A Zero-Emissions Power and Propulsion System for Toronto Island Ferries

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Introduction

This document is intended to provide an overview for the features and functionality of a proposed all-electric power and propulsion system suitable for Toronto ferry services. The design features large lithium battery arrays, electric propulsion motors and NO diesel engines or generators. It is a ZERO EMISSION design.

The system is especially suitable for this application because:

- The voyage profile is predictable and repeatable (in terms of duration and energy required).
- The charging periods – typically during loading/unloading at the dock – are predictable and repeatable.

Although all-electric power and propulsion systems like these are not yet common, many successful examples exist where this technology has been successfully implemented in electric-powered or hybrid propulsion systems. These include tugboats, ferries and offshore support vessels. The team offering this design for Toronto has been deeply involved in many such projects, including the World's first hybrid tugboat, Europe's first hybrid tugboat, and a ground-breaking offshore dive support vessel capable of running on battery power alone for up to 30 minutes.

This document provides a brief overview of the system and is not intended to serve as a detailed functional description. It is intended that this overview should be accessible to readers without a prior understanding of electrical engineering concepts.

The design is being offered by Canal Marine & Industrial Inc (http://canal.ca) , a Canadian owned and operated company based in St Catharines, Ontario. The systems to be implemented as part of this all-electric, zero-emissions design will be largely sourced and manufactured within Canada. Detailed design information is available upon request (and under Non-Disclosure Agreement) from Canal.

Overview of Vessel Operation

A simplified electrical one-line diagram of the electric plant is provided in Appendix A. The equipment has been sized for the Toronto Island Ferry application, as described in more detail later in this document. However, the design is flexible and scalable and can be applied to many other scenarios.

The design utilizes four lithium battery arrays which are connected to the vessel's AC service buses via DCDC converters and Active Front End Converters (AFEs). The AFE is a bi-directional power converter able to support the common DC bus feeding the DCDC converters during charging at the dock. The AFEs are also able to support the AC bus using battery power (during crossings). These AFEs are able to work in parallel or alone to support the AC bus. Indeed they share some output characteristics of a diesel generator but with arguably less complexity and, being electronic in nature, they are more efficient and more reliable.

A split bus arrangement is utilized to ensure autonomy between two separated power and propulsion sub-plants. Each sub-plant utilizes two separate and autonomous battery arrays and supports a propulsion unit. Essential loads and auxiliaries will be supported from the corresponding buses. By maintaining separation (both electrical and physical) it is ensured that there are no single points of failure that can adversely affect important systems on both sides of the split bus.

Additionally, an emergency power system will be included capable of supporting emergency loads for several hours. This will normally be fed from a vessel AC service bus but, if necessary, a local emergency AFE fed from an Emergency Battery Array will take over support of the emergency bus. The emergency system in its entirety is located above the waterline and separated from the main propulsion and power distribution system. The Emergency Battery array will be maintained in a well charged condition by periodic low-level charging. This system is shown as 60kWh on the one-line drawing in Appendix A. The exact requirement can be determined after a detailed load analysis is completed for Toronto's chosen vessel design.

Readers with knowledge of marine power and propulsion systems will be quite familiar with these concepts (split busses, autonomous functions and emergency sources of power). However, in this design traditional diesel generators and fuel systems are replaced with 'electronic generators' and battery arrays. This is entirely a *zero-emission* design.

During charging at the dock, an automated plug-and-socket system is utilized. This has the following advantages:

- A safe and predictable connection can be made.
- Interlocks can be implemented to ensure power is not enabled until connection is complete and correct.
- The connection can be made quickly (maximizing charging time).
- Difficult manual operations (eg manhandling of thick power cables) are avoided.

For the Toronto ferry application, charging and discharging times (in other words crossing and loading times) are known to be roughly equal at around eight to ten minutes. A suitable utility feed at the dock must be present to allow charging at the required rates, although optional use of energy storage at the dock and/or alternative energy sources may reduce the size of the grid connection. This will be explained in more detail later.

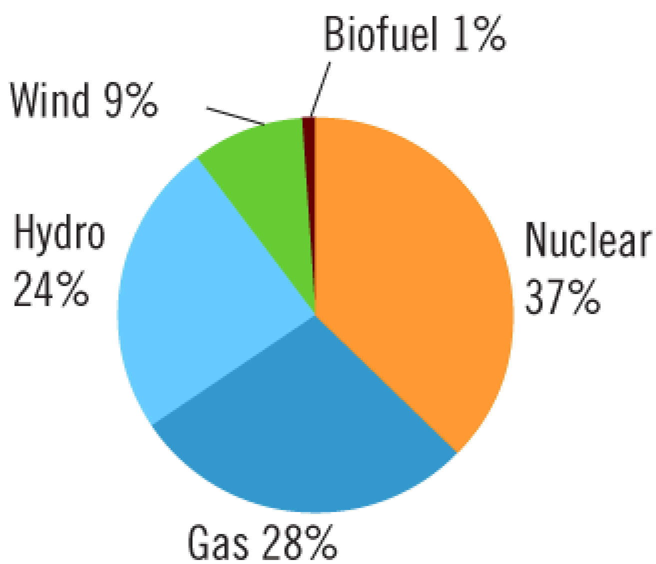
Propulsion is achieved using Variable Frequency Drives (VFDs) to control the propeller or thruster motors. These will respond to a speed reference provided by controls in the wheelhouse in the traditional manner.

Advantages

Environmental

The ferry's electric power and propulsion system does not rely upon diesel fuel for energy. Diesel fuel emits a number of pollutants when it burns including unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) and particulate matter (PM). The greenhouse gas carbon dioxide (CO_2) is also produced in significant amounts (over 2.6kg per litre of diesel).

The electric power that replaces diesel in this ferry system is generated from a variety of sources. In Ontario, significant power is generated from sources that are non-fossil fuel based. The actual sources may vary on a day-to-day basis but the power generation pie chart below can be taken as a guide. Data is from Ontario's Independent Electricity System Operator (IESO). It shows *installed* generation capacity (Dec 2015).



Reliability

As in the automotive sector – where electric cars are proving to be more reliable than their engine based equivalents – marine electric systems have fewer complex moving parts, require less maintenance and are less prone to failures. Fuel, fluid-based cooling, lubrication and exhaust systems are all completely removed from the design to be replaced by power electronics and solid-state components.

Cost Considerations

A more detailed project-specific costing estimate is provided elsewhere in this document. The design introduces power conversion technology and large lithium battery arrays at significant cost. However, diesel engines, with their auxiliary equipment and support systems, are removed completely from the vessel design. This results in a more modest differential in the initial financial outlay. Over time, the savings achieved in removing the need for fuel and reducing maintenance costs will result in a lower cost of ownership.

Additionally – perhaps controversially – an environmental cost can be associated with the release of CO_2 to the environment resulting from selection of a diesel based system. Increasingly jurisdictions are investigating the concept of carbon dioxide emissions carrying a monetary cost or 'price' (referred to as 'carbon pricing'). This can be loosely represented as the 'cost to society' of the damage to the atmosphere, or perhaps as the future cost of removing the carbon dioxide. This remains controversial. However, it seems that most experts are suggesting that this 'cost' is in the region of $30 per metric tonne of fuel. The proposal – adopted in some jurisdictions - is that the producer or purchaser would be expected to pay this cost in return for the right to emit the carbon dioxide into the atmosphere. Most likely it will be gathered in the form of additional taxation. Quebec is an early adopter of carbon taxing with some measures already in place. However it seems likely that more jurisdictions will follow suit in coming years and that tax rates may further increase. Levels of carbon taxation within Canada are currently under political discussion at time of writing.

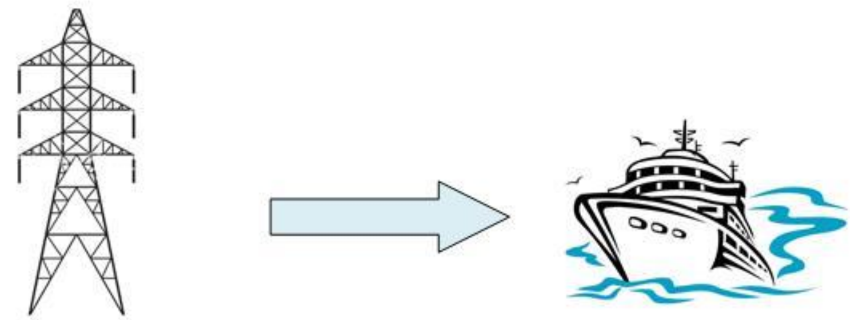
Dockside Infrastructure

Upon arriving at the dock, the vessel will plug in using one or more automated connection points. This will be combined with a proven docking system that ensures the vessel is maintained in a fixed and consistent position during loading and unloading. Once the automated dockside connection is made, the vessel will synchronize its 'electronic generators' with the shore power before completing the connection internally. In this way there is a seamless transition of power without any blackout period.

An existing implementation of an automated docking and charging connection is shown below.

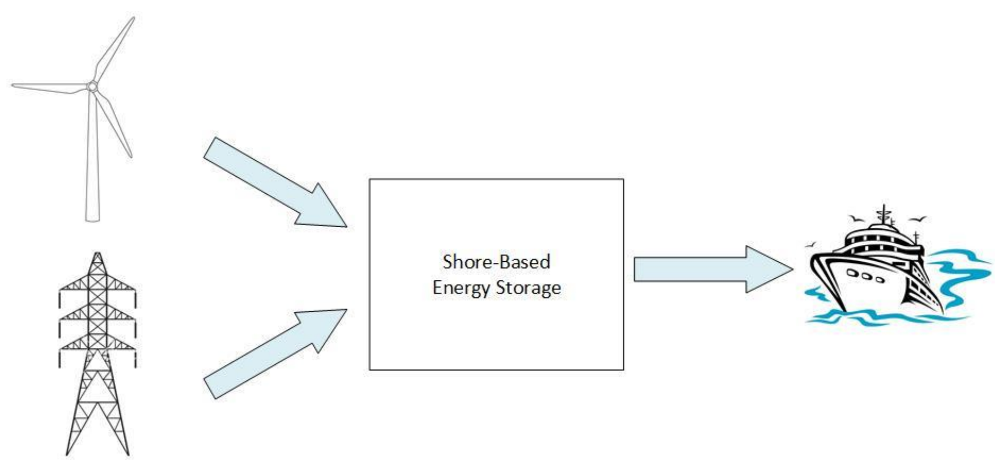
Once the vessel is being supported by shore power, its power converters will begin charging the battery arrays at a controllable rate intended to ensure that the energy deficit from the last transit is recovered while at the dock. It is envisaged that charging will be available at both outward and incoming terminals, although the system can be sized for round trips if necessary.

The electric power may be provided via a suitable step-down transformer from a grid connection (or via the ferry terminal distribution). This is represented in the diagram below. Note that this system, while certainly viable, leads to an irregular load on the feeding infrastructure.



As an additional (optional) refinement, energy storage could be utilized dockside to provide an "energy reservoir" for charging the vessel. This allows power to be drawn from the grid at a lower rate but more consistently. As an example, 100kW could be drawn continuously instead of 250kW for eight minutes every twenty minutes. This is a localized example of the concept often referred to as 'peak shaving'. It can significantly reduce costs because utility companies typically charge customers according to peak usage as well as total energy consumed.

An additional benefit of the shore-based energy storage would be the use of localized alternative energy sources positioned in the vicinity of the terminal. One to four 50kW wind turbines could make a significant contribution to the ferry's total requirements, with the energy storage on the dock forming a buffer to allow for the periodic nature of the wind. These turbines would not be grid-connected. They would be dedicated to serving the needs of the ferry operation.



Finally, an energy storage resource dockside could allow for operations to continue in the event of a power outage affecting the terminal area or a wider geographical area. The number of voyages possible would be dependent on the size of the shore-based energy reserve.

The energy storage technology used dockside would be of an identical type to that used on board the vessel.

Battery Technology

Several lithium-based battery technologies are available in formats suitable for high power / high energy marine applications, and the installed base is increasing monthly. Common applications include workboats, offshore supply vessels, naval vessels and ferries. The design team at Canal has worked to integrate battery systems from several of these suppliers across a range of projects.

Typically these systems consist of battery modules connected in series to form an array. Each module contains electronics for monitoring temperatures and voltages, and 'equalization circuits' maintaining consistent state of charge among the many individual cells within the module.

Should any measurements indicate a dangerous or damaging condition, the array will be disconnected as a precautionary measure. Utilizing several such arrays within the vessel system (in this design we suggest four) provides an element of redundancy. This protection is provided as an autonomous feature of each battery system (as a deliverable of the battery system manufacturer). In addition Canal, as the systems integrator, would provide an additional layer of protection associated with the DCDC converter function, regulating power to and from each array. This protection function would include appropriately rated electrical switchgear. The design intent is to ensure that no single point of failure (either within the battery system or externally) can lead to a dangerous situation, and to ensure that multiple protections are implemented to detect problems and isolate a battery array.

Safety

Safety of vessel systems has been the key factor driving design of the electric ferry. Battery electrical protections are discussed immediately above and these provide a high level of protection from internally-generated thermal events. Individual battery module enclosures and separate battery rooms provide protection from external fire sources but, considering the flammable nature of lithium battery cells, and considering that this is a *passenger* vessel, the design includes a requirement for a sprinkler-based fire-fighting system within the battery rooms. Consideration is also given to venting of gasses in a safe and controlled manner in the event of a fire (no gasses are produced during normal operation).

The split bus design of the vessel's power and propulsion system ensures that no single points of electro-mechanical failure exist that can adversely affect both propellers or thrusters.

An emergency electric power system is included. This is separated from the main power and propulsion systems and, although it is battery-based, it supports an AC emergency bus. In the event of a vessel blackout, this emergency bus disconnects from the main service bus and is supported solely by the emergency battery array.

The system design will conform to the regulations of Transport Canada and/or a Marine Classification Society. The design team is familiar with and has an in-depth understanding of these regulations which are geared towards ensuring robust, reliable and – above all – *safe* design and operation of any vessel.

Sizing for Required Power and Energy

A replacement program for Toronto's ageing Island Ferry fleet is currently under consideration. It is Canal's opinion that this would be an ideal application for an all-electric power and propulsion system.

The existing vessel William Inglis utilizes a pair of 450hp diesel propulsion engines which run midway through their power range during typical crossings of about 10 minutes. From this, we estimate that the energy required for each crossing is approximately 60kWh. The proposed new ferries may be of a larger size (to increase capacity) but they will also be of a more modern and efficient design. Therefore we will take 60kWh as a valid estimate of required energy going forward.

From the system electrical one-line diagram in Appendix A, it can be seen that four main battery arrays are proposed for a total of 380kWh energy storage (power from the emergency array is not available for propulsion). At first glance it may seem that 380kWh is excessive for this application, but the use of these large battery arrays has several advantages:

- Depth of discharge is reduced. During each crossing we expect to discharge the total array size by 60kWh. This is approximately 16% of capacity. For example, if the vessel leaves the dock 90% charged it will arrive 74% charged. This represents a very shallow – in other words gentle – cycle for the proposed lithium batteries and is conducive to an extended life. Working with the battery manufacturers, Canal estimates 58,000 cycles before the batteries are considered to be in need of replacement. Based on 4000 crossings per year, this would be an expected life of around fourteen years. A graph relating depth of discharge to cycle life for various lithium technologies is included in Appendix B.
- Reserve capacity is increased. If a charging opportunity is lost (perhaps due to a failure at a single terminal) the vessel has plenty of stored energy for repeat crossings before the next charging opportunity. Schedule may be affected of course (as charge time will be increased).
- The battery arrays can be organized into autonomous groups (four separate sub-systems are proposed) and the vessel can still function with one or more arrays removed from service. This adds an additional element of equipment redundancy.

Propulsion motors are shown to be 300kW. These are AC asynchronous induction motors controlled by variable frequency drives, an arrangement known to be greater than 90% efficient.

Active Front End converters, or ‘electronic generators’ are able to support the vessel’s AC services, in much the same way that diesel generators do on a conventional vessel. However, the energy source for the AFE’s will be the battery arrays. When connected to shore power, the AFEs change the direction of power flow and charge the battery arrays using current regulation. The current (or rate of flow of charge) is optimized to provide the required energy in the anticipated time at the dock. The power consumption of the vessel services during crossings will be relatively insignificant compared to the propulsion load.

Each of the four battery arrays described here would occupy a volume of approximately eight cubic meters and have a mass of approximately 1200kg. It is not anticipated that this would cause any problems, especially as the traditional machinery – diesel engines and their associated auxiliary systems – are completely removed from the design. Also worth noting at this point, the zero-emissions ferry makes storage of diesel fuel at the dock – and the entire process of refueling – unnecessary. This has been highlighted as an issue with the current arrangements and with proposed future ferry terminal designs.

A shore power source of approximately 500kVA will be required for charging. This is not unreasonably large in the context of downtown Toronto. It can be further reduced by using optional dockside energy storage infrastructure as described earlier in this document.

Costs of Ownership

The hybrid power and propulsion system proposed here would have a budgetary cost of approximately $1.6M Canadian. In addition to this, shore-based equipment directly related to docking and charging of the system at two locations (at the island and main terminals) would add approximately $600K Canadian. This does not include shore-based energy storage arrays or alternative energy sources (which are considered options).

This cost can be offset by the savings that result from the *complete omission* of diesel engines (for both propulsion and for main/emergency power generation), fuel systems, exhaust systems, cooling systems, various pumps, fans and other auxiliaries. It is estimated that the savings in initial outlay would be approximately $1.2M Canadian. A difference of approximately $1M Canadian exists between the zero-emissions and fossil fuel based alternatives.

The annual energy consumption of the zero emissions ferry, based on 4000 crossings at 60kWh per crossing, would be 240,000kWh. Based on an average energy cost of 12c per kWh, the total annual cost would be approximately $29K Canadian per year.

Based on typical engine data (from a Caterpillar C18 used in a marine propulsion application) a diesel powered ferry would utilize approximately 100 litres of fuel to produce 200kWh energy. Again, based on 240,000kWh required per year, 120,000 litres of diesel would be consumed at a cost of approximately $100K Canadian. Please also consider that diesel prices are at historical low levels at time of writing, and may easily rise substantially during the life of the vessel. The average annual maintenance requirements for the engines on board could easily match the fuel cost at $100K per year.

Although these figures are approximate, and a number of assumptions are made, a payback period of six years is indicated. Batteries would require replacement in approximately 14 years (from life cycle projections discussed earlier in this document). However, it is entirely likely that energy storage costs will be lower at that point, or new battery technologies will become available.

Conclusion

A battery-powered ferry design for the Toronto Islands would have the following benefits:

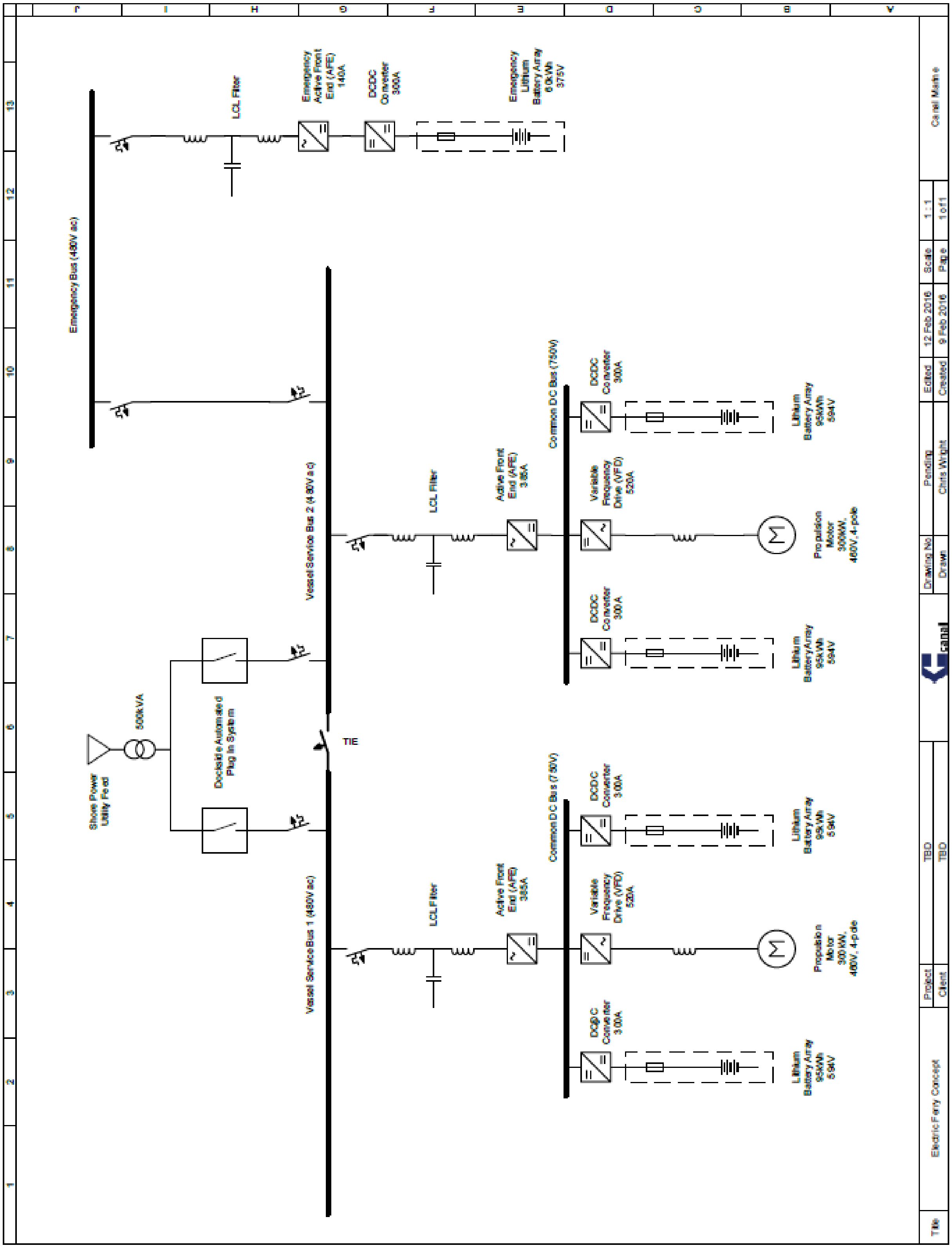
- This would be a zero-emissions mode of transportation for hundreds of thousands of passengers each year, utilizing clean electrical power from the grid to provide a real environmental benefit

- The required technology already exists, is proven, and is already being implemented in marine propulsion applications worldwide (primarily in the workboat industry). Canadian companies are leading the way in developing and implementing these systems.

- While the core technology exists and is proven, an electric ferry system implemented in Toronto at this time would be a genuinely ground-breaking project that would attract interest from around the world.

- The increase in initial outlay (the cost differential between a traditional diesel-based system and a battery-based system) is not excessive, and annual savings in fuel and maintenance will recoup this cost over a number of years. When the benefit to the environment is also considered, the argument in favor of a zero-emissions system becomes compelling.

Appendix A – Electrical One Line (Simplified)



Appendix B – Lithium Battery Array Cycle Life Graph