Practical Application of Energy Storage in Hybrid Commercial Vessels

by Grant Brown

Elektra is Finland's first electric hybrid ferry and is capable of travelling 5 nautical miles on one charge.

Marine engineers have long been aware of the potential efficiency increases from hybridizing their onboard energy systems; the ability to optimize the use of diesel generators by storing excess energy and using it to provide propulsion during low load times. However, only recently has the battery technology been improved to the point of allowing large-scale systems to survive in a commercial marine environment. Not only do these new energy storage systems survive, they are designed for and excel in commercial marine environments. Hybrid tugboats, offshore supply vessels (OSV), ferries and a variety of other purpose built vessels all derive huge efficiencies from the use of onboard energy storage.

These hybrids range from new builds to retrofits of existing vessels. Payback on investment is a critical component in the decision to convert or build a hybrid workboat. However, an often overlooked benefit is the redundancy and increased safety offered to the operator of a hybrid vessel. A vessel employing a large battery or energy storage system (ESS) not only operates more efficiently, it also has an ability to draw upon a reserve of energy instantly. This pool of energy may be used as spinning reserve to keep the vessel from harm's way in the event of power loss, provide emergency navigation and hotel loads, auxiliary propulsion power, and even extra bollard pull to the main drives in the event of an emergency situation while towing. While these and other advantages, such as the environmental and cost savings benefits, are well-documented, real world lessons learned by an experienced integration and engineering team are exceptionally valuable. This experience helps vessel owners, operators and designers understand how to design and integrate a lithium energy storage system for safe, reliable use, now and for years to come.

Simply put, batteries will reduce a vessel's exposure to risk and make it fundamentally safer to operate, while providing economic gain for vessel owners.

Tugboat

Harbour tugs have a unique operational profile; they require huge amounts of thrust to provide the force required to tow ships many times their size, but spend very little total time at the upper range of that power output ability. Instead, the vessel spends much of its day transiting to and from jobs, holding position, or tied up at a dock. Using a five thousand horsepower engine to maintain position in a light tidal current is an extremely inefficient use of such a large engine. Not only does the engine burn as much or more fuel at idle than it does at optimum RPM, the poor combustion from low speed operation results in unburned fuel, wet stacking and results in increased maintenance and emissions.

The hybrid tugboat increases efficiency in all these areas. The vessel still uses its large diesel engines for the heavy bollard pulls, but it also gains the ability of running on a secondary system – the energy storage system. This means the vessel now has the ability to run most (if not all) low speed, low power operation on the batteries alone. The energy storage system eliminates low speed operation of the diesels, allowing them to be shut off until they are required for bollard pull duties. The resulting reductions in typical fuel consumption of 25%, maintenance of 25%, and emissions by up to 75% allows rapid payback of the system cost, often in a few short years, and a greatly reduced negative impact on air quality in and around the port.

OSV and Wind Farm Support Vessels

Considered some of the most brutal environmental conditions on the planet, offshore oil and gas production support vessels must maintain their intense operational duties regardless of the weather (Figure 1). A support vessel uses a dynamic positioning system to hold position relative to the rig despite wind, waves and currents. The vessel will typically ramp up onboard generators to provide the instant power that is needed to offset these forces, using it as needed and dumping the excess energy. This results in huge potential waste of the energy produced, wasted fuel and ultimately excess maintenance.

An OSV using dynamic positioning with integrated energy storage gains significant efficiency over traditional propulsion systems. Rather than constantly run the generators at maximum to service intermittent power demand, the generators provide the mean amount of power. Spikes in load are serviced instantly with lithium batteries – faster than could be achieved by ramping up a generator. Thus, the vessel's thrusters are able to respond to variations in load (wind and waves) as they happen on battery power alone. As the dynamic positioning loads are varied, the onboard generators replace the energy in the batteries during times of lower demand. Often this results in a rapid charge/discharge cycle scenario and requires energy storage systems built to very strict performance parameters. This peak shaving allows smaller generators to be run at far more efficient loading, as they are essentially battery chargers, resulting in dramatically reduced fuel consumption and maintenance requirements.

Ferry

Ferries generally run very predictable routes with predictable loads. Well-established patterns and data (weather, tidal and current information) from years if not decades of operation, and lengthy vessel life spans are typical. In many cases, ferries have been optimized over decades of operation and scheduled maintenance intervals. As a result, additional gains in efficiency come at significant cost and are often incremental. Without commissioning a completely new vessel, a ferry operator may now refit to hybrid propulsion during a scheduled maintenance break and complete the conversion in a matter of weeks, losing no operational time.

In large ferries, the energy storage system for the ship is set primarily for low speed operations, station-keeping positions and house power; avoiding use of diesel engines running at non-optimal load. This enables battery-only operation for loading and unloading, and entry and exit within the harbour. The vessel is now able to meet increasingly strict harbour emission requirements improving quality of life for local residents. Class societies recognize the robustness of the new energy storage systems and now approve their use as stand alone spinning reserve, eliminating the need for a redundant generator. The opportunity for load leveling provides a high level of fuel efficiency and reduces the number of generating sets, enabling the ferry to optimize its fuel consumption by adjusting its engine output. Thus, a typical large (1,000 passenger) ferry is expected to reduce carbon emissions by up to 25%, fuel consumption by 25%, and maintenance by 30%.

In ferries with shorter routes, the vessel may be hybridized to run on electricity while underway and while idling at the dock. In this case, the vessel uses the diesel engines to provide initial propulsion while leaving the dock and then reverts to electric only operation.

Increasingly, the vessels are being refit to full electric propulsion using batteries only. This signals significant trust in the reliability and longevity of today's battery technology and allows the operator to move from fuel, emissions and maintenance reductions to fuel and emissions elimination. Plan B Energy Storage (PBES) batteries are found in the world's largest fully electric vessel, *Tycho Brahe* in Denmark (Figure 2).

Spinning Reserve and Emergency Power

In previous years, the hybridization of commercial vessels was viewed as a novelty, one whose time has not yet come. Today, the reality is far different. The new breeds of hybrid and fully electric vessels have earned their place at the table and provide tangible economic and environmental benefits. These benefits are in and of themselves enough to persuade owners and operators to go hybrid, but it gets better. The hybrid vessels all come

Figure 1: An offshore supply vessel using dynamic position with integrated energy storage gains significant efficiency over traditional propulsion systems.

Figure 2: PBES batteries are found in the world's largest fully electric vessel, Tycho Brahe. The 12,000 ton, 266 m electric ferry has a 4.2 MWh battery that is capable of completing the 45 minute crossing between Denmark and Sweden three days on one charge.

with a huge source of emergency power that responds in milliseconds. The 12,000 ton, 266 m electric ferry *Tycho Brahe* has a 4.2 MWh battery that is capable of completing the 45 minute crossing between Denmark and Sweden three times on one charge. The extra capacity of the battery allows for short power outages on the charging infrastructure with reserve enough to provide uninterrupted service. In the event of an emergency situation, it also provides ample time for other vessels to deliver assistance and enough power to make headway to land.

In a hybrid ferry, the capacity of the battery allows instant spinning reserve any time or place. On an OSV or tugboat, the vessel has similar added capabilities. Depending on the size of the installed energy storage system, the vessel may be able to provide an additional amount of thrust or increased bollard pull to prevent an emergency situation from escalating, additional speed to provide rescue or assistance, or full electric, spark-free operation away from an explosion risk.

Risks of Energy Storage

Despite the obvious advantages to a vessel using energy storage to increase efficiency, redundancy and safety, the batteries themselves may pose risk. Due to an event known as thermal runaway, the batteries, if not managed within certain and specific parameters, may pose risk of combustion (Figure 3).

Thermal runaway occurs if the lithium-ion cells used in marine batteries are subjected to electrical or mechanical abuse, suffer from internal manufacturing defects, or operate over or under the correct voltage or temperature. Heat is generated within the lithium-ion cells and in cases where this heat exceeds a specific temperature (usually in excess of 120˚ centigrade), the internal structure of the cell begins to degrade. This degradation results in the internal separators melting and thus causes a reaction between the cathode material and electrolyte. This can result in the cell temperature increasing until the cell vents toxic and flammable gases. If ignition occurs, these gases can create an unpredictable fire, which can be very difficult to extinguish.

Therefore it is extremely important to a) reduce risk by designing and manufacturing the highest quality product available, b) reduce risk by managing the batteries in the safest possible way and c) provide a system that is capable of containing and suppressing thermal runaway should it occur.

While we have come to accept the risks of maintaining large quantities of flammable diesel on board a vessel, it is due to decades of experience that we now have very little incidence of diesel fire. This is due to trial and error, consistent regulation, and adoption of best practices for management of the systems.

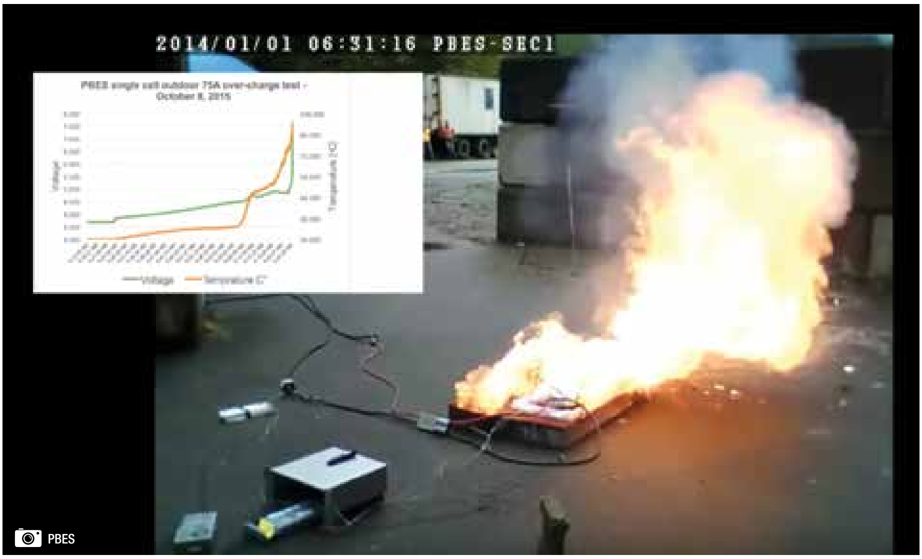

Figure 3: Energy storage systems increase efficiency, redundancy, and safety. The batteries must be designed and operated to reduce risk to avoid risk of combustion.

The same learning curve is occurring in the marine industry regarding large-scale lithium batteries. Currently, regulations do not reflect the realities of the size and types of systems that are now being installed and while it is unfortunate, it may take some sort of significant incident to force the industry regulators to adopt stricter regulation.

Advances in Technology

Battery technology that has been designed for marine use is now commonly used in Europe and is considered reliable and robust. That said, several design considerations must be implemented to ensure a safe, reliable and long-lasting hybrid vessel. For the limited scope of this essay, this technology section will examine the latest in technology for lithium ion battery systems, specifically lithium polymer batteries using a nickel manganese cobalt cathode material (NMC). NMC is the industry standard in heavy industrial energy storage. It contains greater energy density than other types of lithium ion batteries and is able to provide high current power to enable heavy machine starts, such as those of thrusters and main propulsion. In fact, modern energy storage systems are capable of providing multiple times their rated capacity in use, further increasing their usable power. The latest PBES technology offered to the marine industry is capable of providing a three times capacity, 24-hour average continuous discharge current. For example, a 10 Megawatt hour battery is capable of providing an average of 30 Megawatts of power continuously being charged and discharged ~~until all the energy is depleted~~, with no increase in temperature, degradation in performance, or negative effect on lifespan. Modern advances in ESS technology have moved away from the use of high voltage, high amperage single breakers on the DC bus to modular systems, each with its own internal contactor creating a lower voltage, safer and less costly system overall. The lower voltage system reduces the safety risks associated with a single high voltage breaker. When the system is deactivated, it is essentially inert with each sealed module capable of putting out only 100 V. With modern ESS achieving up to 1,500 V on the DC bus, and currents of up to 450 A, the inherent risks to personnel are greatly reduced with the lower voltage system.

Energy vs. Power Cell Differences

In some cases the vessel will never require the extremely high currents and discharge rates required by a high power application like an OSV. In this case, the PBES system will be designed with a low power cell. Outwardly the system looks identical and is the same in all ways except one: the cells have greater energy density (resulting in a 10 kWh module as opposed to the 6.5 kWh module in a high power system). Because the energy density is increased, the battery will have a smaller size, weight, price and installation/integration cost. The form factor in the energy system is identical; therefore, a cost savings is achieved in manufacturing that is passed on to the customer. If a vessel ever changes duty, the battery can be changed to a higher or lower energy density without changing the racks, cooling system or cabling, increasing flexibility over the life of the vessel.

Installation

Each installation (vessel type and size) presents a unique safety and performance challenge; however, most modern hybrid vessels rely on a common format – diesel electric generators – powering electric drives, augmented by high power lithium batteries. Installation is very straightforward and may be completed by any competent shipyard. Typically, the battery is assembled in a modular form factor of 10 kWh or less per module and configured in a series string to meet needed bus voltage. Parallel strings are added to make up the desired system capacity. The modules are loaded into an integral and engineered racking system affixed to the structure of the vessel.

Retrofit hybrids using modern energy storage systems are tuned to communicate with existing onboard power electronics. Software may be written to bridge any gaps that older onboard systems may present. New build hybrids have the advantage of implementing control equipment, generators and inverters from major OEM manufacturers. These major OEM companies work closely with reputable energy storage companies to develop complete systems that communicate freely and allow seamless and quick deployment, usually in line with traditional timeframes for typical haul-out maintenance.

Energy Storage System Location

Due to the limits of typical vessels, space is at a premium; centre of gravity and the displacement of the vessel directly affects the performance during work duties and while transiting. When a potential operator or owner considers the move to a hybrid propulsion system, they are often very concerned about additional weight and size of the energy storage system. Due to the high energy density and discharge abilities of the new generation of batteries, the systems required to meet typical missions are smaller than ever and are not generally considered to affect the balance or handling of the vessel. Often a net savings is achieved by removing generators that are now redundant. The fact that the systems are connected to the DC bus means that the system is light and small enough to be located in any location on the vessel; however, a location near to the engine room is preferred. Generally a completely separate battery room is created with a separate bulkhead and door; however, PBES systems are fully self-contained and in effect create their own room. The PBES system has been tested to the highest standards for thermal runaway propagation and is the only system on the market that is actually proven to prevent thermal runaway in the first place.

Racking for Energy Storage System

The advanced energy storage systems of PBES employ an integrated, highly engineered racking system. Strength and weight are very significant considerations and other components come into play as well. PBES uses integrated liquid cooling to achieve the lifespan, performance and extreme discharge rates demanded by workboat applications. The plumbing of the cooling system, such as pipes, connections and other components, are integrated into the rack design to avoid potential mechanical damage during installation or day-to-day operation. Plumbing considerations aside, the racking system must be strong, lightweight and easily configurable to allow it to adapt to a large variety of vessel designs and configurations. In order to reduce the weight of an installed system, the racking should be integral to the finished system, allowing it to operate without compromise. PBES energy storage systems also provide integrated module venting to prevent risk of explosion. In the unlikely event of a cooling system failure and overheating resulting in the modules entering thermal runaway, flammable gases emitted from the consumed battery cell material will be automatically self-vented to the exterior of the vessel. This effectively eliminates all potential for explosion.

Fire Suppression

Given the possible issues associated with fire and explosion, the class groups have spent a lot of time focusing on how to prevent and manage fires and thermal runaway. No matter the amount of care that the class rules can apply to prevention, it does not remove the battery manufacturers from the responsibility of incorporating sophisticated prevention systems into the design of the batteries. With lithium energy storage systems now regularly being discussed that exceed several MWh of capacity, the risk of thermal runaway or fire cannot be taken lightly. Today's hybrid designs must take this into account and do everything possible to ensure that a fire cannot start in the first place. This has created a shift in thinking that is driving designs to incorporate liquid cooling systems. These liquid cooling systems manage battery safety inside the core of the module through temperature control and management at the cell level. Fire suppression is critically important but must be viewed as a secondary system to manage the issue in extreme circumstances, after all else fails.

Fire suppression systems therefore are recommended to control external fires adjacent to the energy storage system to prevent them from causing a thermal event in the battery room. If desired, fire suppression in the battery room may also be employed to further give peace of mind as a backup system. Mist type fire suppression provides adequate cooling to suppress virtually any fire (outside of a major catastrophe involving the ship itself) that may pose a hazard to the energy storage system. In order to meet class standards, the energy storage system itself must be rated for IP67 water resistance and therefore able to safely withstand activation and use of mist type fire suppression.

Management Systems, Communications and Controls

Modern battery systems provide an ability to not only integrate with existing systems on board the vessel, but also increase longevity of system life and enhanced safety of the system. These systems reside inside the battery modules and the system controller, which in turn communicates with the other vessel power electronics. The Battery Management System (BMS) is able to predict module lifespan using complex algorithms that incorporate historical data and projected future use. This allows vessel owners to alter their use profile of the energy storage system to a) increase lifespan, b) increase vessel fuel efficiency, or c) a combination of both. The BMS is also an extremely important part of the safety system of the ESS. It constantly monitors the internal core temperature of the modules and if they are going out of spec (too hot or too cold), they will warn the vessel captain to limit use. The BMS is also able to actively monitor the state of health of the system within the temperature warnings; if a specific component in any one part of the entire system is out of spec, the system will warn the captain and the team who is monitoring it. The monitoring team will then proactively engage with the vessel and determine what, if any, course of action need be taken. If the warnings continue without intervention from the team, or if the vessel crew ignores the warnings, the system will protect itself and the vessel by disengaging from the DC bus and isolating all the modules in the system via their internal contactors, effectively reducing system voltage from a maximum of 1,000 V to ~100 V (the voltage of a single module). As the controls are powered separately from the ESS, they are safer in that there is redundancy in the system. It will always have an external power source ensuring the cooling system is operating and the management system is communicating with the vessel and system administrator team at all times, regardless of the system status.

Charging Infrastructure

The modern ESS requires the ability to communicate with and control the charging

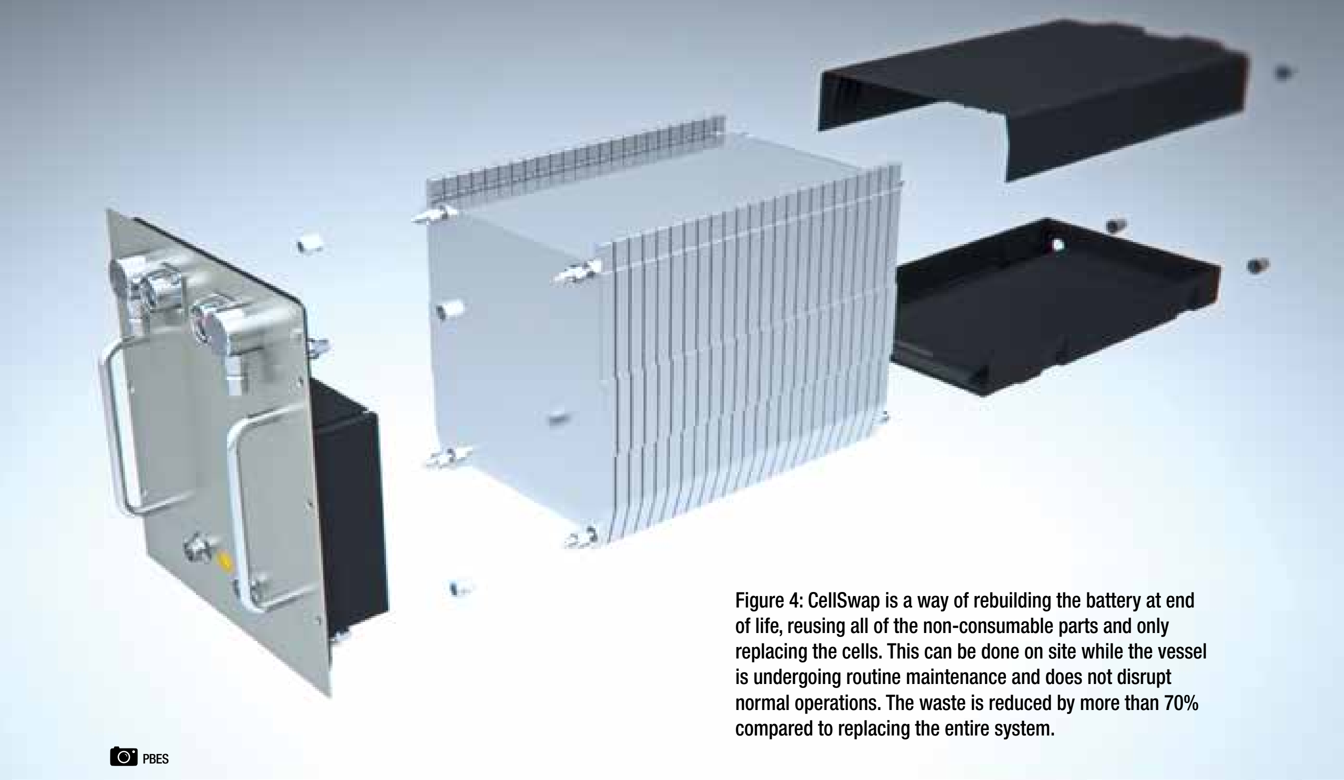

Figure 4: CellSwap is a way of rebuilding the battery at end of life, reusing all of the non-consumable parts and only replacing the cells. This can be done on site while the vessel is undergoing routine maintenance and does not disrupt normal operations. The waste is reduced by more than 70% compared to replacing the entire system.

infrastructure of the batteries. All lithium batteries are very sensitive to voltage and current. Voltage must be kept at a constant setting specified by the manufacturer. The BMS must be able to direct and control the charging system to increase current at specific set points to increase charging rates, ultimately to decrease charge times and optimize usefulness of the system. Conversely, the BMS must also be able to reduce current at other times to increase longevity of the system and meet the vessel owner's objectives for lifespan of the system. The BMS will take all types of information from the modules and surrounding systems, such as temperature, state of charge and system age, to determine the best charging profile at any given time.

Cooling Systems
While the industry standard for many years was passive cooling on all systems, it is increasingly apparent that the smaller systems demanded by industry are required to operate at, or beyond, the limits of passive cooling. Virtually all modern ESS employ some form of liquid cooling, either as an optional addition to the standard system or as an integral component. Advanced, state of the art ESS use individual cell level cooling systems; the coolant circulates within the very core of the battery module at a low pressure enabling far greater charge and discharge currents, increased lifespans, and reduced system sizes. In fact, the most modern of these systems has been validated to discharge approximately 16 times more power than the current industry standard product. Typically the ESS will connect to a standard chiller of specified size, using an inexpensive and small pump and be able to meet the very high demands with a far smaller system size and capacity with resulting cost savings benefits.

End of Life Disposal
PBES takes the issue of electronic waste very seriously. In many jurisdictions where our batteries are sold there are serious requirements for sustainability plans. As a result, we developed CellSwap, a way of reducing the amount of waste put into the e-waste recycling stream and reducing costs for customers (Figure 4). Simply put, CellSwap is a way of rebuilding the battery at end of life, reusing all of the non-consumable parts and only replacing the cells. Similar to an engine block in a generator, it is often more economical to

Figure 5: The new breed of hybrid commercial vessel is capable of huge economic and environment benefits in virtually every application in which it is deployed including cable laying operations, as shown here.

replace pistons, rings, and bearings rather than replacing the entire system. As a company founded and directed by a team with true marine heritage, this only makes sense to us. CellSwap customers only pay for the new cells and the manpower to replace them. All of this can be done on site while the vessel is undergoing routine maintenance and does not disrupt normal operation. Best of all, the amount of waste is reduced by more than 70% compared to replacing the entire system.

Conclusion

The new breed of hybrid commercial vessel is now a proven workhorse capable of huge economic and environmental benefits in virtually every application it is deployed (Figure 5). The added risk mitigation and increased safety has tangible value that should not be dismissed. No longer is the reduced cost of ownership from the decreased fuel consumption and maintenance outweighed by concerns about safety and reliability. As with any updated technology, lithium energy storage is new and system design is currently being refined, as are class rules regarding the use of the technology. As a co-founder of one of the early companies developing energy storage for hybrid marine systems, I have observed the industry develop, grow and mature. It is my assertion that the technology is gaining momentum by leaps and bounds. As it continues to evolve so will advances in the design and safety of the systems and increasingly strict regulations governing their use. The industry is now producing safe, reliable systems that provide meaningful financial benefits for the owners, safe operation for the crew and, ultimately, huge environmental benefits for the planet.

As one of the founders of the first marine energy storage companies, Grant Brown has helped define the industry since 2009. After nearly a decade working with the leaders in OEM commercial marine power systems and involvement in some of the most significant vessels in the industry, he has extensive knowledge of the business, drivers, and the technology that is enabling the shift to green propulsion. A lifelong fly fisherman, boater and outdoorsman, Mr. Brown is driven by a need to "leave it better than he found it." This drive combined with an innate ability to understand power solutions of all types gives him the ability to explain the benefits of energy storage to the world, and inspire others to become a part of the change. He is Vice President of Marketing with Plan B Energy Storage (PBES), a leader in providing lithium batteries designed for marine applications.