Comparative Payback of Lithium-Ion Batteries for Pacific NW Ferries

Will Ayers, P.E., Chief Electrical Engineer
Elliott Bay Design Group

ABSTRACT--This paper will demonstrate the economic viability of battery power on a passenger and vehicle ferry in the Pacific Northwest. Due to impressive gains in cycle life, charging rates, and the ability to handle repetitive and significant charge and discharge cycles, lithium-ion technology has significantly lowered its life cycle costs while increasing its possible applications. In addition, the Pacific Northwest has the unique advantage of abundant and relatively inexpensive electricity. The combination allows for the investment in batteries to have payback in as little as three years. After the first life cycle of batteries, subsequent investments in onboard energy storage can actually provide financial dividends for the life of the system. This paper reveals the basic financial basis that should encourage local companies and governments to pursue rapid electrification of the region's passenger vessels, as well as many other vessels with short and repetitive routes.

INTRODUCTION

Lithium-ion battery technology has already found many niches in the marine world. The high energy density allows lithium-ion batteries to occupy a relatively small space on a vessel, where space is a premium, while outputting power and energy levels that far exceed those of other technologies. Large energy storage on vessels can both enhance safety and decrease environmental impacts.

Traditionally, small battery banks are used to supply emergency power for lighting and essential electronics, but vessel safety can be greatly improved with the large spinning reserve that larger energy storage inherently provides during vessel maneuvering. Applications in support of dynamic positioning are becoming widespread. Passenger vessel safety can be similarly improved by the ability of stored energy to both supply and receive short bursts of energy in support of equipment used to increase the stability of a ship in rough seas.

Battery energy storage can decrease environmental impacts by either optimizing diesel emissions through peak shaving or eliminating them during key periods such as operating in an environmental control area, or an environment deemed environmentally sensitive. Carbon emission taxes, and credits for environmentally conscious operations, will likely continue to increase their presence in the regulatory and environmental landscape. Stored energy from renewable green resources will allow vessels to further reduce their impact on global warming.

The energy market in the Pacific Northwest yields a strong advantage for the use of shore power on vessels. Electricity in the Pacific Northwest is primarily supplied by hydro power, but is supplemented by wind and nuclear. These power sources provide the region with electricity with a very low carbon footprint and very low price. Rates as low as $0.06/kWh can be easily obtained. [1] [2]

This paper demonstrates that the cost of lithium-ion batteries and electricity in the Pacific Northwest can now compete with the cost of diesel power onboard large vehicle and passenger ferries. Much more importantly, this paper will demonstrate that the payback of the initial cost of the batteries and the required shore-side infrastructure can be achieved rapidly. Despite the expense of subsequent replacements of the battery banks, the lower energy cost provided by the use of shore power can yield large financial dividends for the remainder of the service life of the vessel.

BACKGROUND

Energy Cost Comparison

A typical diesel-electric power plant onboard a vessel will generate electricity out on the water at a cost of $0.18/kWh. This is based only on the price of $2.50/gallon of diesel scaled by system efficiencies. [3] Pricing has at times exceeded this over the last 10 years, but the average is used to keep this analysis conservative in nature. In addition, diesel manufacturer and operator data was analyzed that indicates that an additional 10.2% will be incurred for operating expenses other than fuel. These include lube oil, urea, power assemblies, sensors, injectors, SCR modules, and related including associated labor costs. As a result, a total operating expense of $0.20/kWh will be used.

Batteries have a finite life, so their price can be normalized to cost per kWh per cycle based on the number of discharge cycles they can survive. The effective life cycle cost of a battery can be found using the following equation:

$$Effective\ Life\ Cycle\ Cost = \frac{Battery\ cost\ per\ kWh\ \ of\ storage}{Cycle\ life}$$

For example, if a lithium-ion battery costs $1,000/kWh, is used fully, and it supplies 10,000 cycles, it costs 10 cents/kWh per cycle to store energy. The cost of diesel generated electricity at 20 cents/kWh minus the cost of shore-side electricity at 6 cents/kWh represents a potential savings of 14 cents/kWh. A lithium-ion battery at the cost of 10 cents/kWh would more than cover the spread and indicate the ease at which payback would be realized.

Cycle Life and Depth of Discharge

The biggest concern with the use of batteries is the replacement cost when they exceed their cycle life. The cycle life of a battery is defined by the number of times the battery can be discharged until it can only store 80% of its original energy capacity. The definition of cycle life is a legacy leftover from lead acid batteries. Lead acid batteries at this 80% point typically experience a sudden and rapid degradation where they will not be able to supply any more cycle life. Lithium-ion batteries, however, can continue to supply many cycles beyond this point without such an accelerating rate of degradation. Thus the cycle life is an understatement of the actual cycles that will be possible. Figure 1 shows an example performance curve for a 3,500 cycle battery.

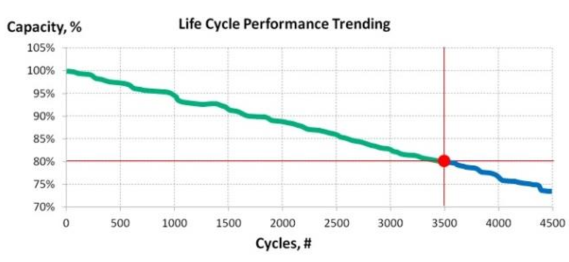

Figure 1: Example lithium-ion battery performance degradation as a function of cycles

The cycle life that a battery can achieve is determined both by its construction and its usage. The cycle life is related to the depth of discharge (DOD), or the percent of the battery's energy capacity that is depleted during each discharge cycle. Halving the use of a battery from 100% to 50% DOD can result in a cycle life improvement of almost three times. This is hard to quantify for any given battery system or lithium-ion chemistry. In fact, this information may be considered proprietary for various lithium-ion battery manufacturers. So for this analysis, it was assumed that lithium-ion batteries of different chemistries and constructions achieve approximately the same measure of cycle life improvement from reductions in DOD. It is believed that this assumption will not noticeably affect the conclusions in this paper.

For the sake of this paper, cycle life improvements based on DOD reduction will utilize Figure C.1 found in Annex C of IEEE Standard 1679. [4] This curve, Figure 2, displays the cycle life as a function of DOD for a generic 2,500 cycle battery. The 2,500 cycles would be determined by repetitive charging and discharging to either 80% or 100% DOD. Testing at lower levels of DOD is difficult because the dramatic increases in cycle life means that the test would have to be conducted for a much longer period of time. Given the advances in lithium-ion battery technology in the last six years, the example 2,500 cycles would be considered low by many standards today. At 50% DOD, Figure 2 indicates that the 2,500 cycle battery would be able to survive 6,900 cycles (the curve is logarithmic on the y-axis).

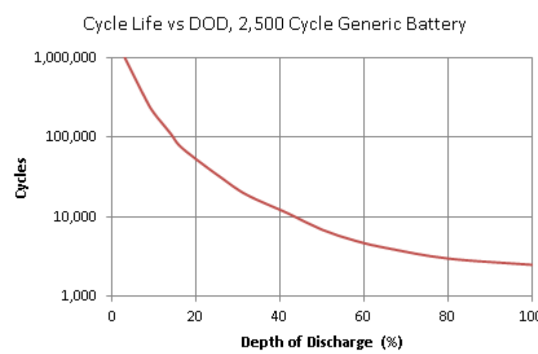

Figure 2: IEEE 1679 Curve with a Generic 2,500 Cycle Battery

This generic 2,500 cycle battery curve was used as a template to define the curve of a 20,000 advanced lithium titanium oxide (LTO) battery, Figure 3. At 50% DOD it is estimated that the 20,000 cycle battery will achieve 55,200 cycles.

The capacity fade as mentioned will lead to an 80% reduction of capacity at the cycle life point. This could impact the ability of the onboard battery bank to supply the necessary energy towards end of life.

But, all three of the lithium-ion chemistries studied have payback points at or below 80% DOD and would be able to supply the same energy at end of life as at the start. The cycle life does have to be adjusted though. During testing, the effective capacity of each charge/discharge cycle decreases throughout the test. Here, we are maintaining the same capacity discharge to make a one-way crossing. So, an onboard battery discharged to 80% DOD after installation will lead to it effectively being discharged at 100% DOD at end of life. For these calculations, each cycle life point at a beginning DOD point is averaged with the cycle life that would be experienced at the effective DOD at the end of life. While perhaps not a truly straight line process, this is believe to accurately account for this effect.

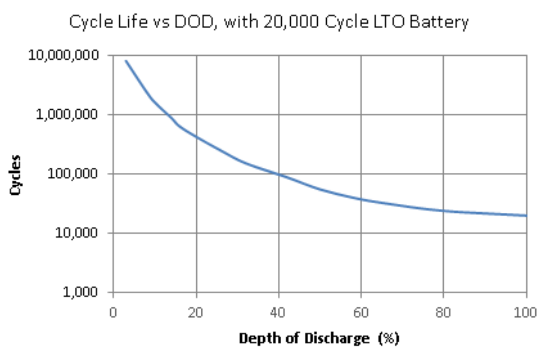

Figure 3: IEEE 1679 Curve with an Advanced 20,000 Cycle LTO Battery

Effective Cost vs Effective Life Cycle Cost

Although reducing DOD increases the life of the battery, there is one distinct disadvantage. If the DOD is decreased by half, then the available energy is also cut in half. To maintain the same available energy capacity, the number of batteries must be doubled. Therefore, as the DOD decreases, the capital cost of the batteries increases. For example, using a DOD of 50% at a battery price of $1,000/kWh leads to only half the battery capacity being used. Storing one kWh on the vessel then yields an Effective Cost of $2,000/kWh.

The financial benefit of reduced DOD is demonstrated by factoring in the cycle life improvement. Let's use the example of a single 1kWh battery module that will offer 2,500 cycles and costs $1,000/kWh. Over the life of the battery, every single charge/discharge cycle would cost approximately $1,000/kWh ÷ 2,500 cycles. This leads to an effective life cycle cost of $0.40/kWh-cycle. The reduction to 50% DOD, while doubling the Effective Cost, would also increase the cycle life to 6,900 cycles. At 50% DOD, the $2,000/kWh divided by 6,900 cycles leads to a reduced Effective Life Cycle Cost of $0.29/kWh-cycle. As the effective cost increases with reduced DOD, the effective life cycle cost will be expected to drop as the cycle life continues to increase at a more rapid rate than effective cost.

Figure 4 shows the relationship of increasing cycle life and decreasing effective life-cycle cost of the generic 2,500 cycle battery as a function of the DOD. As expected, despite a brief uptick, the curve takes the effective life cycle cost from $0.40/kWh-cycle all the way down to roughly $0.03/kWh-cycle.

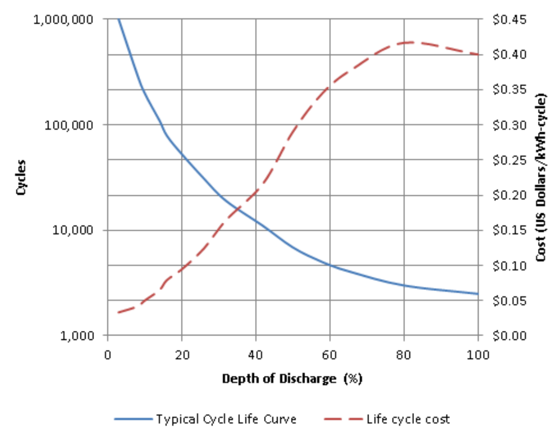

Figure 4: Typical Cycle Life Curve and Effective Life Cycle Cost

Battery Chemistries

This investigation evaluated three different representative chemistries: lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium titanium oxide (LTO). LFP is composed of the least expensive elements found in a lithium-ion battery. It will be expected to be the lowest cost option of the three. Unfortunately, the low price of LFP is generally coupled with a lower cycle life compared with other chemistries. LFP has the least volatile chemistry and is often considered the safest chemistry available, but all of the chemistries can be made safe with proper water or air cooling, battery management, containment, and fire suppression systems. Safety is further advanced with battery testing standards such as IEC 62619, marine certification testing, and regulatory testing such as the Norwegian Maritime Authority propagation test RSV-12. The LFP is anticipated to cost $700/kWh and yield a cycle life of 3,000 at 100% DOD.

Lithium nickel manganese cobalt oxide (NMC) has higher energy density and cycle life than LFP. NMC has the highest energy density of the three chemistries considered making it a popular choice for vehicle manufacturers who need the proper mix of energy density and safety. NMC chemistry is expected to cost $900/kWh and supply 8,000 cycles at 100% DOD.

Lithium titanium oxide (LTO) is the least energy dense of the three chemistries, yet the weight of battery rooms and batteries is a fairly small percentage of vessel weight, in contrast to a hybrid or all-electric vehicle. LTO has traditionally been the most expensive of the three chemistries, but also has outstripped the other chemistries regarding cycle life. For this analysis, the LTO is expected to cost $1,500/kWh and offer 20,000 cycles at 100% DOD. While not affecting the results in any major way, LTO can also double the charge rates of other chemistries. This could lower a charging time at the dock from 20 minutes to 10 minutes. Nevertheless, the operational advantage of lower charging rates comes at the expense of a more costly shore power charging system.

The relatively low energy density of batteries is not expected to be a significant factor with the large car ferries being studied. For one, the battery weight represents a very small percentage of vessel weight. But, the batteries would require much less fuel onboard for the rarely used spinning reserve of diesel engines. Therefore, any financial impact from the addition of a fairly large battery pack or difference in energy densities of the examined chemistries has not been included in this study.

THE APPLICATION

This analysis compares the energy cost of a battery powered ferry to that of a conventional diesel-electric powered ferry. The example new vessel used in this analysis is similar to one of the larger vessels in the Washington State Ferries (WSF) fleet. The subject vessel uses 2,000kWh to make a single one-way crossing, after which time the battery bank must be fully recharged with the inexpensive shore power available from the Pacific Northwest power grid. The batteries would be sized for a single crossing at 2,000kWh.

Battery Support Systems

The battery bank is assumed to be composed of four 500kWh battery racks in four dedicated battery rooms. Each room will have its own air or water cooling system that will cost $50,000 and its own dedicated fire suppression system, such as FM200, that will cost another $50,000. Thus, the total additional price of the battery rooms for the vessel is $400,000. As the DOD is reduced, the increased battery capacity will require more space and larger support systems. To accommodate this relationship, the cost of the battery rooms is scaled inversely to DOD.

Shore Charging Systems

The costs of the shore power charging infrastructure do not increase with decreasing DOD. Once the ferry arrives at the dock and begins charging, the rate, and thus price tag, of the charging system will be determined by the time frame and kilowatt (kW) throughput needed to charge a battery system back up to 2,000kWh. If operations desire this in 20 minutes, well within the 3C charge rate capabilities of most lithium-ion technologies, then a 6,000kW charging system will be needed. The costs for this shore power charging system are fairly difficult to quantify. As will be described later, this is because these innovative systems are currently under development. For the purposes of this evaluation, the infrastructure cost for both sides of a single ferry route was assumed to be $1,000,000. The sensitivity of the analysis to this infrastructure cost is discussed in the results. Given the example of central Puget Sound ferry routes with WSF, both sides of the route can be expected to be on a fairly significant utility grid capable of supplying the high power demand. It is also expected that about 18 full charge-discharge cycles will be utilized during the service day, a cycle count that would be typical for the WSF routes of focus. To determine the effective payback period, the price of the shore power system is normalized to the cycle life of the batteries, such that at the end of the life of the first set of batteries the shore power system has also been paid off. The $1,000,000 price of shore power charging normalizes to $500/kWh.

Excluded Costs

The battery room structural costs of this new vessel will be offset by savings in other structural costs such as engine room spaces. The use of batteries would allow the vessel to operate with only the minimum number of diesel engines necessary to maintain propulsion, not levels to maximize it or account for the unlikely loss of one diesel engine. But, the vessel would have sufficient back-up electrical generation from the diesel engines to finish a one-way trip and in fact keep the vessel in service. Since the base diesel-electric without energy storage would require them, the diesel engines and their support systems are not included as an extra cost.

Figure 5 shows the relationship between DOD and effective cost using LTO chemistry. Decreasing the DOD increases the cost of the batteries, vessel cooling and fire suppression costs. Again, these costs are relative to each 1kWh of energy storage used onboard the vessel. These increasing costs put pressure on solutions that try to lower DOD too far to accomplish payback.

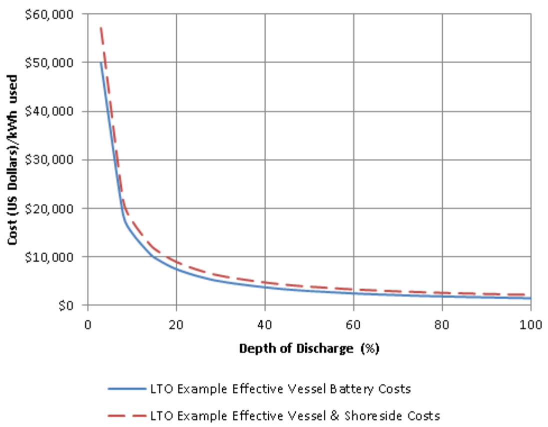

Figure 5: Effective Vessel Battery Cost plus Effective Vessel and Shore-side Costs

PAYBACK CALCULATIONS

The payback calculation determines three main quantities. First, a given DOD at the number of cycles per day will lead to a certain expected life in years for the onboard battery bank. In this analysis, initial payback must cover all initial costs during the life of the first set of batteries. As well, battery life must exceed the payback period at a given DOD. Second, the expected gross savings per year (in dollars per kWh per year) is computed, simply the difference in price between the cost of producing electricity from diesel (calculated to be $0.20/kWh), and that of shore power, (assumed to be $0.06/kWh), multiplied by 18 cycles per day times 365 days/year. This yields a gross savings of $920/kWh-year, or $1.8 million/year for the subject vessel ignoring installation costs. Lastly, the payback period is determined, including a discount rate of 5% to account for the diminishing present value of these savings over time.

RESULTS

Figures 6 through 8 show the payback period and expected battery life for each of the three chemistries. The DOD at the point where the curves cross is the maximum at which battery power will pay itself off over the period of one set of batteries.

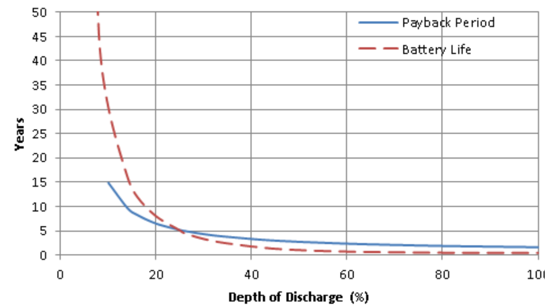

Figure 6: LFP Chemistry Payback

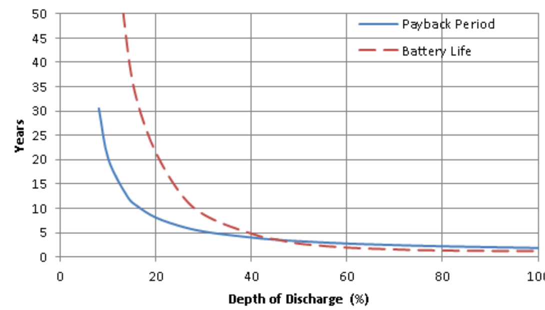

Figure 7: NMC Chemistry Payback

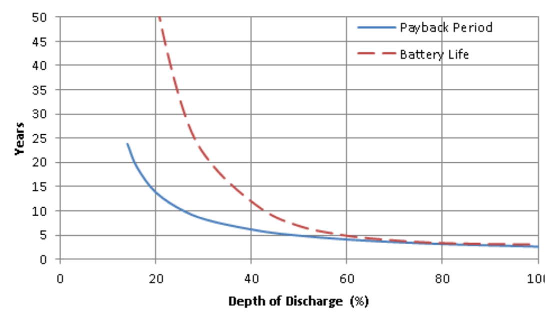

Figure 8: LTO Chemistry Payback

As can be seen in Figure 6, the LFP chemistry does achieve payback. But, it has to drop the DOD down to 25% to do so. By doing so, these base 3,000 cycle life batteries will be able to achieve 33,400 cycles and about 12 cents/kWh-cycle. Payback at this DOD would take over five years, and require the largest battery bank. At the 25% DOD, the LFP battery bank would have to be approximately 8,000kWh in size to offer the 2,000kWh of actual energy storage per one-way trip.

Figure 7 shows that the NMC chemistry performs at a higher point. The payback point can be achieved at approximately 45% DOD and after only three and a half years. By doing so, these base 8,000 cycle life batteries will be able to achieve 24,000 cycles and about 12 cents/kWh-cycle. At this DOD, the batteries would have to be approximately 4,400kWh in size. Given NMC's energy density advantage, such a bank would be smaller and lighter than an LFP or LTO bank of the same size.

Figure 8 shows that the LTO chemistry achieves payback after just over three years at the highest DOD of the three, roughly 80%. So, the base 20,000 cycle life batteries will achieve 22,000 cycles and about 12 cents/kWh-cycle. At this DOD, the battery bank would have to be only 2,500kWh in size.

After the first cycle life of the batteries, all three chemistries would continue to yield large economic dividends with successive battery replacements. This is because the initial payback has paid for the shore power charging, battery cooling and fire suppression costs that can continue to be used for the life of the vessel. After the initial payback, an LTO system operated at 80% DOD with subsequent battery replacement periods of three years would save $590,000/year, or $17.7 million over 30 years.

Sensitivity Analysis

Two large assumptions were made in this analysis. The shore power charging costs are perhaps the most difficult to define, so Table 1 shows how the minimum payback period of each battery chemistry varies with the cost of the shore-side infrastructure. As can be expected, the minimum payback period increases with the shore-side infrastructure cost, yet not prohibitively so. The cost of fuel can be predicted based on decades of historical fuel prices, but, because history doesn't define the future, the sensitivity of the minimum payback period to fuel prices is shown in Table 2. As the price of fuel increases, the minimum payback period decreases.

Table 1: Payback Period Sensitivity to Shore Power Charging System Cost

Shore-side Charging System Cost	Minimum Payback Period (years)		
	LFP	NMC	LTO
$500,000	4.7	3.0	2.8
$1,000,000	5.2	3.5	3.2
$2,000,000	6.6	4.6	4.8
$4,000,000	9.9	6.9	7.6

Table 2: Payback Period Sensitivity to Fuel Cost

Fuel Price $/gal, $/kWh	Minimum Payback Period (years)		
	LFP	NMC	LTO
$2.00	15.3	6.9	7.5
$2.50	5.2	3.5	3.2
$3.00	3.3	2.3	2.4
$3.50	2.2	1.5	2.0

THE TRUE CHALLENGE

Battery-based energy storage has proven itself to be an economically viable solution, but the steeper hurdle is with the shore power charging infrastructure. As previously discussed, assuming a 20 minute charge time to meet schedule, the shore power charging system would have to be able to supply 6,000kW. This would require roughly 833A at 4,160V 3-phase or 317A at 11,000V 3-phase, a very significant level of power. Such a shore connection could be both dangerous and unwieldy. Direct interaction by vessel crew would not be possible, so to make a quick, safe connection at each docking, the system would have to be automated and efficient.

As of a few years ago, there was no technology that would have allowed for such a quick, high-power shore connection to be made, but advances have already been made. The car ferry AMPERE in Norway is equipped with at least two different forms of shore power charging developed by Siemens, Cavotec, and Corvus Energy. The charging system used on AMPERE did not require direct involvement of the crew and allowed connections to be made very quickly. While it was a significant advancement in the current technology, this vessel's charging system could not supply the charge rates required for the application analyzed in this paper.

But, more significant advances are on the horizon. ABB and Plan B Energy Storage (PBES) will supply the battery and shore systems for two Scandlines Helsingborg-Helsingör ferries operating between Denmark and Sweden. Each ferry will have 4.16 MWh batteries and will be in operation by late 2017. ABB is developing a shore power charging robot that will automatically make up the medium voltage shore power connections. [5] [6] And, the 10kV shore connection will be able to charge 1200kWh in up to 5.5 minutes at a 10MW rate. [7]

As another possible solution to the challenges of high-power charging, Wartsila has announced that they are partnering with Cavotec to develop a magnetic resonance coupling concept that wouldn't even require a mechanical connection to be made. Instead, once docked, high frequency AC power will inductively cross a short air gap between two transformer-like coils, one on shore and one onboard the vessel. This system will also allow high rate medium voltage charging without need for operator involvement. [8]

CONCLUSIONS

The lithium-ion battery chemistries have achieved performance levels that could not have been imagined a few years ago. The increases in cycle life can allow demanding applications such as the one used here to achieve payback, and do so rapidly. The level of safety; the knowledge of how to manage these systems and diagnose developing problems with modules; and the way in which battery management systems diagnose issues and alarm onboard crew have all greatly improved.

The current state of the art in lithium-ion battery technology can achieve a watershed event in the marine world. Battery storage can now compete financially with diesel-generated electricity by utilizing even lower cost shore power. The payback is direct and without any subsidies or social costs factored in. The lone remaining challenge, shore power charging, will soon fall by the wayside with technical advances powered by the growing international support for green shipping.

This paper demonstrates that there is impressive and rapid payback possible for the subject vessel. It is in the best interest of the ferry fleets and other short-haul vessels in the region of the Pacific Northwest to investigate the financial benefits of energy storage. While the operators may enjoy substantial financial benefits, the region will also benefit from the other advantages including lowered emissions and reduced greenhouse effects.

REFERENCES

[1] Puget Sound Energy, Summary of Total Current Prices - Electric, Bellevue, WA: Puget Sound Energy, 2016.

[2] Seattle City Light, Seattle City Light Residential Rates Spreadsheet, Seattle, WA: Seattle City Light, 2016.

[3] US Energy Information Agency, New York Harbor Ultra-Low Sulfur No 2 Diesel Spot Price, New York: US Energy Information Agency, 2006-2016.

[4] IEEE Power & Energy Society, Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications, New York, NY: The Institute of Electrical and Electronics Engineers, Inc, 2010.

[5] ABB Group, June 21, 2016 Press Release: ABB to Power World's Largest Emission Free Electric Ferries and Deliver First Automated Shoreside Charging Station, Zürich, Switzerland: ABB Group, 2016.

[6] Plan B Energy Storage (PBES), Press Release Oct 3, 2016: PBES Lithium Energy Storage Selected for New HH Ferries Contract, Trondheim, Norway: PBES, 2016.

[7] S. R. Petersen, "Vandkølede batterier sikrer lynladning af elfærger på Øresund (Water-Cooled Batteries Ensure Fast Charging of Electric Ferries Across Øresund)," 27 August 2016. [Online]. Available: https://ing.dk/artikel/vandkolede-batterier-sikrer-lynladning-elfaerger-pa-oresund-186321. [Accessed 10 December 2016].

[8] Wärtsilä Corporation, Press Release Jan 25, 2016: Wärtsilä and Cavotec to Develop World's First Marine Wireless Charging and Mooring Concept, Stord, Norway: Wärtsilä Corporation, 2016.

ABOUT THE AUTHOR

Will Ayers has been working in the marine field as an electrical engineer for almost twenty years. Will currently serves as Chief Electrical Engineer at Elliott Bay Design Group in Seattle, Washington. A graduate of the University of Washington with a BSEE, Will has excelled in vessel electrical system studies, electrical system software modeling, and all levels of system design on a marine vessel. For the last seven years, Will has had the opportunity to pursue hybrid and all electric propulsion opportunities in various applications, ranging from small passenger only vessels to large car ferries carrying as many as 2000 passengers and 144 vehicles.