Nova Scotia Boatbuilders Association

Review of All-Electric and Hybrid-Electric Propulsion Technology for Small Vessels

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EXECUTIVE SUMMARY

Electric boats in one form or another have been around for over 100 years. The advantages of all-electric or partial-electric boats are the reductions in pollution, noise, vibration, and potentially, cost. The Nova Scotia marine community has a growing interest in the business opportunities offered by all-electric and hybrid-electric propulsion systems. The Nova Scotia Boatbuilders Association has therefore undertaken this review, which provides a snapshot of the current state of all-electric and hybrid-electric propulsion technology for small vessels – and takes a look at what developments we can expect in the near future.

All-electric systems are comprised of an electric motor driven by a battery pack. Hybrid-electric systems include an internal combustion engine, generator, battery, and electric motor, typically allowing the diesel or gasoline engine to do the heavy work when needed, and charge the electric system and allow it to respond to lighter loads such as low-speed cruising or providing power for lights and electronics, and other “hotel” loads.

There are many technical challenges associated with the proper design and engineering of all-electric and hybrid-electric propulsion systems, both in terms of current technical limitations such as battery life, charge rate, size, and weight and the larger issue of integrating and controlling the added complexity of hybrid systems and obtaining components that are properly designed and certified for use in a marine environment.

However, if a hybrid system is properly engineered and matched to the duty cycle of a boat, then a benefit can result. Currently, large international companies and certification bodies are investing in the development of all-electric and hybrid-electric propulsion technologies, either in individual components or in systems for particular types of vessels. While the economic case for these systems is currently difficult to make in most situations, a breakthrough in, for example, battery technology will dramatically change the situation. While the marine market is not a primary driver of the activity in battery development, it would certainly be one of the secondary markets to benefit.

The ability to maintain and find replacement components for all-electric and hybrid-electric propulsion systems also affects their adoption. Owners and operators need access to components and qualified repair and service personnel in close proximity to their operating locations. Standardization will help, but in many ways the technology is still at a developmental level.

Several business opportunities exist for the Nova Scotia marine sector, and in fact several companies are already active or engaged in the technology. In particular, new build and retrofit services hold potential for both the early-adopter market and the working vessel market. In Nova Scotia, there are four vessel types that appear to be suited for hybrid-electric propulsion systems:

- In-shore fishing boats
- Short distance water taxis
- Short haul ferries
- Yachts

Other business opportunities include the development of system integration and controlling technologies, component manufacturing and supply, and the service and maintenance of all-electric and hybrid-electric propulsion systems.

The following conclusions are drawn from the result of the review:

- Currently, there is limited market acceptance of all-electric and hybrid-electric propulsion technology for small vessels, but there are a growing number of practical applications in use in the recreational and commercial boat industry. These early adopters will drive further development which, in turn will increase the number of viable applications.
- The viability of any configuration of hybrid-electric system on a small vessel is affected by three main considerations: economy, environment, and strategic. Depending on the application, economy may not be the deciding factor when choosing the most effective propulsion solution.
- To become more viable, hybrid propulsion technology needs better collaboration between designers of the main components: engines, motors, propellers. One example of this need is the technical challenge of matching the load performance of permanent magnet electric motors to propellers.
- Future developments in battery technology and integrated system controllers will significantly increase market acceptance and viability of hybrid systems in small vessels.
- Not only will the economic viability of hybrid systems be improved through future technology developments, but also through changes in the behaviour of small vessel operators. The latter will require education and demonstration of the savings hybrid can bring within specific operational profiles.
- For recreational boaters, lifestyle priorities will play a big part in the choice of using a hybrid system on board – even if it costs more than a traditional internal combustion engine system. The virtual elimination of noise, vibration and smell from using electric drive is worth the cost difference to some boaters.
- Two small vessel applications that are commonly seen in Nova Scotia and elsewhere in the world that show potential for viable hybrid systems are nearshore fishing boats and racing sailboats.
- As all-electric and hybrid-electric propulsion technology matures and becomes better accepted by the marine community, business opportunities will be created for Nova Scotia companies with expertise in research, design and engineering, manufacturing, installation, testing, and service and maintenance of components or complete systems.

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1.0 INTRODUCTION

This review addresses the current state of all-electric and hybrid-electric propulsion technology for small vessels – not ships. For purposes of this review, a small vessel is considered to be 24m (79ft) or less in length.

Electric boats are not new. The first vessel known to use lead acid batteries was the *Eureka* built in 1881 by Gustave Trouvé in France, but the vessel's development was hampered by energy storage constraints and the resulting limited range.

Water pollution, noise, vibration, environmental regulations and the idea of 'being green' are all motivators for implementing electric options in marine propulsion. The Nova Scotia marine community has a growing interest in the opportunities presented by marine all-electric and hybrid-electric propulsion systems as oil prices trend upward (despite the recent drop in price). While much work has been completed on electric options in ships this report is focused on the options for boats (less than 24m in length).

In the face of these different 'pushes' and 'pulls', it is important to understand the factors that currently keep all-electric and hybrid-electric systems from being widely adopted, and how changes in those factors could see broad acceptance of the technologies.

The economics are driven by a range of considerations such as fuel costs, environmental regulations, quality of life, noise, and access to environmentally sensitive locales. Those working in vessel design, construction and operation want to know where the technology currently stands and when to consider investing in all-electric or hybrid-electric options.

Diesel-electric propulsion systems and drives have been developed and brought into common use by the marine industry over the past 30 years. Thrusters, azimuthing propellers and podded systems have become commonplace, and while the scope of this report does not include direct diesel electric technology, the growth of that technology has brought acceptance to the idea of alternative power sources and put systems in place that present the opportunity to develop electric power sources.

In the marine world, the move toward all-electric and hybrid-electric propulsion technology has been slow compared to cars and trucks. One factor is the absence in the marine setting of an easily-accessible regenerative energy source such as braking or downhill energy capture that helps to make motor vehicle systems viable. Cars also have different duty cycles: high acceleration and low cruising loads compared to marine vessels with low acceleration and high cruising loads.

Electric technology for small vessels has also been hampered by the lack of appropriate battery technology. A lightweight, large-capacity battery with fast recharge capability is needed to give the development of electric small vessels a major push.

Sailboats offer an option for battery charging because the propeller can be left to spin free when under sail allowing the batteries to charge. This "free" energy source significantly impacts the attractiveness of the electric power option long term. In this case batteries become the cost driver.

There are existing markets for both hybrid and all-electric vessels. Aspin Kemp & Associates have developed a successful model in hybrid tugs by using electric power when transiting to work locations and switching to diesel at the site, which then provides a significant power source for battery charging.

Companies such as Covey Island Boatworks in Lunenburg, NS are finding that there is significant interest in the high-end private yacht market for "green" options and a resulting demand for all-electric and hybrid drives.

Many Nova Scotia communities are considering wind, solar and tidal power generation in their communities. The integration of these renewable power sources with electric propulsion systems provides a viable opportunity for communities to invest in new technology and prepare for the future. In this situation, electric vessels and vehicles can act as storage systems for renewable energy, accepting it when there is low consumer demand, such as overnight.

The following sections of this report describe the types of all-electric and hybrid-electric propulsion systems, and how key components, duty cycles and external factors have significant effects on the technical and economic viability of these systems. Examples of typical systems and their performance in typical duty cycles are provided along with a snapshot of the current state of the technology. Current research and development is also discussed to give an idea of how some of the obstacles to wide adoption may be eliminated. Finally, the report gives an opinion of the market potential for these systems and suggests actions that Nova Scotia's marine industry could take in an effort to benefit from these developments.

2.0 TYPES OF ALL-ELECTRIC AND HYBRID ELECTRIC PROPULSION

To begin the discussion of all-electric and hybrid propulsion systems, it is valuable to define what is meant by each of these terms. This section begins by defining an all-electric propulsion system and then moves to hybrid-electric propulsion systems, which have different possible configurations and more complex operational profiles.

2.1 All-Electric

The basic idea of a marine all-electric propulsion system is very simple: an electric motor is driven by a battery pack. That battery pack can be charged by plugging it into the on-shore power grid while docked, by a renewable energy source located on-shore, or by a renewable energy source on-board such as solar panels or wind turbines (**Figure 1**).

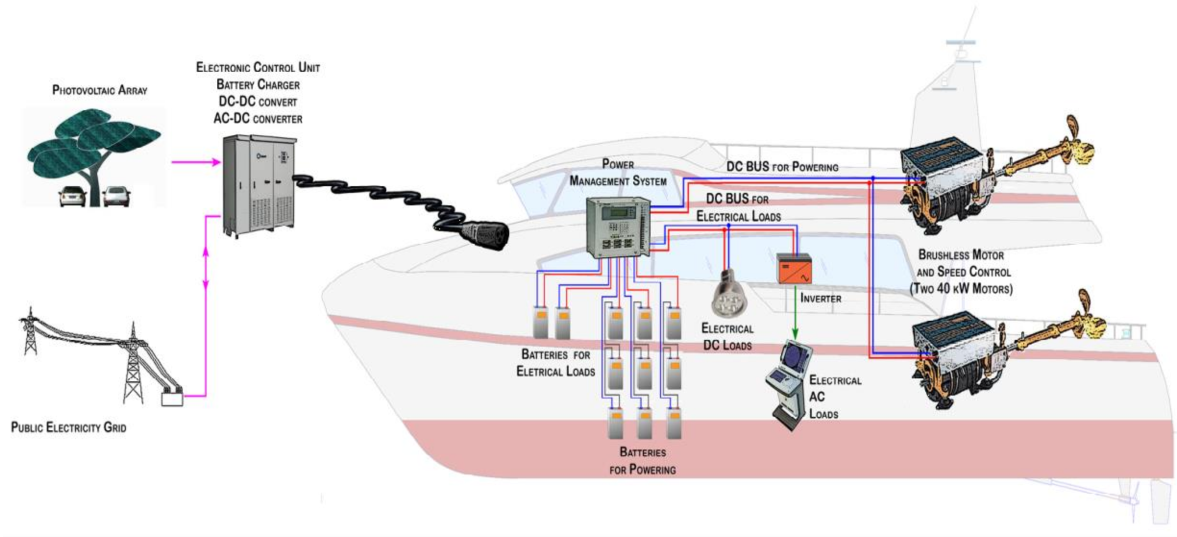

Figure 1 Schematic of Eco Friendly Electric Propulsion Boat (Spagnolo et *al*, 2011)

Whether an all-electric boat is technically feasible or not depends on the capability of a battery to meet the energy and power demands placed on it by the vessel's range and duty cycle, and the ability of the vessel to accommodate the size and weight of the batteries.

Short-range and low-speed vessels are ideal for the adoption of all-electric propulsion systems given the current state of the technology. Using renewable energy sources to charge the battery can make the idea of investing in an all-electric solution even more attractive.

In general, manufacturers only offer all-electric propulsion on a custom design or refit basis, with a small number doing low production runs, showing that there is market interest but it is very sensitive to concerns around cost and performance. A common motivation for installing these systems is their silence rather than their savings.

Batteries are a significant part of the cost consideration; the current capabilities of battery technologies are limited and all have high weight-to-energy ratios. But battery developers are quickly moving to provide low-cost marine options (see **Section 3.1**).

One viable market for all-electric propulsion systems is sailboat retrofits and new construction. Sailors can recharge batteries when under sail and only use the motor for in-shore manoeuvring or docking. As mentioned, battery regeneration can also be accomplished using solar panels, wind turbines and grid power at shore. The opportunity for a cost effective installation can be significantly leveraged by the power sources that are paired with the system.

Existing all-electric propulsion systems such as the canal "narrow boats" in the United Kingdom have proven the economic viability of these systems as well as emphasised their environmental viability (**Figure 2**). These boats are driven at a speed and on a schedule that optimises the amount of electric power available from the battery, and then charged overnight while they are shore side. These boats can be driven on the canals near communities without air emissions or noise impacting the local environment.

Figure 2 UK Narrow boat
www.castlenarrowboats.co.uk

Norway has all-electric ferries run from a grid connected cable (**Figure 3**), showing that large scale, specific applications of all-electric vessels are both economically and environmentally viable.

Figure 3 Norwegian all-electric cable ferry by Electrovaya
www.fleetsandfuels.com/wp-content/uploads/ferryMVFjon2-1111.jpg

2.2 Hybrid Electric

Unlike an all-electric system, a marine hybrid systems includes an internal combustion engine (ICE), a generator, an electric storage unit, and an electric motor. As mentioned before, diesel electric systems are different from hybrids because they produce power using a diesel generator that is directly connected to an electric motor. In a hybrid system there is an electric storage element in the system.

The following sections present different configurations of hybrid systems as well as their associated energy use and efficiency profiles.

2.2.1 Configurations of Hybrid-Electric Systems

The performance of a given hybrid propulsion system is heavily affected by its specific configuration. This section describes the three general arrangements of hybrid options: series, parallel, and a combination of both serial and parallel configurations.

> A series marine hybrid only runs an Internal Combustion Engine if it can be run at peak efficiency; in between, it runs off the batteries.
>
> A parallel marine hybrid adds and subtracts electric machine loads to hold the ICE at peak efficiency when it is running; in between, it runs off the batteries.
>
> *Calder, 2014*

Series Hybrid

In a series hybrid setup, the electric motor is the only means of providing power to the propeller (**Figure 4**). The motor receives electric power from either the battery pack or a generator run by an ICE. This lets a vessel continue to operate even after the batteries are discharged.

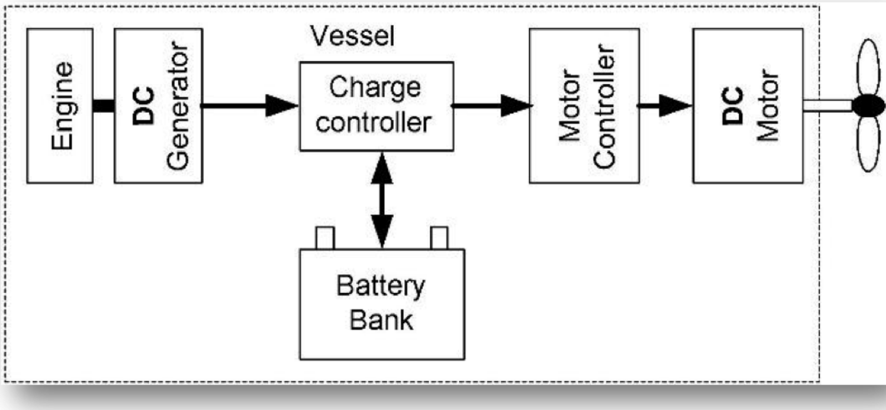

Figure 4 Series or Serial hybrid system from Hybrid Marine UK

Parallel Hybrid

In a parallel hybrid system (**Figure 5**), both the ICE and the electric motor are able to provide power to the propeller. The motor/generator can either drive the propeller with energy from the battery, or be used to charge the battery.

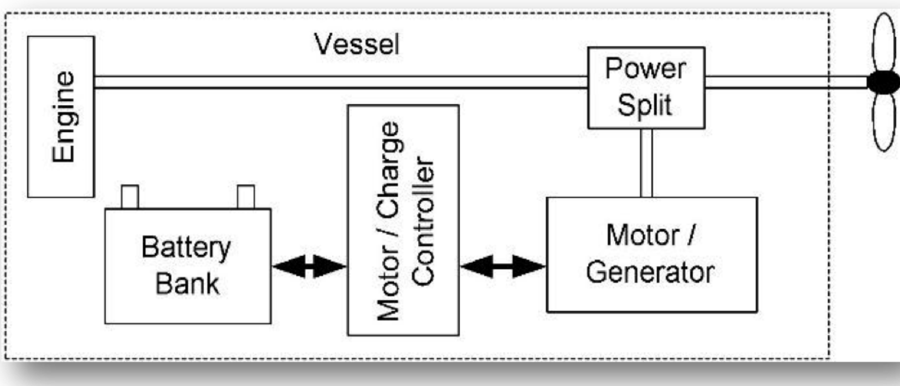

Figure 5 Parallel hybrid system from Hybrid Marine UK

Series/Parallel Hybrid

The third type of system is a combination of the series and parallel configurations. The Union of Concerned Scientists in the United States says that this combined system brings together the good and the bad of both the series and parallel systems:

"*By combining the two designs, the engine can both drive [the propeller] directly (as in the parallel drivetrain) and be effectively disconnected so that only the electric motor powers [the propeller] (as in the series drivetrain). The result is a system that operates more closely to optimum efficiency more often*".

Table 1 gives a brief summary of the features and application of the series and parallel configurations.

Table 1 - Features of Series and Parallel Systems

Series hybrids	Parallel hybrids
Poorly optimised but potentially easy to optimise, underpowered with control and reliability issues	Captures efficiency benefits without penalties in conversion losses other than with the battery
Large battery capacity required	Fewer batteries required than series
Suited to vessels with renewable alternative power sources e.g. catamarans with large surface area for solar panels	Can also exploit alternative power sources
Suited for: • Sailboats that sail • Short Haul ferries	Suited for: • Canal boats • Sport fishing boats when trolling • Trawler yachts • Motor sailing sailboats
Work well where electric power range is limited and house loads are a high proportion of total energy budget	Lower voltage required which minimizes battery management and minimizes safety issues. Create lots of energy for house loads
Electric motor has to be big enough to handle peak load	Electric motor can be smaller as power can be shared with ICE
No redundancy if one machine fails	Added redundancy is available as power to propeller can be drawn from ICE or battery bank
Potentially increased maintenance costs as machinery is not running at optimum load	Reduced maintenance costs likely as machinery is running at optimum load

Serial systems are suited to 'niche' markets' such as short haul ferries sailing catamarans, vessels with high “house” loads. Parallel systems can be more efficient than conventional ICE systems if they are optimized. They have the potential to fully exploit non-ICE energy and provide house power at close to peak efficiency.

2.2.2 Performance of Hybrid Systems

Typically, the ICE is shut down during low power requirements and the vessel is powered using the electric motor. The batteries for the electric motor are recharged from shore power, on-board renewables, or free-turning propellers when under sail.

The success of a hybrid system depends heavily on how efficiently power is transferred from mechanical to electrical and back to mechanical. As a general rule when the power needed by the vessel is greater than 400 hp the losses in the electrical system are about 5% per rotating device (generator, motor). When the power requirement is less than 400 hp the losses increase. The mechanical parts (shaft, bearings, etc.) together account for another 1% of total losses.

The key to understanding the potential for marine hybrid propulsion systems lies in the Specific Fuel Consumption (SFC) efficiency plot (**Figure 6**). The SFC is the amount of fuel it takes to produce 1 kilowatt-hour (kWh) of energy and is expressed in grams/kWh. Peak efficiency occurs at the lowest SFC, which occurs at or near peak torque. In Figure 6, the line of peak efficiency lies through the centre of the graph and when developing hybrid solutions the primary goals are to use the ICE during these times of peak efficiency and also to charge the batteries for the electric motor during peak efficiency. The electric motor is then used at times of lower efficiency. Under this situation, there is real opportunity for efficient fuel use offered by hybrid systems.

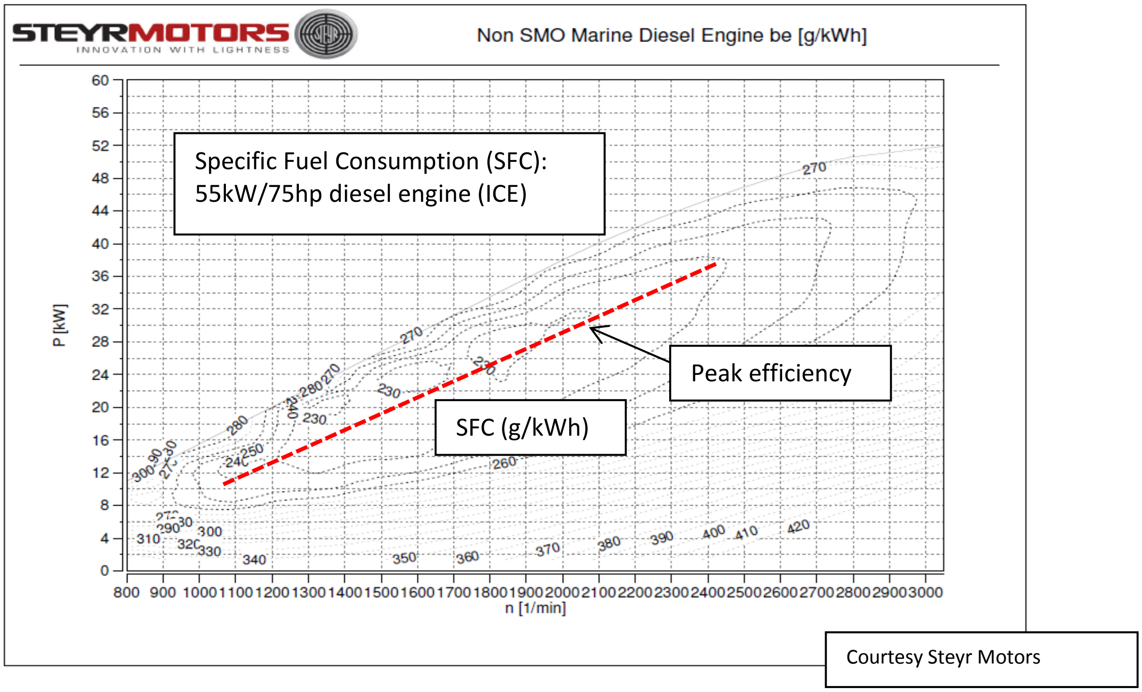

Figure 6 Sample SFC plot (Calder 2014)

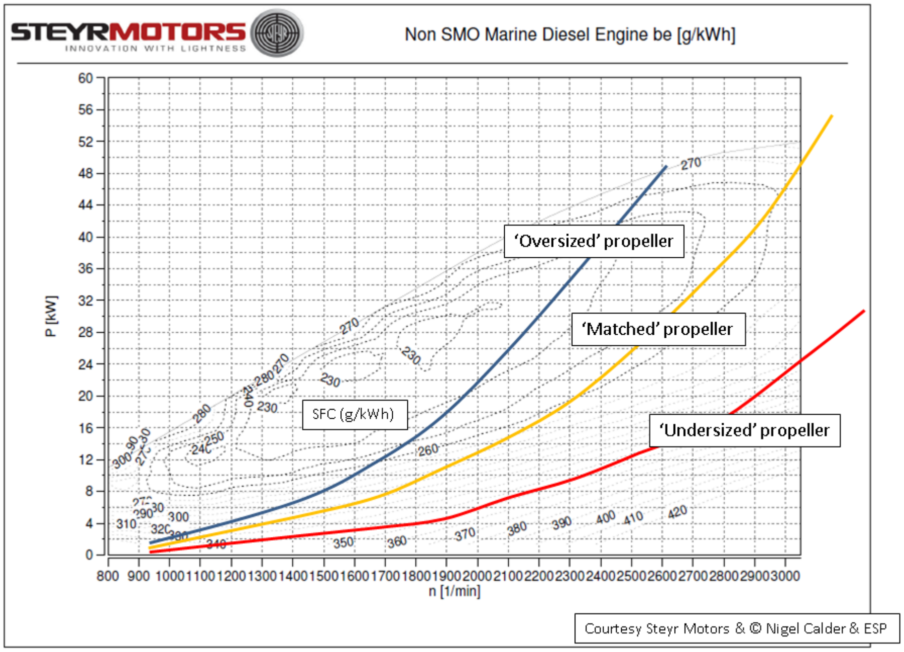

Figure 7 Sample Propeller curves over SFC plot (Calder, 2014)

Those familiar with marine propeller power curves will see in Figure 7, that the peak operating range for a marine propeller lies outside of the peak efficiency of the SFC plot. The best option is to choose a propeller that will cause the engine to work in the high efficiency zones. However this means choosing an oversized propeller or operating in a higher gear (engine cycling), which can cause damage to the engine.

The most efficient way for the ICE to recharge the batteries occurs when the engine is operating in the high efficiency region. In practice this usually only happens with vessels such as tugs under load and cruise ships with high hotel loads. Most marine vessels are in the low load and lower efficiency range of the SFC plot when cruising, which requires much less fuel.

This is the challenge affecting the efficiency of hybrid systems. While some engine manufacturers are developing marine engines with a different efficiency profiles to accommodate hybrid systems, the time line on this development is still uncertain.

When analysing the viability of a hybrid system, the cost of energy is not just based on the efficiency of the system. When marine vessels are operating at low cruising speeds, the cost of fuel is less than when they are operating at higher speeds. As conventional engines become more efficient the value of hybrid systems may be reduced due to the energy required to charge the batteries and the losses in conversion from mechanical energy (ICE) to storage and then to electrical energy.

2.3 Summary

Table 2 provides a summary of the main features of conventional ICE propulsion systems, hybrid-electric systems, and all-electric systems. Overall, if an electric system is properly engineered and matched to the duty cycle or usage of the boat then almost all boats will benefit from either a serial or parallel hybrid propulsion system or an all-electric system. Currently, costs are being lowered through the development of hybrid equipment and components in the automotive industry and ongoing research and development will help increase commercially viable hybrid and all-electric propulsion options for small vessels in the near future.

Other general considerations for all-electric and hybrid-electric propulsion systems include the type of energy used to charge batteries and the space occupied by the systems. As mentioned above, the potential for the integration of shore power and renewables is an important consideration and of particular interest to short range applications where a smaller amount of energy is sufficient.

Depending on the system chosen, the space occupied by an electric motor and batteries can be optimised or located in a way that improves payload space. For example, a hybrid system may take up more space than conventional ICE long shaft systems in a new build, but the vessel can be designed to accommodate the volume of the chosen system and configure the remaining space to make it more valuable.

Table 2 - Conventional versus Hybrid-Electric Propulsion Systems

	CONVENTIONAL (Gas or Diesel)	HYBRID ELECTRIC	ALL-ELECTRIC
Efficiency	Modern engines are increasingly efficient, many in the range of 90-95%. It is noted however that power is measured at the flywheel so there are additional losses not accounted for in the efficiency rating	AC motors – efficiencies generally in the range of 80%-89%. DC motors – efficiencies generally in the range of 55%-60%. It is noted that electric power is measured at the shaft and may be a more “true” rating of the efficiency	Electric marine motors have a much flatter torque curve than conventional motors, which means there is plenty of torque available at every engine speed. This allows systems to operate high efficiency propellers. Overall efficiency is15-25% higher than conventional engines.
Air Emissions	Improving and reduced if operations are focused in high efficiency range. Higher emissions during low efficiency operation	Dependant on operating range, moving the propeller curve into the higher efficiency range will violate emissions standards. Emission reductions of 45% possible.	There are no emissions or exhaust gases when in use. Emissions are dependent on the source fuel (grid, generator, renewables)
System Losses	Low losses in direct drive systems. Losses at reduction gear and shaft/bearings	System losses during mechanical to electrical and back to mechanical conversions. Losses at reduction gear and shaft/bearings, generator and electric motor	Electrical losses can be significant in electrical motors and cooling systems need to be well designed for the marine environment. System losses during converting from electrical power to mechanical propulsion, bearings losses from mechanical components.
Noise	Improving in modern engines	Significant reductions over conventional engines	Minimal noise
Fuel	Low fuel consumption when operating at low cruising speeds	Dependant on application. If larger engine is required to accommodate lower efficiencies and the operation is at high loads the fuel savings may not meet expectations. Some applications have seen fuels savings of 25%.	Grid power, renewable energy sources, on vessel solar charging, Generator can be options for off grid charging but that introduces much lower efficiencies dues to conversion losses
Operational Life	Rated life expectancy if used according to specifications. Quality of engine will deteriorate over time as expected.	Dependant on operation. For higher efficiency the engine will be operated at high torque levels and cylinder pressure. This can cause additional stress on bearings and valves. Life expectancy can be as rated if engine is built for marine hybrid use.	Rated life expectancy if used according to specifications. Quality of motor will deteriorate over time as expected.
Financial Costs	Standard costs dependent on duty and modelling power prediction. Research suggests significant uncertainty in this powering prediction	Large generators for optimum fuel efficiency are expensive and heavy. Systems designed for hybrid should be cost comparable in time but currently are unavailable	The motor is the bulk of the cost if the charging source is the grid or a renewable power source. If a large generator is required this would greatly increase expense
Maintenance and Repair	Technicians have long experience with internal combustion engines and many hobbyists are comfortable with basic repairs. Basic replacement parts are readily available. Newer engines require more expertise, computer analysis and specific parts.	Dependant on operation, pushing the engine to reach higher efficiency will cause more wear and require more maintenance. Specialised engines will require specialised technicians and may have parts that are not as widely available as for conventional ICE systems. This may impact the ability to repair in smaller locales.	Wear may be less than with a hybrid system trying to operate in the efficient zone. There is some experience with basic electric motors, but as they develop there may be some specialised expertise required. Non-standard components or specialised parts may be required. This may impact the ability to repair in smaller locales.

> If the hybrid system incorporates other sources of power such as shore power or renewables (solar and wind) or can capture power through regeneration, then the efficiency of the hybrid over conventional systems can be significantly increased.
>
> *Calder, 2014*

3.0 CURRENT STATE OF THE TECHNOLOGY

The first consideration when looking at hybrid or all-electric propulsion systems is the size of the vessel. In large vessels the electrical losses can be 5% per rotating device throughout the system but in smaller vessel systems this number increases.

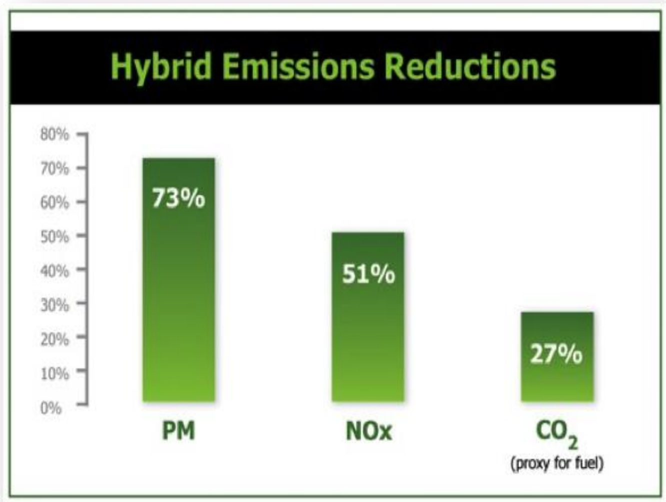

Figure 8 - CARB results for Aspin Kemp & Associates Tugs

There have been significant successes with large-scale systems such as the tugs from Aspin Kemp & Associates' Xero Point. Their tug hybrid system was studied by the California Air Resource Board (CARB) and while Aspin Kemp & Associates knew that their fuel reduction is more that 20% from conventional tugs, their air emissions reductions dropped by 73% for particulate matter and 51% for NOx (**Figure 8**). These are very important numbers when looking at the community or societal benefits of electric.

The second generation of tugs showed even greater reductions in emissions and the evidence is clear that for tugs the hybrid system can have real financial and environmental benefits.

DNV-GL recently presented the benefits of a hybrid support vessel to a conference in Athens and showed reductions of 15% in fuel consumption, 25% in NOx emissions and 30% in GHG emissions (**Figure 9**).

Figure 9 Viking Lady

The marine industry has a long history of borrowing technology after it has been developed and trialled in niche markets such as the military or high performance racing. Navies were early adopters of hybrid-electric propulsion due to the need for submarines to operate silently underwater, and economics played little if any role in the decision. While at the surface, the main diesel engines would propel the subs and re-charge the large bank of onboard batteries. Once submerged, the diesels no longer had an air supply so propulsion and all other loads were drawn from the batteries. This "hybrid" propulsion system was first used effectively on subs 100 years ago in WW1. The Oberon class submarine of the British Royal Navy was all-electric (**Figure 10**).


Figure 10 Oberon Class Submarine Royal Navy c. 1970

Another niche market is the America's Cup race series, which has provided the marine industry invaluable information on cutting edge composite materials. Cruise ships championed diesel electric systems because they wanted podded propulsors that would allow them to place diesel generators in locations that reduced vibration in dining rooms. The podded propulsors also allowed cruise ships to make tighter turns, giving them access to ports where manoeuvring is more difficult. As hybrid and all-electric propulsion systems become more common on large vessels, the technology will 'trickle down' to smaller vessels.

The traditional ICE needs to be significantly modified to be an effective option for use with marine hybrid propulsion systems, and some companies are already beginning to develop solutions. Hybrid Marine, based in the United Kingdom, has developed a range of hybrid systems based on Yanmar Marine engines (**Figure 11**).

In late December 2014 the first two systems were shipped to ISARA Yachts, a Taiwan-based boat builder, for their luxury sailing catamaran. The dual hybrid systems provide over 100hp of engine propulsion power, 20kW of electric drive and 20kW of generation capability, which enables electric cooking and air conditioning onboard. Power regeneration under sail provides all the vessel's power requirements and provides "go anywhere" luxury.

A selection of companies that have had success or are developing all-electric or hybrid-electric vessels are listed in **Table 3,** demonstrating that this industry is steadily growing and becoming more established.

Figure 11 Yanmar hybrid engine developed by Hybrid Marine, UK

Table 3 - Existing Hybrid-Electric and All-Electric Power Vessels

Company	Location	Hybrid or Electric	Types of Vessels	Years in Operation
Torqueedo	Germany	Electric and Hybrid	Motor boats, sailboats	10
Aspin Kemp	Canada	Hybrid	Tugs	6
Scottish Ferries	United Kingdom	Hybrid	Ferry	3
Norwegian Ferries/Electrovaya	Norway	Electric	Ferry	2
SolarWaterWorld AG	Germany	Electric	Pleasure boats, ferry	14
LMC Marine	Denmark	Electric	Sailboats, catamarans, canal boats	20+
Canadian Electric Boat Company	Canada	Electric	Pleasure craft	20
Greenline Hybrid	Slovenia	Hybrid	Pleasure craft	-
Castle Narrowboats	United Kingdom	Electric	Canal boats	4

3.1 Batteries

There are a number of different battery types and most common for all-electric and hybrid-electric propulsion applications are Lithium Ion or Lithium Polymer batteries. Lithium Ion batteries weigh considerably less than lead/acid batteries, can be recharged in 1 hour, are smaller, and have a longer service life. While lithium ion batteries have a lower capacity than some of the other types of lithium batteries they are the safest and have a long service life.

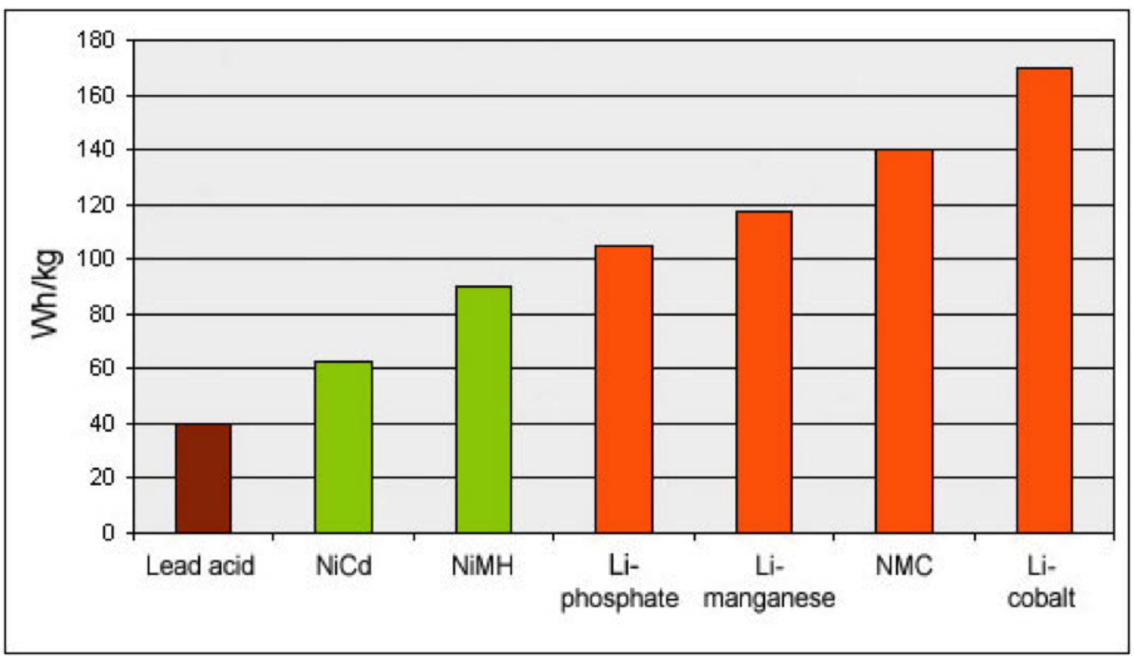

Figure 12 Energy Densities of Batteries (www.super-b.com)

Lithium Polymer batteries are a focus of many developmental plans and while there is some concern over the safety of the battery when punctured or overcharged, Corvus (a Canadian Company located in Vancouver) has had significant success with lithium polymer battery types and recently made an exciting deal to have their batteries installed in new hybrid ferries being built for Vancouver. **Figure 12** shows the change in energy density with battery type; the higher energy densities are showing great promise for electric propulsion.

Flow Batteries are another technology that is advancing rapidly. These batteries have two tanks of electrolyte liquid that is pumped into a chamber separated by a membrane, generating electron flow via a chemical reaction across the membrane. Flow batteries recharge by way of chemical components dissolved in the liquids (**Figure 13)**. These batteries can be very large and store very large amounts of energy. Flow batteries are considered very safe and as component performance issues are resolved, the batteries are being considered for very large storage: 250kW and higher.

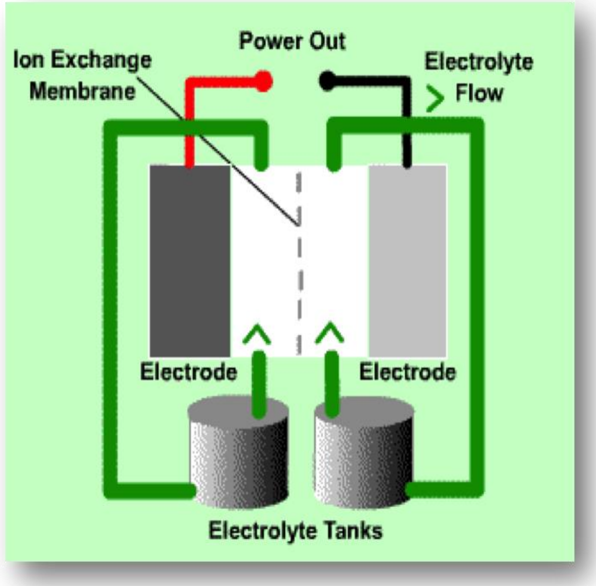

Figure 13 Flow Battery, Electropaedia

Battery maker Tesla recently developed a product intended to backup off-grid homes when live sources are not available. Although Tesla to date has not offered a line of marine batteries, their technologies could be developed for such applications.

Overall, the current state of battery technology is limiting small-scale all-electric and hybrid-electric propulsion system development, but new developments such as those described above hold great promise for opening up significant opportunity.

3.2 Maintenance

The maintenance of all-electric and hybrid-electric propulsion systems affects their adoption in a few different ways. First, owners and operators need to be able to repair and build their knowledge of electric and electric hybrid systems to a level comparable with their knowledge of conventional ICE systems in order to consider electric and electric hybrid as an affordable option.

Similarly, the ability to find qualified service personnel and supplies is currently difficult because the market for these services is small. Standardization of systems would aid in the spread of knowledge, but in many ways the technology remains at a novel level without standardized systems.

This is likely to remain the case until advances are made to make the systems viable in a wider range of small vessel applications and therefore produced on a larger scale. Proprietary ownership of technology will make things difficult in the earlier years and the sooner standardization is agreed upon by industry the faster these technologies will become economically viable.

The frequency and cost of maintenance is the other aspect that must be addressed before systems will be widely adopted. In the end, if the life cycle cost is more than a conventional propulsion system competitor, many users will not consider an electric or electric hybrid system.

Maintenance plays a large part in life cycle cost, especially with a new technology with many electronic systems and controls. As with most technologies, advances and standardization will eventually lead to more robust systems with less scheduled and unscheduled maintenance but early adopters will have to factor this into their decisions.

To move forward quickly with hybrid marine options, industry collaboration between engine manufacturers and electric motor designers is necessary, and battery developers need to be attracted to the marine world. Initiatives such as the Marine Battery Forum by DNV GL will help bring marine industry concerns to battery manufacturers, as will the American Boat & Yacht Council (ABYC) work on standards development for the small-scale hybrid marine world.

Lastly, warranties for new technology are necessary to increase adoption. For early adopters and government-supported work this may not be a high priority however to get widespread acceptance and to affordably insure vessels there needs to be some guarantees on the products being purchased.

4.0 FUTURE TECHNOLOGY DEVELOPMENTS

> It is important to point out that a leap forward in hybrid engine development or battery technology will instantly make hybrid-electric marine propulsion systems a more viable alternative to traditional ICE
>
> Molloy, 2015

New developments have been referenced throughout this review, but the areas of research and development that will have the biggest impact on the future of all-electric and hybrid-electric propulsion systems for small vessels are:

- Behavioural change in vessel operation to maximise gains
- Warranties for hybrid systems
- Safe, lightweight, inexpensive batteries, with rapid CAR
- Marine engines suited for hybrid configurations
- Robust electric motors, matched to propellers
- Synchronized inverters
- Integrated system controllers

Looking at some specific examples, the marine hybrid industry needs:

- A current limit that keeps the generator's maximum output close to its peak efficiency (+/- 70% of rated capacity)
- An inverter controller that regulates its battery charging output to maintain the generator at its peak efficiency
- Batteries with a sufficient charge acceptance rate (CAR) to keep the generator at its peak efficiency, and with sufficient capacity to support the design loads when in inverter mode

In the next 5 years it is reasonable to expect a large shift in the viable applications for marine all-electric and hybrid-electric vessels. Aspin Kemp & Associates have proven that certain hybrid systems, given the right application, can be more fuel and environmentally efficient. With today's efficient high-speed marine diesel engines, it is likely that hybrids will only be economically viable in specific applications, but the expected gains in battery technology will impact the cost effectiveness of both hybrid-electric and all-electric propulsion system installations.

Battery technology is currently an exciting area of innovation. The advancement of many different technologies requires new battery options, and topping the list of desired qualities are safety, weight and cost. The automotive company Tesla has invested in a $5bn factory in Nevada with the expectation of producing 50 GWh of advanced lithium-ion battery capacity annually by 2020, with the high-volume production decreasing the unit cost of the batteries. Apple is developing an internal battery division and Dyson has recently invested $18 million in a solid-state battery company, Sakti3 of Michigan. These are large companies with a considerable stake in the advancement of battery technology and the availability of more lightweight, inexpensive, fast charging batteries. Successes in battery innovation will be a significant factor in determining the future options for electric propulsion in small vessels.

The US Army Tank Automotive Research and Development and Engineering Center, TARDEC, recently completed a lithium battery roadmap (**Table 4**) and the results are very promising. Developing a plan to be ready for battery developments over the next 5 years would be a prudent approach for Nova Scotia companies interested in investing time and resources in electric hybrid-electric propulsion for small vessels.

Table 4 - Battery Road Map to 2020 (TARDEC)

TARDEC (US Army Tank Automotive Research Development and Engineering Center)

Lithium Battery Road Map

	Year		
	2015	**2020**	**Improvement (%)**
Energy Cells			
Specific Power (kW/kg)	0.3	0.5	67
Specific Energy (kWh/kg)	200	350	75
Power Cells			
Specific Power (kW/kg)	4.8	16	233
Specific Energy (kWh/kg)	60	60	0
Life			
Charge / Discharge Cycles	1000	5000	400
Years	10	20	100
Cost ($ / kWh)	$1000	$300	233

In another interesting development, the marine certification group DNV-GL is supporting the Norwegian government in their goal to make Norway a leader in the marine sector through the creation of a Marine Battery Forum. There is a firm belief in the Norwegian government that electric and hybrid ships will become an important part of their future environmental policies.

> Electric ships and hybrid ships with energy storage in large batteries can provide significant reductions in fuel costs, maintenance and emissions, as well as improved responsiveness and thereby improved regularity and safety in critical situations. The importance of cleaner energy in shipping makes use of batteries becomes increasingly important. In the future, probably most ships will be hybrid or plug-in hybrid.
>
> *DNV GL, 2014*

Very recently, a new non-profit organization called Hybrid Marine Technologies has formed in Maine to act as a nexus for hybrid marine technology in that US state.

In addition, university and industry groups are carrying out research into:

- Hydrogen fuel cells for small and large battery systems
- Hybrid DC distribution systems
- Intelligent controllers to reduce losses
- Flywheel storage of energy
- Power management systems
- Performance testing and evaluation techniques
- Standards for hybrid industry
- Propulsion systems to increase available space
- Quick charging technologies
- Photo-voltaic integration
- Use of on board systems for energy storage (e.g. Dynamic Positioning Systems)

Groups that are focusing on electric and hybrid vessels include, as mentioned previously, a European Union collaborative hybrid research project called Hy-Mar that is sponsored by the EU FP7 program, and the IEEE has an electric ship technologies initiative that meets biannually.

MARINELIVE is an initiative of the School of Naval Architecture & Marine Engineering of the National Technical University of Athens (NAME-NTUA) aimed at the European community with goals for “All-Electric Ship” (AES) research and technology. The University of Newcastle in the United Kingdom runs the International Conference on Marine Science and Technology for Environmental Sustainability (ENSUS) that focuses on a number of areas specific to the marine operating environment and was one of the first themed venues for publishing on electric ships. The most recent conference was in 2011.

In Canada there have been pockets of interest in all-electric or hybrid propulsion systems but there is no focused initiative or community-building activity to date. There are a few Canadian success stories such as Aspin Kemp & Associates and Canadian Electric Boats, and there is room to build on this success.

An international event being held in Amsterdam this June (2015) shows the growing interest in electric and hybrid systems for the marine industry. The Electric & Hybrid Marine World Expo will have exhibits of hybrid-related products, equipment and service providers, and a full conference program. More details available at www.electricandhybridmarineworldexpo.com .

5.0 EXISTING AND POTENTIAL MARKETS

All-electric and electric hybrid propulsion technologies are in a state of rapid development, but significant challenges to their broad viability remain. There are some applications, however, where there is great potential for all-electric or hybrid-electric propulsion systems. Certain types of tugs, sailboats, canal boats, water taxis and lobster boats for example all seem to be candidates for adoption of electric and/or electric hybrid technology if the systems can be designed and operated properly and after-sales support established. As technology advances, the cases will be strengthened for those vessels and expanded to other types of vessels.

In most cases, new builds have an advantage since it tends to be more cost effective to design and install an entire system from scratch rather than retrofit one into an existing vessel. However, local companies have made it clear that there is interest from customers in retrofitting vessels or simply adding an electric propulsion system to operate when the conventional system is not in necessary.

Retrofitting may not be ideal from a financial perspective, but is a beneficial way to gain technology acceptance before large financial outlays are made on new builds or larger-scale deployments. Retrofits can also provide an opportunity to begin changing mind-sets around vessel operation through introducing electric propulsion components, which need to be operated in a particular way for their efficiency to be maximized.

When considering the opportunities for Nova Scotia in the hybrid-electric and all-electric propulsion sector, retrofits or adding a side-by-side all-electric system hold potential for both the early-adopter market and the working vessel market. As discussed above, types of Nova Scotia vessels that may be well suited for electric options include:

- In-shore fishing boats
- Harbour water taxis
- Short haul ferries
- Yachts

One consideration to be noted as a greater number of all-electric and hybrid-electric vessels become available is maintenance: access to parts and qualified service providers can be a challenge due to the newness and robustness of the technology. There is opportunity for companies and institutions in Nova Scotia to provide training and maintenance services to this sector, with some focus on retrofits. The market for components, then, also becomes an opportunity for Nova Scotia companies.

On the new build side, initiatives such as Covey Island Boatworks' partnership with technology developer Aspin Kemp & Associates to target the market for pleasure boats that incorporate green technology shows that Nova Scotia's marine industry is already responding to opportunities.

On the technology development side, there are companies in Atlantic Canada that have the capability to capitalize on wider technical opportunities such as power management control systems, marine-specific hybrid engine systems, hull design, and route optimization.

Community and customer motivations for supporting electric propulsion options in small vessels include:

- Environmental regulations
- Noise reduction
- Air emission reduction
- ‘Green’ image and attitude
- Type and cost of available energy

5.1 Potential Applications

It is useful to examine the potential for all-electric and hybrid-electric propulsion systems in common vessel types and operations. Here we examine two groups that are common in Nova Scotia – lobster boats and racing sailboats – and look at how all-electric or hybrid-electric propulsion systems would perform in those boats compared to typical ICE systems.

5.1.1 Lobster Boat

For this simulation model, two lobster boats with slightly propulsive machinery and operational profiles or duty cycles were considered for electric drive conversion. Their specifications are shown in **Table 5**, and operational profiles in **Table 6**.

Table 5 - Boat particulars

Particulars	Lobster Boat #1	Lobster Boat #2
boat type	Cape Island	Cape Island
operation	lobster fishing	lobster fishing
length overall	48'	49' 2"
beam	24'	24'
est. displacement	120 tons	125 tons
installed power	475hp @ 1800 rpm	400hp @ 1800 rpm
main engine type	single GM diesel	single GM diesel
max speed	10.5kts	10kts
cruise speed	8.5kts	7.5kts
cruise power	380hp @ 1400rpm	325hp @ 1400rpm
fuel cons at cruise	9gph	8gph
gen set	12kW, 220v, 60HZ	12kW, 220v, 60HZ

Table 6 - Duty Cycles for typical nearshore lobster boats

24 hour cycle	Lobster Boat #1	Lobster Boat #2
dock to fishing grounds	4 hrs at cruise	4 hrs at cruise
at fishing grounds	10 hrs	4 hrs
power while hauling	engine @ 750rpm, 29hp, 2 gph	engine @ 700rpm, est 20hp, 2 gph
power between traps	intermittent at cruise	intermittent at cruise
fishing grounds to dock	4 hrs at cruise	4 hrs at cruise
at dock	6 hrs	12 hrs
power at dock	main eng block htr, w/h heater, fridge	main eng block htr, w/h heater, fridge

Note: Based on information received from Fraser Challoner, Wedgeport Boats, NS

Assumptions:
- Fuel cost of $1.00/litres
- 50% time hauling and 50% moving to new location at cruise speed
- running at 50% rating while operating
- a 30Amp 120 Volts shore connection and $0.15/kwh cost

The operational profiles in **Table 6** were developed from the predicted energy consumption and sources of power for these boats (**Tables 7 and 8,** and **Figures 14 and 15**).

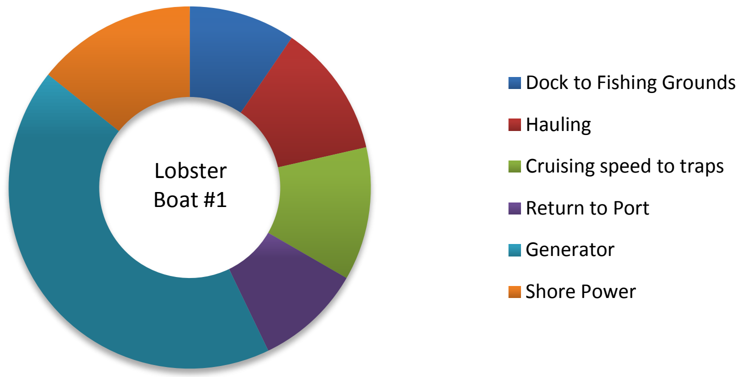

Figure 15 – 24-hour cycle of power usage and power generation Lobster Boat #1

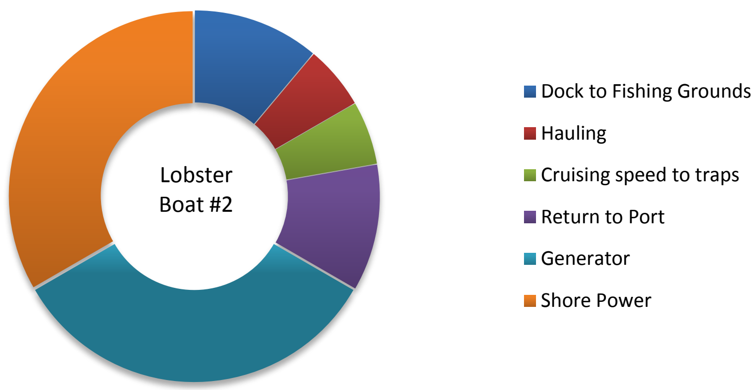

Figure 16 – 24-hour cycle of power usage and power generation Lobster Boat #2

Table 7 - Lobster Boat #1

Replace Low Power Operations with Batteries		**108.17**	**kWh**
Using 24 Volt System	850 A-hrs	16.32	kWh
Increase load on generator to charge batteries		8.64	gallons
Power available from Generator		60	kWh
Power Deficit		31.85	kWh

The cost of a battery of sufficient capacity comprised of 6-volt cells is in the range of $3000. In order to provide enough power to run the hauling functions will the vessel will require three times the battery capacity. An alternative would be to run a larger generator with hydraulic power pack in order to run it at full power and gain efficiency through matched operation. The loads need to be much lower for electric to be practical solution here.

Table 8 - Lobster Boat #2, Scenario 1

Replace Low Power Operations with Batteries		29.84	kWh
Using 24 Volt System	850 A-hrs	8.16	kWh
Increase load on generator to charge batteries		2.88	gallons
Power available from Generator		24	kWh
Available Power form Generator/Battery Pack		2.32	kWh
Reduced fuel on main engine		4	gallons

The lower load demand makes this application work with a reasonable sized battery pack and using the generator at full capacity. The potential saving is quite low however at $5.10/day, which is a 1.23% reduction in fuel cost. It might be possible to use starting batteries as the storage medium reducing cost somewhat but there may additional complication when either running the haulers on electricity or using an electro-hydraulic power pack.

A second scenario was considered using Lobster Boat #2 but with a 48v battery bank, a 8kW electric motor driving a separate shaft with a folding propeller, and using an electric hauler.

Table 9 - Lobster Boat #2, Scenario 2

Replace Low power Operations with Batteries		24	kWh
Using 48 Volts	500 A-hrs	48	kWh
Cost of shore power to charge batteries @ $0.15/KW		3.6	CAN$
Power available from Generator		Not Required	kWh
Available Power form Generator/Battery Pack		24	kWh
Reduced fuel on main engine		20	gallons

The lower load and operation time makes this application work with a reasonable-sized battery pack and use of the generator at full capacity.

The potential saving is good at $87.40 per day; a 25.73% reduction in fuel cost. If the electric motor is on a separate shaft it would provide slow speed “get-home” capability. The cost would be roughly $8,000 for motor system, $4,000 for batteries, and $4,000 for a shaft line with a folding propeller. The total cost of $16,000 at $87.40/day takes approximately 182 days to pay back which could be two to three lobster seasons.

The distance between lobster traps would have to be close enough to justify operating at 5-6 knots and any more than two hours of trap-checking time would require larger batteries. Regeneration from the propeller is considered less valuable than reducing drag with a folding propeller. Limited recharging, while not efficient, could add time or provide power in the event of an engine breakdown.

The use of electric power could also open up new, more sensitive areas for fishing.

Conclusion: From the three lobster boat examples used above, the scenario using a separate prop shaft driven by an electric motor for use when moving between traps, shows the most promising return on the initial investment of this hybrid configuration. It would, however, require a behavioural change in the way the fishing boat is operated while at the fishing grounds.

5.1.2 Racing Sailboat

Another popular category of boat found in Nova Scotia and elsewhere in the world is the racing sailboat. Two scenarios have been developed for our racing sailboat: one a conventional system using an ICE and the other where a battery is used to propel the boat to the race starting line.

Scenario A: Round-the-buoys - 29 ft. Club Racer

From May 1 to October 31, twice per week, the J29 boat is raced in round-the-buoy races; once on Wednesday night and once on Saturday. The boat is kept at a dock for the remainder of the week and is plugged in to shore power when at the dock. From start to finish, the race takes about 2.5 hours.

For each race, the boat is motored from the dock to a location close to the starting line where the sails are raised and the motor is shut off. The distance from the dock to the starting line is 3 nautical miles, which is travelled in about 36 minutes at 5 knots under power.

Sailboat racing off Halifax Harbour

For the gasoline engine option, the engine is a 9.9 HP outboard. Throttle is set at ¾ while motoring to and from the race course. At ¾ throttle setting, the engine is generating 7 HP and consuming about 4 litres / hr of fuel.

For the electric motor option, the motor is a Torqueedo Cruise 4.0 (recommended replacement for a 9.9 HP outboard). This motor operates on 48 Volt DC and has a nominal electrical input power of 4 kW.

Table 10 details the costs of operating both a gasoline motor and an electric motor on this boat over a 10 year equipment life.

Table 10 - Round the Buoy Racer Battery Profile

Duration of run each way and from start line:	36	minutes
Gasoline Engine Output While Motoring	7	HP
Fuel Consumption / hr:	3	litres/hr
Total Fuel Consumption per race:	3.6	litres
Electric Motor Power Consumption while Motoring:	4000	Watts
Watt-Hours Consumed per Run:	2400	W-h
Amp-Hours @ 48 Volts:	50	A-h
Battery Energy Consumption per race:	100	A-h
Using Group 31 Deep Discharge Marine Batteries discharged to 50% of Rated Capacity:		
A-h per Battery:	100	A-h
Number of Batteries Required:	4	
Cost Per Battery:	$379	
Weight Per Battery:	34.6	kg
Total Cost of Batteries:	$1,516	
Total Weight of Batteries:	138.5	kg
Number of Charge Cycles to end of life:	1000	
Racing Season Duration (weeks):	26	
Number of charge / discharge cycles per yr.:	104	
Life of Batteries based on cycles (years):	9.6	

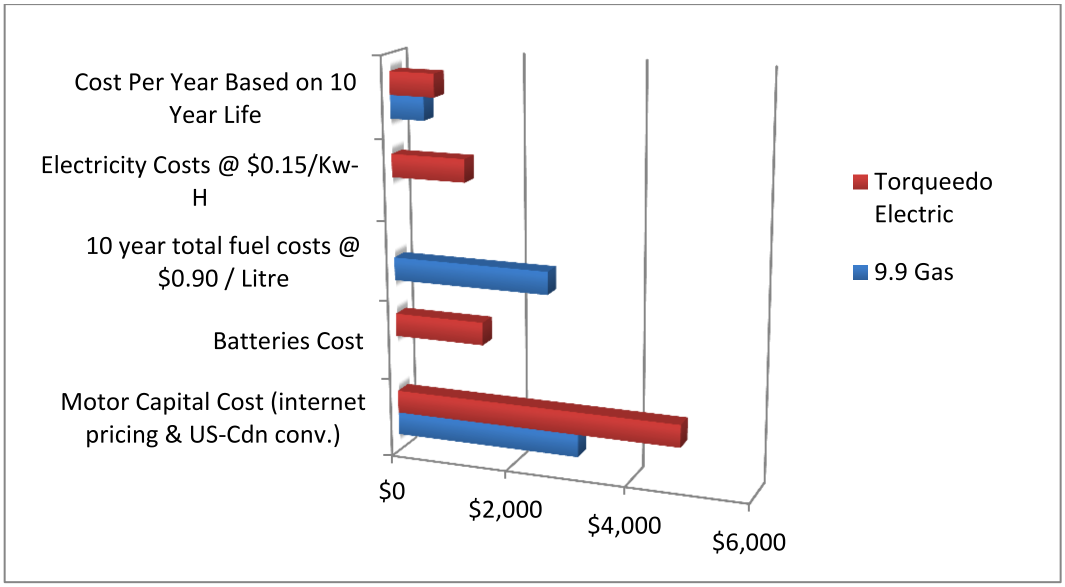

Figure 17 Comparison of ICE and electric motor over 10 years

Figure 16 shows that the electric option is less cost effective using a dollar for dollar comparison than the ICE option for this application. This however does not show the other benefits electric offers, which will in many cases be considered to be “worth the cost” as these benefits include:

- Quiet nights at anchor while the AC or heater is being run off the electric motor
- No air emissions
- Access to environmentally sensitive areas
- Option to run off solar or wind turbines installed on board

When comparing the dollar amounts for the racing scenario above, the final costs are not significant for many sailboat owners and if the weight of batteries is reduced in the coming years as is expected, the electric system has the potential to weigh less than the traditional ICE system long term, which is an important consideration for sailboat racers.

Conclusion: It is feasible to use an electric motor and batteries instead of a gasoline outboard in this scenario. The cost per year of operation of the electric motor option, based on a 10 year life and on current fuel and electricity costs would be about 50% higher than that of a gasoline outboard, dominated by the capital cost of the batteries and motor. This cost disadvantage is reduced to only 30% if gasoline prices return to $1.40/litre.

For a racing boat, the other consideration is the weight of the batteries – almost 140 kg. To avoid being disadvantaged during racing these batteries would have to be mounted very low in the hull and replace some of the keep weight.

Early adopters interested in the cost of adding an electric system are often concerned with the cost, life and performance of batteries. Table 8 summarises the battery power requirements for a racing sailboat over a racing season and costs the batteries as $1,516 for 9.6 years. The cost comparison between a traditional ICE and an electric motor is presented in **Figure 16**.

6.0 CONCLUSIONS

As a result of the review of current and future all-electric and hybrid-electric propulsion technology as applied to small vessels, the following conclusions can be drawn:

- Currently, there is limited market acceptance of all-electric and hybrid-electric propulsion technology for small vessels, but there are a growing number of practical applications in use in the recreational and commercial boat industry. These early adopters will drive further development which, in turn will increase the number of viable applications.
- The viability of any configuration of hybrid-electric system on a small vessel is affected by three main considerations: economy, environment, and strategic. Depending on the application, economy may not be the deciding factor when choosing the most effective propulsion solution.
- To become more viable, hybrid propulsion technology needs better collaboration between designers of the main components: engines, motors, propellers. One example of this need is the technical challenge of matching the load performance of permanent magnet electric motors to propellers.
- Future developments in battery technology and integrated system controllers will significantly increase market acceptance and viability of hybrid systems in small vessels.
- Not only will the economic viability of hybrid systems be improved through future technology developments, but also through changes in the behaviour of small vessel operators. The latter will require education and demonstration of the savings hybrid can bring within specific operational profiles.
- For recreational boaters, lifestyle priorities will play a big part in the choice of using a hybrid system on board – even if it costs more than a traditional internal combustion engine system. The virtual elimination of noise, vibration and smell from using electric drive is worth the cost difference to some boaters.
- Two small vessel applications that are commonly seen in Nova Scotia and elsewhere in the world that show potential for viable hybrid systems are nearshore fishing boats and racing sailboats.
- As all-electric and hybrid-electric propulsion technology matures and becomes better accepted by the marine community, business opportunities will be created for Nova Scotia companies with expertise in research, design and engineering, manufacturing, installation, testing, and service and maintenance of components or complete systems.

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