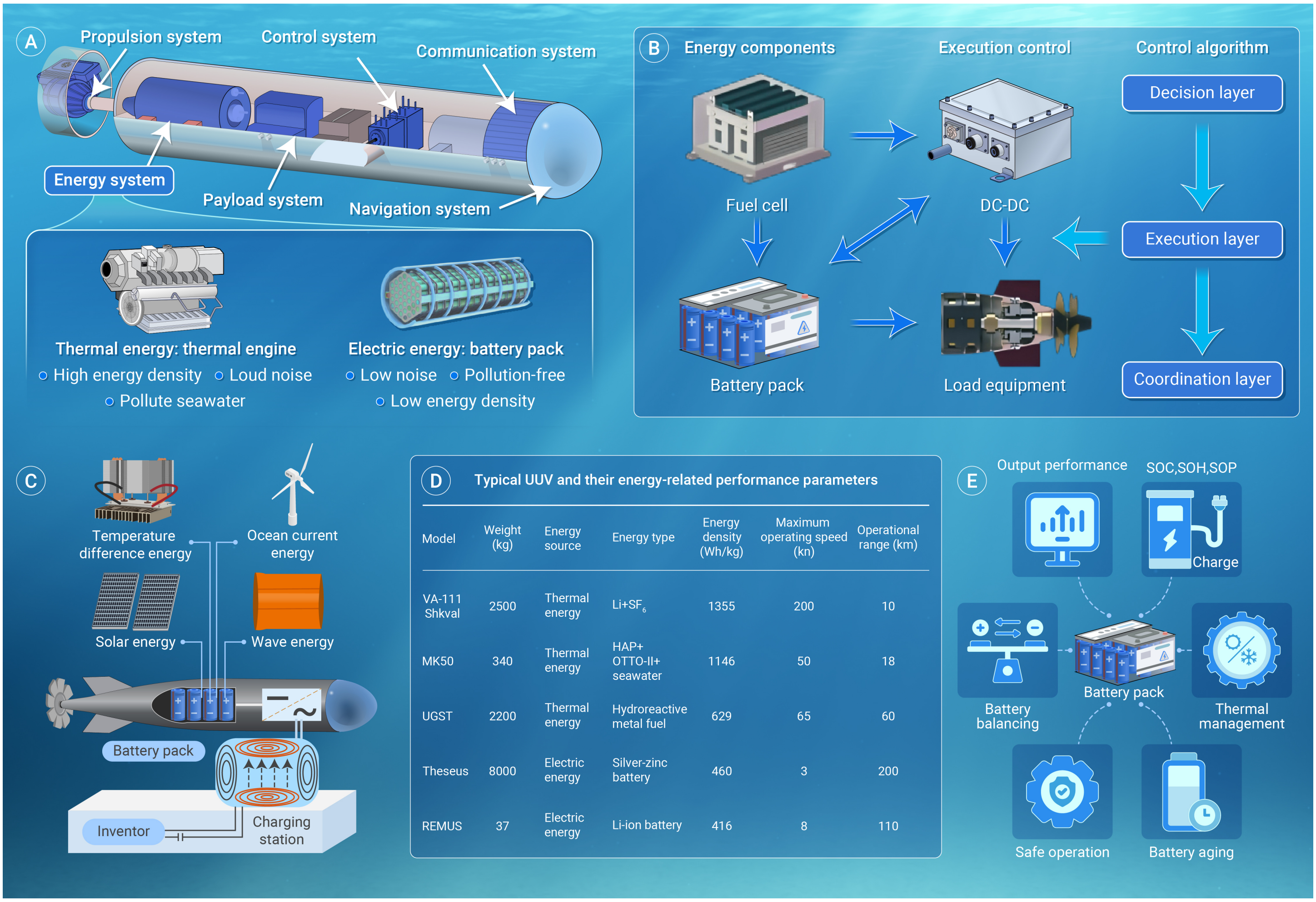
UUVs can be classified into thermal energy-based UUVs and electric energy-based UUVs, as shown in Figure 1A. Thermal energy-based UUVs typically rely on internal combustion engine which has high energy density and power density to achieve long-term, high-speed navigation. Figure 1D displays some typical UUV and their energy-related performance parameters. A comparative analysis of thermal energy-based and electric energy-based UUVs reveals distinct performance characteristics. Thermal energy-based UUVs (e.g., VA-111-Shkval, MK50, UGST) are often used as torpedoes due to the exhibit superior energy density (629-1355 Wh/kg) and higher maximum speeds (50-200 kn), allowing them to hit targets in a shorter amount of time. Taking Russia's "VA-111 Shkval" as an example,[3] its metal water reaction ramjet engine is a typical application of internal combustion engines. The engine uses magnesium-based metal fuel, which undergoes a violent chemical reaction with seawater in the combustion chamber, efficiently converting chemical energy into heat energy, thereby producing a high-temperature and high-pressure working fluid. This unique internal combustion engine design allows the "VA-111 Shkval" weighing 2500 kg to accelerate at a super high speed of over 200 kn, covering a wide water area of 10000 m. Nonetheless, the operation of such thermal power systems involves mechanical components—such as pistons and crankshafts—that produce relatively large noise. Furthermore, the waste heat generated during the combustion process is dissipated into the surrounding seawater via the cooling system, resulting in an obvious thermal signal. These noise and thermal signals can easily be detected by enemy's sonar or infrared detection equipment, thus reducing the underwater vehicle's stealth. At the same time, the exhaust gas or other pollutants generated by combustion will cause damage to the environment, especially when UUV is performing environmental monitoring tasks, these pollutants will affect the accuracy of the collected data. With the increasing requirements of low noise, zero emissions and fast energy replenishment for large UUVs performing specific tasks, traditional thermal energy systems are gradually unable to meet these needs.

Electric energy-based UUVs represent a versatile and widely adopted class of underwater systems,[4] are powered by batteries and use electric motors or thrusters to convert electrical energy into mechanical energy. Compared to thermal energy-based UUVs, electric energy-based UUVs (e.g., Theseus, REMUS) demonstrate lower energy density (416-460 Wh/kg) and speeds (3-8 kn) but achieve extended operational ranges (110-200 km), likely due to efficient energy utilization in prolonged missions. They have virtually no noise or pollutant emissions, which makes them ideal for certain tasks. In addition, the electric energy system usually has a sound energy management system, which can dynamically adjust the energy output according to the task demand, and improve the efficiency of energy utilization. At present, the energy storage systems used by UUVs are mainly lithium-ion batteries, but their energy density is relatively low. This restriction limits the full load operation time of UUV powered. Consequently, these systems fall short of meeting the demands for prolonged, logarithmic-scale operations required in deep-sea scientific exploration or military reconnaissance missions. Therefore, augmenting the endurance of energy systems for UUVs has emerged as a formidable and pivotal challenge that underpins their long-endurance navigation, successful mission execution, and combat capabilities.

SOLUTIONS

Hybrid energy systems

Hybrid energy systems that combine batteries and fuel cells are increasingly being used to improve the endurance of underwater equipments.[5] The Type 214 submarine developed by Germany adopts a hybrid energy system that combines fuel cell and lithium-ion battery.[6] The system achieves optimized energy utilization and ensures operational redundancy through a tiered dynamic cooperative control, architecture as shown in Figure 1B. The coordination stratum employs control algorithms to real-time optimize both the hydrogen consumption rate and the depth of discharge of the batteries within the fuel cell system, aiming to enhance the overall energy conversion efficiency. The execution stratum leverages bidirectional DC/DC converters to attain seamless switching between dual energy sources, maintaining a stable power output via feedback regulation. This integrative approach permits UUVs to exploit both the substantial energy density and long-term power supply capabilities of fuel cells, coupled with the rapid response and short-term high-power supply characteristics inherent to battery technology. Based on this energy system, the Type 214 submarine can continuously navigate underwater in snorkeling state at a speed of 6 kn for a range of 12000 nautical miles and a maritime endurance of 12 weeks. Hybrid energy system also



Model	Weight (kg)	Energy source	Energy type	Energy density (Wh/kg)	Maximum operating speed (kn)	Operational range (km)
VA-111 Shkval	2500	Thermal energy	Li+SF_6	1355	200	10
MK50	340	Thermal energy	HAP+ OTTO-II+ seawater	1146	50	18
UGST	2200	Thermal energy	Hydroreactive metal fuel	629	65	60
Theseus	8000	Electric energy	Silver-zinc battery	460	3	200
REMUS	37	Electric energy	Li-ion battery	416	8	110

Figure 1. Next-generation energy systems for UUVs (A) Primary modules of an UUV and classification of UUV energy systems. (B) Technical Roadmap of hybrid energy system. (C) Energy resources available for UUV use and the conceptual diagram of underwater wireless charging technology. (D)Typical UUV and their energy-related performance parameters. (E)The functions of BMS.

provides a degree of redundancy. If there is a problem with one of the energy sources, the other can still provide partial power to ensure the safe return of UUV. However, the design and control of hybrid energy systems are more complex than single energy source systems. It requires an advanced energy management system to optimize the operation of both the battery and the fuel cell components to achieve the best performance and energy efficiency.

Marine energy capture and utilization

Marine energy capture and utilization also play a crucial role in augmenting the endurance of UUVs,[7] The ocean presents a wealth of untapped energy sources, as shown in Figure 1C. Ocean temperature difference energy, for instance, exploits the significant thermal gradient between surface and deep waters. The thermoelectric generator integrated into the UUV hull can achieves an energy conversion efficiency ranging from 3% to 5% by harnessing a temperature differential of at least 15°C between the surface and deep water. Through a modular series design, it has the capacity to provide 1.2 to 1.8 kWh of electricity daily, this supplementary power lessens the UUV's dependence on its primary energy storage, prolonging its operational time.

Wave energy, harnessed by miniaturized wave energy converters attached to UUVs, captures the kinetic energy of ocean waves. These converters, adaptable to varying wave conditions, can generate substantial power, especially in high-wave areas.[8] The extra energy empowers UUVs to execute power-intensive tasks like high-speed navigation or operating additional instruments. For example, the piezoelectric electromagnetic hybrid wave energy converter achieves a power density of 50 to 200 W/m^2 at wave heights of 0.5 to 4 m, with a capture efficiency increased to 22% to 25%. Similarly, the small turbine generator, integrated into the propulsion shaft system, achieves a water kinetic energy-to-electricity conversion efficiency of 15% to 18% at flow rates equal to or exceeding 0.8 m/s, and optimizes the reverse flow resistance through variable pitch control. By capitalizing on predictable currents, UUVs can conserve onboard energy, stay submerged longer, and carry out more complex missions.

By deploying solar panels on the surface of UUV's hull, photoelectric conversion is utilized to transform light energy into electrical energy. A portion of the electrical energy generated by the solar panels is directly supplied to UUV's navigation, communication, and other systems, while the remaining energy is stored in batteries. Meanwhile, ocean current energy harvesting devices such as water turbines or oscillating hydrofoils can be installed at the bottom or on both sides of UUVs. When in areas with suitable current velocities, ocean currents drive the rotation of the impellers or the oscillation of the hydrofoils, which in turn drives the generator to produce electrical energy. Capture and utilization of these marine energy sources not only extend the physical endurance of UUVs but also unlock entirely new scientific research paradigms through autonomous power supply methods, propelling humanity's cognition and exploration of the deep sea into a new phase.

Underwater wireless charging technology

Underwater wireless charging technology has emerged as a highly promising and innovative solution to bolster the endurance capabilities of UUVs. This technology provides autonomous energy supply, bidirectional data exchange, and fault self-diagnosis for UUVs through non-contact energy transmission and intelligent collaborative control technology (Figure 1C). By doing so, UUVs can remarkably expand their operational envelopes and undertake more extensive and complex missions. WiSub's Torden underwater wireless charging system utilizes magnetic resonance coupling technology to achieve an output power exceeding 3 kW. Operating at depths of several kilometers, it is suitable for a diverse range of applications, spanning from shallow coastal waters to deep-sea environments. Currently, the power output and charging efficiency of underwater wireless charging systems have reached a level where they can adequately satisfy the energy demands of small-sized UUVs. However, this technology continues to encounter engineering challenges, including eddy current losses induced by dynamic seawater media, electromagnetic interference during high-power transmission, and interface electrolytic corrosion arising from prolonged operation. Further advancements are essential, necessitating multi-physics coupling optimization and the exploration of novel corrosion-resistant materials to address these obstacles effectively.

Intelligent battery management system

An intelligent battery management system (BMS) is of utmost significance in bolstering the endurance of UUVs. The functions of the BMS are shown in Figure 1E. Firstly, it can precisely optimize the charging and discharging processes of autonomous underwater vehicles through multi-level balanced topology circuits and dynamic load sensing algorithms. This capability enables the battery pack to adaptively adjust within the 0.1 C to 2 C charging and discharging rates range, mitigating the risks of overcharging and over-discharging while significantly extending the battery cycle life.[9] Secondly, BMS can monitor the temperature,[10] state of charge, and state of health values of the battery pack within the temperature range of -20°C to 60°C using embedded multimodal sensors. By integrating temperature control strategies and fault self-diagnosis protocols, BMS ensures the stability of power output in extreme underwater environments. Additionally, BMS achieves energy-efficient power distribution. In scenarios where UUVs need to concurrently execute multiple tasks, BMS optimizes energy utilization efficiency based on dynamic energy allocation models prioritized by task requirements. This optimization can enhance comprehensive endurance by up to 30% and collaborates with UUV main control systems through interfaces to achieve adaptive energy allocation in multitask environments, such as dynamically switching sensor/thruster power. These advancements collectively enhance the overall endurance of UUVs, paving the way for more extensive and successful underwater operations.

CONCLUDING REMARKS

In conclusion, the evolution of UUV energy system is at a critical juncture. We have dissected the existing challenges, from the noise and emissions of thermal energy-based UUVs to the endurance limitations of electric ones. However, the proposed solutions herald a new era of underwater exploration. By integrating hybrid energy systems, marine energy capture technologies, underwater wireless charging, and intelligent battery management systems, the combat capability of UUVs is poised to achieve multidimensional breakthroughs. Hybrid energy systems can potentially extend endurance by 30% to 50%, while ocean energy and wireless charging technologies reduce reliance on mother ships and broaden mission coverage radii. BMS plays a crucial role in enhancing battery life through dynamic balancing and thermal management, thereby optimizing power distribution to improve energy efficiency. The combined effect of these technologies significantly enhances the long-term operational capacity, stealth, and system reliability of UUVs, offering sustainable energy support for tasks like underwater reconnaissance, military deployments, and resource exploration. Future UUV energy systems are advancing towards heightened integration and intelligence. Fuel cells and solid-state batteries will be integrated with ocean energy devices to create modular energy supply units, while AI-driven dynamic management algorithms will enable real-time optimization of energy allocation. The underwater wireless charging network, leveraging the "Ocean Internet of Things," will enable collaborative operations among multiple UUVs. Breakthroughs in laser/acoustic long-distance charging technology will overcome the limitations of electromagnetic coupling. Environmental energy capture technologies, including biofuel cells and flexible frictional materials, will provide enduring support for low-power devices. Standardized interfaces and the accelerated military-civilian technological convergence will propel UUVs towards full autonomy, high stealth, and broad area coverage as "underwater combat nodes," reshaping the strategic landscape of ocean monitoring and military operations.

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FUNDING AND ACKNOWLEDGMENTS

This study was supported by the National Natural Science Foundation of China (No. 52376175), the China Postdoctoral Science Foundation (No. 2023M741515), and the Fundamental Research Funds for the Central Universities (No. D5000240321). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

DECLARATION OF INTERESTS

Yongchen Song is an Editorial Board member of The Innovation Energy and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.