



Optimizing Submarine Energy Systems: Engineering Trade-Offs and Future Pathways

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Abstract

Conventional submarines face a fundamental engineering trade-off between submerged endurance, acoustic and thermal discretion, propulsion power, safety, cost, and platform integration. No single energy or propulsion technology simultaneously maximizes all of these parameters. This paper evaluates five technological pathways relevant to the future of the Indian Navy: nuclear propulsion, air-independent propulsion (AIP), lithium iron phosphate (LFP) batteries, AIP–LFP hybrid systems, and emerging lithium titanate/solid-state battery architectures.

Particular attention was given to the interaction between propulsion and energy-storage systems, since changes in one subsystem can impose constraints on weight distribution, cooling, internal volume, maintenance, and platform architecture.

The analysis indicates that the principal challenge is not selecting a universally superior technology, but optimizing complementary technologies around distinct operational requirements. Nuclear propulsion provides exceptional endurance and sustained power but introduces substantial cost, infrastructure, safety, and acoustic-management requirements.

For India, the findings suggest that future submarine development should prioritize indigenous, modular energy architectures that balance endurance, power, safety, lifecycle cost, and technological sovereignty rather than pursuing a single propulsion solution. The study ultimately frames submarine energy design as a multi-objective optimization problem in which operational effectiveness is determined by system-level integration rather than any individual technology.

Keywords submarine propulsion; air-independent propulsion; lithium iron phosphate; lithium titanate; indiscretion rate; energy storage

TECHNICAL EVALUATION OF NEXT-GENERATION SUBSURFACE POWER ARCHITECTURES

One limitation that every navy in the world has been working to solve, is the problem of depleting batteries, increasing the time submerged, and the classic issue of minimizing detectable acoustic and thermal signatures to the point of operational near-invisibility.

Many possible solutions have been emerging in today's world, and a few prominent ones are the adaptation of Lithium-Ion Batteries by the Japanese Maritime Self-Defence Force, who have been researching ways to make this highly flammable and risky technology safe enough for them to start housing in their submarines. They have launched the Taigei-Class, whose all units now have Lithium Nickel Cobalt Aluminium Oxide (NCA) Lithium-Ion Batteries as their main power unit. However, another emerging technology that complements conventional submarine battery systems rather than directly competing with them is Air Independent Propulsion (AIP). Developed indigenously by DRDO for integration into the Indian Navy's Kalvari-class submarines, the system is designed to extend submerged endurance by enabling submarines to generate power underwater without relying on atmospheric air. (Nuclear Threat Initiative, 2025)

Although integration was previously expected to take place during 2026, the installation timeline should be verified against the latest project updates. (Naval Materials Research Laboratory, n.d.)

Another major propulsion system already implemented by both the United States and the United Kingdom is nuclear propulsion. The U.S. Navy operates nuclear-powered attack and ballistic-missile submarines, while the Royal Navy's submarine fleet consists entirely of nuclear-powered submarines.

These are submarines that have no need for snorkeling, and are also one of the main focuses of The Indian Navy, with two commissioned nuclear-powered ballistic missile submarines (SSBN's) which are the INS Arihant and the INS Arighaat (Nuclear Threat Initiative, 2025).

There are many ongoing research operations being conducted by the Defence Research and Development Organization (DRDO) on AIP Fuel Cells (Naval Materials Research Laboratory, n.d.; Ministry of Defence, 2015), Lithium Phosphate Batteries (Naval Science and Technological Laboratory, n.d.), etc. However, during my own research in this topic, I understood that in submarines, each component is ultimately interlinked to each other. If we swap out lead-acid batteries for lithium-ion batteries, which are much lighter, it changes the entire weight distribution of the submarine. However, naval architects mitigate this by adding fixed lead ballast to the keel. This maintains the Centre of Gravity (CoG) while providing the boat with a 'weight margin' for future sensor or weapon upgrades, rather than risking stability or a rollover.

Furthermore, retrofitting legacy diesel-electric submarines with lithium-ion batteries presents challenges involving compatibility with existing charging equipment, generator capacity, and thermal-management systems (Gartner, n.d.). Although certain lithium-titanate (LTO) cells support exceptionally rapid charging under specified operating conditions (Toshiba, n.d.-b), the charging rate achievable aboard a submarine depends on the capacity of its electrical infrastructure and the thermal limits of the integrated battery system. These constraints must be evaluated at the system level rather than inferred from cell-level charging specifications alone.

Procurement costs remain a significant consideration when evaluating alternative submarine energy systems. Lithium-ion battery retrofits can entail substantial expenditure beyond the battery cells themselves, including modifications to charging infrastructure, battery-management systems, cooling arrangements, and onboard safety mechanisms. Air Independent Propulsion (AIP) retrofits likewise require considerable investment in equipment, hull integration, and supporting systems, while potentially necessitating an extended period out of service for installation and testing. Nuclear propulsion presents a substantially more complex undertaking, requiring specialised reactor technology, extensive supporting infrastructure, stringent regulatory oversight, and long-term arrangements for nuclear safety and waste management. These financial and logistical demands must therefore be weighed alongside the operational benefits of each technology.

Keeping these factors in consideration, this review evaluates several propulsion and energy-storage technologies that could address the endurance, stealth, power, safety, and integration challenges faced by conventional submarines. Each system is examined in terms of its technical advantages, limitations, operational constraints, and integration requirements. Rather than identifying a universally superior technology, the review examines the trade-offs

between these systems and considers how different technologies may be combined to achieve an effective balance between submerged endurance, power availability, acoustic and thermal discretion, safety, cost, and maintainability.

These systems are :-

1. Nuclear-Powered Submarines

India has continued to expand its indigenous Arihant-class nuclear-powered submarine programme, with three SSBNs reportedly commissioned as of 2026 (International Institute for Strategic Studies, 2026).

This has been a leap in technology, as fitting an entire nuclear reactor in a metal tube is not an easy feat. It allows the boat to stay submerged for several months at a time, without needing to surface for snorting. This effectively eradicates the issue of repeated surfacing for snorting when using Diesel-Electric Propulsion.

Nuclear powered submarines operate by using a nuclear reactor inside which uranium atoms (often highly enriched Uranium-235) are bombarded with neutrons. This causes the atoms to split (fission), releasing a massive amount of heat, which boils water to create steam. The high-pressure steam spins large turbines that are connected to reduction gears that turn the submarine's propeller shaft directly, or they power an electric motor (In newer French Suffren-class and US boats of the Columbia-class) that drives the propeller. The steam also spins smaller turbines connected to electrical generators, providing power for lights, computers, sonar, and life support systems. This system also includes a Pressurizer that maintains high pressure to keep the primary coolant in a liquid state at temperatures well above 100°C. A major advantage of nuclear propulsion is its ability to sustain a closed steam cycle. Steam produced in the secondary loop is condensed back into water and returned to the steam generators, where it is reheated through heat transfer from the reactor's primary coolant system (National Museum of American History, n.d.). The same working fluid can therefore be circulated repeatedly rather than being continuously consumed. This contributes to the submarine's ability to remain submerged for extended periods, although its overall endurance is ultimately constrained by factors such as food, maintenance requirements, crew endurance, and other onboard provisions.

Radiation protection aboard nuclear-powered submarines is achieved through multiple layers of engineering and operational controls, including reactor shielding, radiation monitoring, controlled access to reactor spaces, and established radiological safety procedures.

Nuclear propulsion also provides a high and sustained power output, allowing nuclear-powered submarines to maintain high submerged speeds for extended periods. Some modern nuclear-powered submarines can exceed 25 knots while submerged. This combination of sustained power and endurance provides significant operational flexibility, including the ability to reposition rapidly while remaining submerged.

The biggest disadvantage is that a nuclear reactor cannot be turned off. Even when the submarine is sitting perfectly still, the cooling system must run continuously to prevent the reactor from overheating. Mechanical pumps must constantly circulate coolant through the reactor. These pumps create a steady hum and vibration that can be detected by sensitive enemy sonar, whereas a Diesel-Electric boat can be turned off completely, with little to no

machinery noise. A nuclear-powered submarine, on the other hand, is always making some level of noise, which is a massive hurdle in today's increasingly "transparent" ocean.

Submarine operations can produce thermal wakes through interactions between the vessel, its discharged heat and the surrounding seawater. These disturbances may create subtle warm or cold temperature anomalies at the ocean surface (Gao et al., 2025). Their detectability using infrared (IR) imaging depends heavily on operating depth and environmental conditions, making infrared detection a supplementary rather than consistently reliable means of locating submerged submarines ("Review on the Hydro- and Thermo-Dynamic Wakes," 2024). Another disadvantage is that Diesel- Electric submarines can safely sit on the sandy seafloor to hide. A nuclear submarine generally cannot do this because its cooling intakes are on the bottom of the hull and sitting in the sand would suck silt and debris into the main seawater condensers and cooling intakes, potentially leading to a catastrophic reactor event. Furthermore, large nuclear-powered submarines face additional navigational constraints in shallow waters, where limited under-keel clearance restricts their ability to manoeuvre vertically. This reduces their room to respond to sudden hazards or depth-control problems, increasing the risks associated with operating in confined maritime environments (U.S. Naval Institute, 2010). To silence their cooling systems, the United States Navy focuses on source silencing through advanced engineering rather than just relying on external coatings. A significant innovation in submarine reactor design is natural circulation, which uses convection driven by temperature-induced density differences to circulate coolant without mechanical pumps at low and moderate operating speeds, reducing machinery noise and improving acoustic stealth (Holbert, 2025).

For necessary machinery, the Navy uses raft mounting, where pumps and turbines are suspended on isolated platforms to prevent vibrations from "ringing" through the hull. Every internal component, down to the precision-tested bearings, is manufactured to extreme tolerances to eliminate mechanical clicks or whines. While anechoic tiles help absorb some sound, it is this combination of pump-less cooling and mechanical decoupling that truly allows a nuclear submarine to maintain its acoustic invisibility. To further eliminate noise from the water leaving the ship, modern subs utilize pumpjet propulsion, which shrouds the blades in a nozzle to significantly reduce cavitation, the formation of loud vacuum bubbles.

In conclusion, while nuclear propulsion remains the gold standard for global power projection and blue-water operations, it is not a universal replacement for the versatile diesel-electric fleet. Transitioning to an all-nuclear force is a herculean task that involves more than just fitting a reactor into a pressure hull; it requires a massive, high-cost investment in specialised shore-based infrastructure and a dedicated nuclear safety culture. Moreover, a single nuclear submarine can cost 7 to 10 times more to build and operate than a conventional boat. They require a highly skilled pool of nuclear-qualified engineers and physicists, which is a limited talent pool for most navies.

Ultimately, the future of the Indian Navy lies in a balanced hybrid fleet. While SSBNs like the Arihant-class secure our second-strike capability, advanced conventional boats equipped with Air Independent Propulsion (AIP) and Lithium-Ion batteries remain indispensable for silent, lethal operations in the crowded littoral zones of the Indian Ocean.

2. Air Independent Propulsion Systems (AIP)

India is rapidly developing its prowess in the Air Independent Propulsion Systems (Ministry of Defence, 2015, 2023), and aim to equip the INS Khanderi (Kalvari-class Scorpene) (Nuclear Threat Initiative, 2025) with an AIP system by the end of 2026, when it is docked for a Major Refit and Certification (MRLC).

Air Independent Propulsion (AIP) systems allow non-nuclear submarines to operate their engines and generate electricity while completely submerged, without the need to surface or use a snorkel for atmospheric oxygen. While traditional diesel-electric submarines must snorkel every 2–3 days to recharge batteries, AIP-equipped vessels can remain underwater for 14 to 21 days.

AIP systems typically serve as an auxiliary power source to the primary diesel-electric plant. They generate electricity to drive the propulsion motor at low speeds (usually 4–6 knots) or to keep the submarine's "hotel load" (electronics, life support) running while the main batteries remain charged for high-speed maneuvers.

These systems are effectively add-ons to a Diesel-Electric Propulsion system, and allows the boat to reduce machinery noise and remain submerged and undetected for potential weeks. The Defence Research and Development Organization (DRDO) has been researching the system of AIP Fuel Cells, in particular Phosphoric acid fuel cells (PAFC) (Naval Materials Research Laboratory, n.d.; Ministry of Defence, 2015; Defence Research and Development Organisation, n.d.). This system converts chemical energy from a fuel (hydrogen) and an oxidizer (oxygen) directly into electricity through an electrochemical reaction. In this reaction hydrogen and oxygen react across a membrane (like a Proton Exchange Membrane or PEM) to produce DC power and water as the only byproduct. These systems have no moving parts, are extremely quiet and have a good efficiency in real-world situations (over 40%). Existing submarines with such a system is the German boat Type 212/214 (which use Siemens PEM Cells). While most of the world (like Germany) uses PEM cells, DRDO's choice of PAFC is notable because it is more rugged and tolerant to impurities in the hydrogen fuel, which is a major advantage for operational durability. The DRDO system is unique because it generates hydrogen onboard as needed, rather than storing it in bulk (Ministry of Defence, 2015, 2023). It produces hydrogen by hydrolysis Sodium Borohydride.

By eliminating the need to snorkel every few days, AIP reduces the submarine's Indiscretion Rate, the time it is vulnerable to radar and visual detection, from roughly 20% to less than 1%. Furthermore, the lack of acoustic signature of the fuel cell AIP makes them complete game changers in littoral waters like the Arabian Sea, and in situations where stealth and endurance are more necessary than speed. Their ability to remain submerged for 2–3 weeks allows them to lie in wait at strategic choke points for long-duration surveillance or surprise attacks.

AIP submarines are approximately 3 to 4 times cheaper to procure and operate than nuclear-powered attack submarines, while providing "semi-strategic" capabilities to medium-sized navies.

Another benefit of such systems is that they produce only pure water as a byproduct and generate less vibration and heat than diesel engines, improving crew comfort and reducing the vessel's thermal signature. However, AIP has its own limitations. While a nuclear submarine can sustain 30+ knots indefinitely, AIP typically provides only about 10% of the power of a traditional plant, limiting underwater "sprint" speeds to roughly 4–6 knots for long endurance. While this speed does provide an Acoustic Optimum speed, that is the boat effectively blends into the

ocean's ambient background noise, we must understand the kinetic limitations of such a system. Even if the AIP is shut down and the batteries are used, in case of a requirement of an intercept of a fast-moving target, or escaping a kill-box, if detected, the battery power produced may not be enough.

Another threat of these systems is that storing liquid oxygen (LOX) and highly volatile hydrogen inside a pressurized hull presents significant fire and explosion risks (Moinuddin, 2021; Defence Research and Development Organisation, n.d.). Managing these flammable substances requires complex, heavy safety systems like metal hydride tanks.

The most prominent limitation of this system is that installing an AIP Hull Extension Module typically increases a submarine's length and weight. This extra bulk can negatively affect the boat's maneuverability and takes up space that could otherwise be used for weapons or crew. The process of installation itself is a complex and time-taking procedure, and requires cutting of the hull, and an entire redesign of the layout of the boat, effectively putting it out of commission for 2 to 3 years.

AIP systems are also quite technically sophisticated and require highly specialized technicians for upkeep. Initial procurement costs are 15–25% higher than standard diesel-electric boats, and the specialized parts often have limited supplier competition.

In conclusion, while AIP provides unprecedented 'static' stealth, it lacks the energy density for high-speed 'kinetic' maneuvers. To prevent an AIP boat from being tactically limited by its low transit speeds, the integration of Lithium-Ion Batteries is essential. This hybridization allows for long endurance low-speed patrolling (AIP) combined with high-capacity 'sprint' endurance (Li-ion), providing the Indian Navy with a truly multi-role subsurface asset (Naval Group, 2024). Ultimately, we must understand that no system is perfect on its own, or even with an add-on. The main issue is that when one system provides stealth, it takes away speed, and vice-versa. The Indian Navy should direct its resources on building indigenous solutions and alternatives that help us reach the best compromise as mentioned earlier.

3. Lithium Iron Phosphate (LFP) Battery

As submarine technology continues to evolve, lithium-ion batteries offer opportunities to enhance energy efficiency, submerged endurance, and onboard power availability. Their potential benefits also include reducing routine maintenance requirements compared with conventional lead-acid battery systems, while supporting the Indian Navy's broader pursuit of advanced, reliable, and efficient submarine capabilities.

Flooded lead-acid submarine batteries require regular monitoring and maintenance, including electrolyte management, ventilation checks, adherence to prescribed charging procedures, and periodic inspections and capacity testing to ensure reliable performance throughout their service life (U.S. Navy, n.d.; Institute of Electrical and Electronics Engineers, 2010).

Consequently, battery maintenance represents not only a recurring technical requirement but also a factor in the submarine's overall lifecycle maintenance schedule.

Lithium-ion technologies can reduce some of these burdens while offering substantially greater energy density than conventional lead-acid systems. This allows a given amount of stored energy to be accommodated with potentially lower battery mass and volume, creating greater flexibility in the allocation of internal space and weight. For a submarine, where displacement,

centre of gravity, internal volume, and weight distribution are tightly constrained, reducing the mass and physical footprint of the energy-storage system can have implications beyond the battery compartment itself.

However, the transition to lithium-ion batteries does not simply remove the engineering constraints associated with lead-acid systems. Lithium-ion batteries require sophisticated battery-management systems, thermal monitoring, protection against cell failure, and appropriate fire-safety measures. The engineering advantage therefore lies not in eliminating maintenance or structural constraints altogether, but in replacing a comparatively heavy and maintenance-intensive energy-storage system with one that can provide greater energy-storage efficiency while introducing a different set of integration and safety requirements.

Furthermore, traditional PbA cells utilize a sulfuric acid electrolyte which, during the "gassing phase" of charging, releases a corrosive acidic mist. This mist is hygroscopic; it settles in the bilges and creates localized "hot spots" of corrosion on the internal frames and longitudinals of the pressure hull. In every Major Refit (MR) for legacy boats of this class, significant man-hours and funding are diverted to "bilge remediation", the expensive process of stripping, neutralizing, and re-coating the internal hull steel to stop acid-induced thinning. Li-ion cells are primarily sealed in prismatic cans (Naval Science and Technological Laboratory, n.d.), eliminating electrolyte leakage and preserving the submarine's primary structure for a longer service life.

Another important consideration is battery cycle life. Lead-acid battery longevity depends on operating conditions, depth of discharge and maintenance practices, with electrochemical degradation eventually necessitating replacement (U.S. Navy, n.d.). By comparison, lithium iron phosphate (LFP) batteries can achieve approximately 3,000–5,000 cycles under specified test conditions, depending on depth of discharge and battery design (Renogy, n.d.; NPP Power, n.d.). If comparable performance can be demonstrated in submarine-grade systems, LFP technology could extend battery replacement intervals, reduce long-term maintenance demands and improve operational availability.

In current times, with Japan adopting Lithium Nickel Cobalt Aluminum Oxide (NCA) batteries, and skipping AIP completely, the world has opened up to newer and much more efficient technologies.

Japan's introduction of NCA batteries in its Taigei-class has been a very closely looked-at global event. NCA batteries are known for their high energy density (3.5 to 4 times the power density of lead-acid batteries) and that charging these batteries take around 1 to 2 hours.

However, NCA is chemically volatile. During a Thermal Runaway event, NCA cells release their own oxygen, creating a self-sustaining fire that cannot be smothered by traditional firefighting agents (Gamble, 2020). Furthermore, the emission of toxic Hydrogen Fluoride gas in a sealed pressure hull is a "hull-loss" scenario (Moinuddin, 2021). Japan spent over a decade developing automated cell-isolation and high-capacity ventilation systems to mitigate these risks. For the Indian Navy, adopting NCA would mean introducing a high-risk safety culture that reduces the margin for error during combat damage.

Of course, there is the point that Japan has developed technology that can reduce the chances of a thermal runaway, but we must understand that a high-tech boat cannot run without its crew.

By putting the very crew at risk, we are going against the fundamentals of engineering. We must understand the complex trade-offs and that the risk is not really worth the reward.

After understanding the threat posed by NCA batteries, I started researching alternatives that are already being heavily focused on by the DRDO, that are Lithium Iron Phosphate Batteries (Naval Science and Technological Laboratory, n.d.), also called "Soldier's Battery". These batteries are far more stable than NCA and can withstand punctures, short circuits and high temperatures without reaching the "point of no return". It effectively provides a critical safety buffer in the high stress, closed environment of a submarine. While Lead-Acid batteries require a slow "gassing phase" (taking up to 10 hours to fully charge), LFP can accept a maximum bulk charge (maximum current) almost to 100% capacity. This drastically reduces the Indiscretion Rate by up to 60%.

Most importantly, LFP chemistry is a primary focus for the DRDO (Naval Science and Technological Laboratory, n.d.) as it can be produced locally which ensures a secure supply chain, free from foreign "end-user" restrictions, and allows India to maintain sovereign control over its subsurface energy systems. This also reinforces the idea of an "Atmanirbhar Bharat", and also supports local companies and production centres.

However, LFP also has its own limitations. The most prominent drawback is its lower energy density compared to Nickel Manganese Cobalt (NMC) or Nickel Cobalt Aluminium (NCA) chemistries. Because LFP stores less energy per unit of weight and volume, a battery pack must be roughly 30% larger and heavier to achieve the same range or capacity as its competitors.

In terms of environmental resilience, LFP faces a notorious "cold cliff." While it handles high heat exceptionally well, its internal resistance spikes in freezing temperatures, leading to a loss of 20% to 50% of its usable capacity below 0°C. More critically, charging an LFP battery in the cold can cause "lithium plating"—a phenomenon that permanently damages the cells and creates internal short-circuit risks. To combat this, LFP systems often require integrated heating elements, which consume a portion of the battery's own energy just to bring the cells up to a safe operating temperature before charging can even begin.

However, this is primarily a concern during surface transit in high-latitude winters or for unheated storage. Once submerged, the boat's own internal "Hotel Load" (electronics/crew) usually keeps the battery pits well above the danger zone. Also, we can also consider a Hybrid take, in which the waste heat generated by AIP Fuel Cells could be redirected to the battery pits, thereby reducing the thermal wake of a submarine and also keeping the temperature in the battery pits in check.

Although lithium iron phosphate (LFP) batteries generally offer lower energy density than nickel-rich alternatives, they provide advantages in cost and material composition. LFP batteries contain neither cobalt nor nickel, and their battery packs have historically been less expensive per kilowatt-hour than nickel-based NMC alternatives (International Energy Agency, 2025b). However, LFP technology typically performs less effectively in cold climates, and its suitability for submarine applications must be assessed against the vessel's power, volume, thermal-management and safety requirements. Furthermore, domestic LFP production could support India's defence-indigenisation objectives, although manufacturing independence would require development of the wider supply chain, as production of LFP cells and cathode materials remains heavily concentrated in China (International Energy Agency, 2025a).

Lithium-ion batteries may also offer maintenance and usable-capacity advantages over conventional flooded lead-acid systems. Lead-acid batteries typically require electrolyte monitoring and water replenishment, while lithium-ion systems use battery-management systems to monitor cell conditions and control charging. However, lithium-ion batteries are not maintenance-free, and submarine installations still require appropriate monitoring, cooling and protective systems. Although lithium-ion batteries can generally utilise a greater proportion of their rated capacity than lead-acid batteries, the usable capacity of a submarine battery must be determined by its specific chemistry, design and operating limits rather than a universal capacity ratio. Any potential savings in maintenance, weight or volume would need to be established through a vessel-specific engineering assessment before being allocated to other systems.

In conclusion, LFP batteries offer a promising balance of safety, durability, and cost-effectiveness, while hybrid energy systems present another avenue for combining acoustic stealth, energy efficiency, and high-power delivery. Exploring these complementary approaches can help shape more adaptable and resilient submarine power architectures for future operational demands.

4. Hybrid Systems (Air Independent Propulsion and Lithium Phosphate Batteries)

The "sweet spot" isn't choosing between AIP or Lithium; it's making them work as a team. It's clear that a hybrid system - Fuel-Cell AIP for sneaking and LFP batteries for fighting - is the only way to optimize the submarine's energy systems.

In a standard AIP boat, as I mentioned earlier, the boat has stealth, but does not have the required capacity for a tactical maneuver or a fast-paced intercept. AIP is wonderful to wait, stage an attack, and remain submerged for potential weeks without the enemy detecting you, but it is not meant for escaping the kill box of an enemy destroyer if the boat does get detected. With the ocean getting more and more "transparent" with the highly developed Anti-Submarine Warfare (ASW) Technology, we don't just need stealth and endurance, but we also need speed. If we compare our AIP equipped boat with a nuclear-powered boat of the US Navy, we can see the limitations of our boat. Therefore, we require a method to achieve speed as well as endurance.

This method is by equipping an AIP Fuel-Cell and an LFP Battery in our boats. The LFP Battery equips the boat with the ability to "sprint" when required, and also intercept fast-paced targets, and simply have more kinetic maneuverability. By using AIP to handle the "hotel load", we can keep our LFP batteries at maximum capacity. If the boat is detected, the crew does not have to wait for a slow fuel-cell to spool up, rather, we draw a massive "slug" of current from the Lithium bank and hit a "sprint" instantly (Naval Group, 2024).

It is true that all boats have a Cavitation Inception Speed (CIS). When a propeller turns too fast, the pressure drop on the blade tips creates vacuum bubbles that collapse violently, creating a distinct "crackling" sound detectable at long ranges.

A possible solution could be the integration of Skewed-Back Propellers or Pump-Jets (Used by the US Navy for their Nuclear powered submarines, such as the Virginia-class). These designs allow the boat to maintain higher "tactical speeds" before the cavitation threshold is reached. By equipping such propulsion systems in our Hybrid Boats, we enable them to go at faster speeds, without being detected by enemy sonar.

Furthermore, if AIP Fuel-Cells and LFP are introduced together, to keep the Li-ion batteries from melting when the boat pulls massive power for a high-speed sprint, the crew has to run high-capacity cooling pumps and heat exchangers. These pumps are acoustic killers. A smart sonar tech on a nearby destroyer could easily hear these pumps "ringing" through the hull. It poses a tactical paradox, that the very system designed to help the boat "sprint" is creating a beacon that gets the boat tracked.

Current technical mitigations observed on Project 877 EKM's are the Anechoic Tiles (which cover the external hull), rubberized coatings designed to absorb incoming sonar pulses from enemy ships and damped internal noise escaping the boat.

It is true that there exist other systems that could be integrated into the submarine such as piezoelectric tiles that use Active Noise Cancellation to cancel out whatever frequency of sound is being produced by the machinery, however, we must also keep in mind, that such devices drain battery power, and are expensive. Such devices increase the parasitic load on the batteries, potentially increasing the Indiscretion Ratio.

Therefore, AIP-hybrid systems represent a potentially important pathway for the next generation of conventional submarines, particularly in improving submerged endurance and reducing dependence on conventional lead-acid battery systems. Their relevance becomes clearer when considering contemporary submarine designs such as the Virginia-class and Taigei-class, which employ advanced energy and propulsion architectures to support extended submerged operations and acoustic discretion. However, direct comparisons of stealth and endurance are difficult because detailed performance data for modern submarines are not publicly available. The development of nuclear-powered submarines provides another pathway toward extended submerged endurance and sustained power. Consequently, both AIP-hybrid and nuclear architectures present distinct advantages and constraints, and their suitability depends on the specific operational, technological, and platform requirements being considered.

A potential challenge for fuel-cell-based AIP systems is managing fluctuating onboard electrical demand, as repeated load changes can contribute to fuel-cell degradation (Wang et al., 2019). One possible solution is to integrate an LFP battery bank as a buffer, allowing the fuel cell to operate at a more stable output while the battery supplies short-duration power peaks. Hybrid fuel-cell–battery energy management has been shown to offer opportunities to improve fuel-cell durability by reducing transient loading (Wang et al., 2019). Research under simulated maritime conditions also indicates that dynamic loading can increase irreversible performance degradation in PEM fuel cells (McCay et al., 2026). However, the extent to which battery buffering would extend the service life of a submarine AIP system requires further system-specific testing.

Lead-acid batteries have a relatively low energy density, making them a substantial constraint on the weight and volume allocation of conventional submarines. Lithium-ion batteries can provide greater energy capacity within a comparable mass and, depending on the system design, may reduce the volume required for energy storage (Fina & De Cicco, 2025). However, replacing lead-acid batteries with lighter lithium-ion systems changes the submarine's weight distribution and stability characteristics, potentially requiring ballast redistribution and a reassessment of internal arrangements (Gartner, n.d.). Where a vessel-specific engineering

assessment confirms that usable space can be recovered, this could create opportunities to accommodate additional mission equipment, such as unmanned underwater vehicles (UUVs), or increase weapon-storage capacity.

In conclusion, we can see that even though this developing system has its drawbacks, such as hindering acoustic stealth during "sprints" and more, the potential positives are many more, and while the Upfront Capital Expenditure (CAPEX) is higher for Lithium and AIP, the Operating Expenditure (OPEX) is lower due to reduced dry-dock time.

5. Wetted Solid State Lithium Titanate Batteries (WSS-LTO)

These batteries are being researched by every Navy in the world, as these are the true solutions to the issue of constant compromise and trade-offs present in each system we analysed earlier. It is true that Solid State batteries like the SS LPF have issues like the growing of dendrites which crack the ceramic of the battery and effectively short-circuit the battery and make it practically unusable, current research in Solid State Batteries of Lithium Titanate are ongoing. Lithium Titanate (LTO) is something that feels like a myth to most engineers. This battery, even in liquid state, has zero strain (no dendrite growth), can operate at extremely high temperatures (Gamble, 2020). They can charge in approximately 45 minutes, if a modified and well-developed diesel engine is charging it, and has no problem providing a high amount of energy to the motors if required (Yan, 2021). However, Titanium is extremely expensive, and these batteries are great for momentary "sprints" but have extremely low energy densities, i.e., even if they can be charged quickly, they need to be recharged more frequently.

A key limitation of conventional diesel-electric submarines is the need to periodically recharge their batteries by operating diesel generators while surfaced or at snorkel depth. The charging duration depends on the battery bank's capacity, its state of charge, and the power available from the onboard generators; therefore, a universal charging time of two to four hours cannot be assumed without platform-specific data. Nevertheless, operating diesel machinery during charging increases acoustic noise and exposes the submarine to additional detection risks, including radar detection of the exposed snorkel mast and, under suitable conditions, infrared detection associated with the exhaust (Howard, 2010; *Submarine Technology*, 1990).

This creates an operational trade-off: while a submarine can operate relatively quietly on battery power when submerged, recharging requires it to enter a more vulnerable operating condition. Lithium-ion batteries could reduce the frequency or duration of charging under suitable design and operating conditions, but the extent of this benefit depends on the battery system, generator capacity and the submarine's energy demands. Consequently, faster charging should not be treated as an unconditional advantage; its value must be assessed alongside power-generation limits, thermal management and the need to minimise detectability during charging.

The development of solid-state batteries represents a significant advancement in electrochemical energy storage, although challenges involving interfacial resistance, ionic conductivity, long-term stability and large-scale manufacturing remain (Janek & Zeier, 2023; Xiao et al., 2020). In conventional liquid-electrolyte lithium-ion batteries, the electrolyte facilitates lithium-ion transport between the electrodes, while electrons flow through the external circuit. In

all-solid-state batteries, replacing the liquid electrolyte with a solid electrolyte can introduce additional resistance at solid–solid interfaces, particularly where contact between electrode and electrolyte materials is incomplete or where interfacial reactions impede ion transport (Pervez et al., 2019; Liu et al., 2025). Hybrid solid–liquid electrolyte configurations have therefore attracted research interest as a potential means of improving interfacial contact and ionic transport while retaining some of the benefits of solid electrolytes. However, these configurations can introduce their own interfacial reactions and stability challenges, and should not be assumed to eliminate resistance or achieve maximum efficiency automatically (Zhang et al., 2023).

Building on the limitations identified in the preceding analysis, I propose a hybrid energy-storage architecture that combines lithium iron phosphate (LFP) batteries with lithium titanate (LTO) batteries, rather than relying exclusively on LTO cells. This proposal addresses the trade-off between energy storage and high-power delivery: LFP is intended to provide the principal energy reserve for sustained submerged operation, while LTO would provide supplementary power during short-duration, high-demand events. LTO cells are used in applications requiring high charge and discharge rates, and manufacturer data demonstrate that certain LTO cell designs can sustain high-rate operation over many cycles; however, their performance varies with cell design and operating conditions (Toshiba, n.d.-a).

As an initial conceptual configuration, I propose allocating approximately 80% of the installed battery capacity to LFP and 20% to LTO. These proportions are a starting design assumption rather than an experimentally established optimum for submarines. Under this arrangement, the LFP bank would provide the principal energy supply during normal submerged operations, while the LTO bank would be reserved for brief propulsion-power peaks. A comparable division of roles has been investigated in hybrid LFP–LTO battery systems for electric vehicles, where LFP serves as the primary energy source and LTO supplies supplementary power through a controlled power-electronics architecture (Li et al., 2019). This provides a precedent for the proposed energy-management principle, although it does not demonstrate that the same configuration would be suitable for a submarine.

The proposed architecture would seek to separate two competing requirements: high energy capacity for sustained operation and high power availability for transient demand. Achieving this would require a suitable electrical configuration, battery-management and energy-management systems, and control strategies to regulate power sharing between the two banks. The LTO reserve would also need to be maintained at an appropriate state of charge, with its usable reserve balanced against the need to minimise unnecessary charging and degradation. Because LFP and LTO cells have different voltage characteristics and operating limits, their integration cannot be treated as a simple direct connection; system topology, converter requirements, thermal management, protection and fault isolation would need to be evaluated during detailed design (Li et al., 2019).

A smaller LTO reserve could require less energy to recharge after a comparable proportional discharge than a full-capacity LTO bank. However, this would not automatically guarantee faster charging: actual recharge time would depend on the energy removed, permitted charging rate, available generator power, thermal limits and charging strategy. The proposed 80:20 arrangement should therefore be treated as a hypothesis for further modelling and testing, with

the final allocation determined by the submarine's propulsion-load profile, endurance requirements, available volume and mass, and electrical-system constraints.

The proposed configuration is therefore intended to exploit the complementary characteristics of the two chemistries rather than treating either as a universally optimal solution. Its feasibility would, however, depend on further analysis of power requirements, battery-management architecture, thermal behaviour, mass and volume distribution, charging capacity, electrical integration, and the safety implications of operating two lithium-ion chemistries within the same submarine platform.

Conclusion

Through this research, I have come to realise that the challenges faced by submarines cannot be solved by searching for a single, flawless technology. None of the solutions explored in this report is without its limitations, because submarine design is fundamentally an exercise in compromise. Greater energy density may introduce different safety considerations; higher power output may demand more complex thermal management; and a technically superior system may prove economically or operationally impractical. The objective, therefore, is not to find a perfect solution, but to identify the best possible balance between competing requirements through rigorous research, intelligent system integration, and the indigenous development and production of critical technologies.

These requirements differ considerably between navies. Japan's adoption of lithium-ion batteries reflects its own operational priorities, industrial capabilities and approach to submarine development. The United States, with its global operational reach and demanding requirements for sustained high-speed underwater operations, has strong reasons to favour nuclear propulsion despite its substantial financial and technological costs. India, meanwhile, must evaluate its choices against its own strategic geography, financial constraints, existing submarine infrastructure and the practical consequences of introducing new technologies into an established fleet. A solution that is optimal for one navy cannot simply be assumed to be optimal for another.

For India, this makes a balanced, adaptable approach particularly important. Introducing a new battery technology is not merely a matter of replacing one set of cells with another; it requires careful consideration of integration, safety, cooling, power management, maintenance and the time a submarine may spend undergoing refit. Rather than committing the entire fleet to a single technology, India should investigate architectures that combine complementary systems, allowing each to compensate for the limitations of the other. Such an approach must be supported by sustained research, rigorous testing and indigenous manufacturing capabilities, so that operational independence does not come at the expense of reliability or crew safety.

Ultimately, the success of a submarine cannot be measured by energy density, endurance, speed or stealth in isolation. These are means to an end: a submarine must accomplish its mission, remain operational under demanding conditions and bring its crew home. Technological advancement matters only when it translates into a dependable operational advantage.



A submarine is not made exceptional by the sophistication of its technology alone, but by how intelligently that technology is made to work together. Because when every calculation, every system and every compromise is finally put to the test beneath the sea, the most advanced submarine is of little value if it cannot protect the people entrusted to it. A submarine without its crew is nothing more than a tin can.

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