Advances in Efficient Vessel Design

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Introduction

Designing efficient vessels is the heart of what naval architects do. Efficiency in this case is defined as the ratio of useful travelled distance of goods or cargo divided by the total energy put into the transportation propulsion means. In other words, a more efficient vessel design will require less fuel (cost) to move a given cargo a certain distance. This paper will explain why efficiency is important and will explore some aspects of vessel design that can greatly affect a vessel's efficiency. It will further detail some of our companies' experience applying these techniques and will finally discuss some ideas that our naval architects and marine engineers are working on for the future. The authors of this paper are both employed by The Shearer Group, Inc. (TSGI) of Houston, Texas. Greg Beers, P.E. is also a Principal with TSGI's sister company, Bristol Harbor Group, Inc. (BHGI) of Bristol, Rhode Island.

Company Background

BHGI is a full-service naval architecture, marine engineering and consulting firm located in Bristol, Rhode Island. BHGI has been in business for over twenty-five years, and has produced numerous designs, to which hundreds of vessels have been built. BHGI specializes in commercial vessel design and consulting, and has experience with tugs, barges, Articulated Tug & Barge (ATB) units, passenger vessels, workboats, dredges and floating dry docks.

TSGI is a full-service naval architecture, marine engineering and marine surveying firm located in Houston, Texas. TSGI was established in 2010 when Greg Beers, P.E. and Cory Wood, owners of BHGI, bought the assets of Shearer & Associates, Inc., which was established in 1986. TSGI is the global leader for the design of inland towboats and barges and has a rich history of providing naval architecture and marine engineering services to the marine industry with a focus on the inland sector. Inland barges built to Shearer designs number in the thousands, along with a myriad of towboat, dry dock and other specialty designs.

Further, TSGI is one of the only naval architecture and marine engineering members of The American Waterways Operators, Inc.

Naval architecture services BHGI/TSGI provide include but are not limited to structural analysis, finite element analysis (FEA), deadweight surveys, hydrodynamic analyses utilizing computational fluid dynamics (CFD), and hydrostatic analysis. BHGI/TSGI mechanical and marine engineers have many years of hands on experience both aboard vessels and in shipyards. This practical experience allows BHGI/TSGI engineers to better understand both operational and technical issues. BHGI/TSGI engineers focus on the design and construction of new vessels, re-powerings, and mechanical and electrical upgrades to existing vessels. BHGI/TSGI offer many marine engineering services including but not limited to crane specification and integration, piping design, fuel system design, main engine specification, and electrical load analysis.

Recent BHGI projects include the design and engineering of North America's first LNG bunker barge and a number of tasks through an Indefinite Delivery/Indefinite Quantity (IDIQ) contract with the U.S. Army Corps of Engineers (USACE) ranging from conceptual vessel designs; to biodiesel and LNG studies; to detail design and analysis of vessels. Other recent experience includes the design of several 80,000 BBL ATB unit oil barges and the design and construction support for two new tug vessels.

Recent TSGI projects include the design, engineering and construction oversight of a new 500 passenger, 70 car diesel electric ferry for the Texas Department of Transportation (TxDOT), functional design and production engineering of sixteen Subchapter D/O 30k BBL barges, design and engineering of a 6,600HP triple z-drive towboat for SCF Marine, and marine surveying services to towboat operators to help bring their towboats into Subchapter M compliance.

Discussion:

Marine transportation is exceptionally efficient. When comparing inland barge transportation to trucks and rail, the differences are stark. One train operator runs a wonderful advertisement that notes that trains are four times more fuel efficient than trucks[1]. However, they fail to mention that barge transportation is even more efficient. The advert speaks in terms of ton miles, noting that one ton of freight is moved 471 miles on one gallon of fuel by trains. However, a report for the U.S. Maritime Administration and the National Waterways Foundation[2] notes that inland towboats and barges move one ton of freight 576 miles on one gallon of fuel. Both modes primarily use medium speed diesel engines as prime movers, so the comparison is quite valid.

Historically, vessels have been either fast <u>or</u> efficient. The two attributes often oppose one another. In this paper, we will focus on efficiency, not speed. There are many things vessel owners do operationally to increase efficiency, such as slow steaming, coating the hull with slick bottom paint, and keeping the hull clean. Additionally, there are many aspects of a vessel's mechanical design that can improve efficiency such as the use of diesel electric and / or battery technologies. When hunting for efficiency, these other avenues are ripe with opportunity, especially as the U.S. fleet wrestles with the implementation of Tier IV compliant engines. This paper will focus three things that naval architects can do to improve efficiency: hull design, power generation, and power delivery.

Hull Design

Naval architects have been working to reduce the resistance of vessels (thereby increasing the efficiency) for centuries. A simple truth about marine transportation that is well understood is the efficiency of scale. Marine vessels can generally move more cargo at the same speed with less power per ton of cargo as they grow in size. Furthermore, the lighter the part of the ship that is NOT cargo (i.e. the lightship weight of the

[1] https://www.csx.com/index.cfm/about-us/the-csx-advantage/fuel-efficiency/

[2] *A Modal Comparison of Domestic Freight Transportation Effects on the General Public*, Center for Ports and Waterways, Texas Transportation Institute, December 2007.

vessel), the more tons of cargo the ship can move at a given speed for a given horsepower. Therefore, lighter vessel structure and minimal use of ballast both contribute to the efficiency of a vessel.

These first two concepts are simple and easy to understand. A large light vessel is more efficient than a small heavy ship. However, there are other aspects of hull design that are harder to understand. For instance, a longer, finer vessel will produce less wave making (and eddy) resistance, but will likely have more wetted surface which adds to the vessel's frictional resistance. We will look at two specific methods of testing and analysis that can be used to quantify the resistance of a vessel. We will first investigate the use of model testing in towing tanks, and then the application of Computational Fluid Dynamics (CFD) which can be used to test hull models virtually (i.e. on a computer).

Tow Tank Testing

Tow tank testing is accomplished by using a ship model basin to perform hydrodynamic tests to refine the design of a vessel to improve its performance. The world's first facility to perform this type of testing was a shipbuilding company called William Denny and Brothers in Dumbarton, Scotland in 1883. Modern towing tanks vary in size with one of the longest being the 2,968 ft long high-speed basin at The David Taylor Model Basin at the Carderock division of the Naval Surface Warfare Center. Generally, a carriage runs on two rails on either side of the basin and is equipped with computers that are able to control the speed, propeller thrust, torque, etc. to run resistance and propulsion tests to determine how much power the vessel will need to achieve the desired speed.

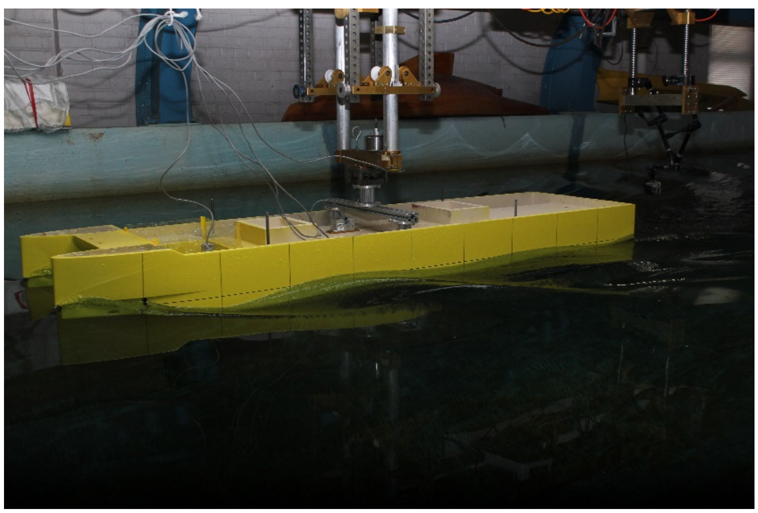

Figure 1: Resistance Testing

Computational Fluid Dynamics

CFD is an alternative to tow tank testing that allows naval architects to obtain engineering data they need to verify or alter a design early in the design process. This form of hydrodynamic analysis looks at the interaction between the hull, its propulsor, its appendages and how they all interact with environmental conditions. Performing physical hydrodynamic testing at a model scale as described above can produce uncertain results regarding vessel performance. CFD allows for full-scale tests that eliminate some of these uncertainties. Furthermore, by using CFD technology such as Simerics®-MP+ for Marine or STAR-CCM+, naval architects are able to virtually test hulls and improve the design of the vessel without building the expensive physical models that are required for tow tank testing. An important distinction for the use of CFD for the inland market is the need to model not just the towboat, but the barges in its tow as well. This is very hard to do in a tow tank, but can be modeled fairly easily on the computer using CFD.

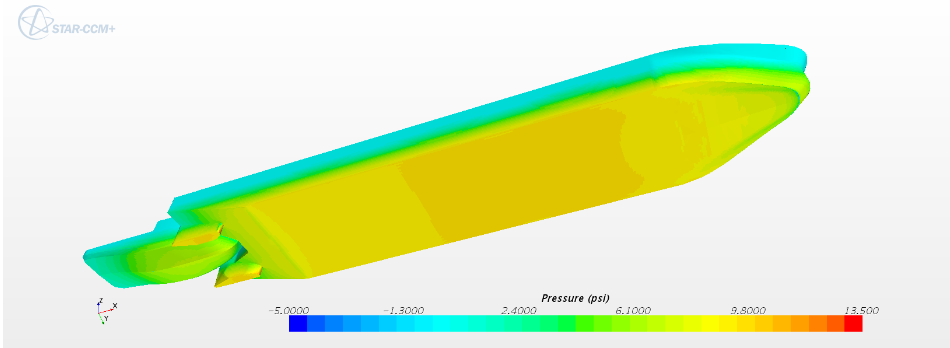

Figure 2: Hull Pressure Plot

The changes to the hull needed to reduce the resistance can be obvious (like a bulbous bow); or can be fairly insignificant, perhaps even hard to notice (a slightly longer stern rake, a modification to a stern strut, or a change to the bilge radius), but even single digit improvement in the propulsive efficiency of a vessel can yield fuel savings far in excess of the cost of said analysis or increases in the construction cost of the vessel due to added complexity to the hull shape.

More information regarding our experience using CFD to reduce hull resistance by up to 10% for both ocean going vessels and inland towboats can be found in the following white pages available on our websites, www.bristolharborgroup.com and www.shearer-group.com: "Designing for Efficiency" by Greg Beers, P.E.; and "Inland Towboats: Applying Modern Design Methods to Inland Towboat Hull Shapes" by Joshua Sebastian, P.E..

Power Generation

Conventional commercial vessels are mechanically driven by one or more main propulsion engines. However, power can also be supplied electrically which leads to some interesting efficiency opportunities. When electric power is supplied by diesel generators it is commonly referred to as "diesel electric" propulsion. Typically, diesel electric propulsion consists of multiple power generators that develop electrical power and supply it to propulsors via electric motors.

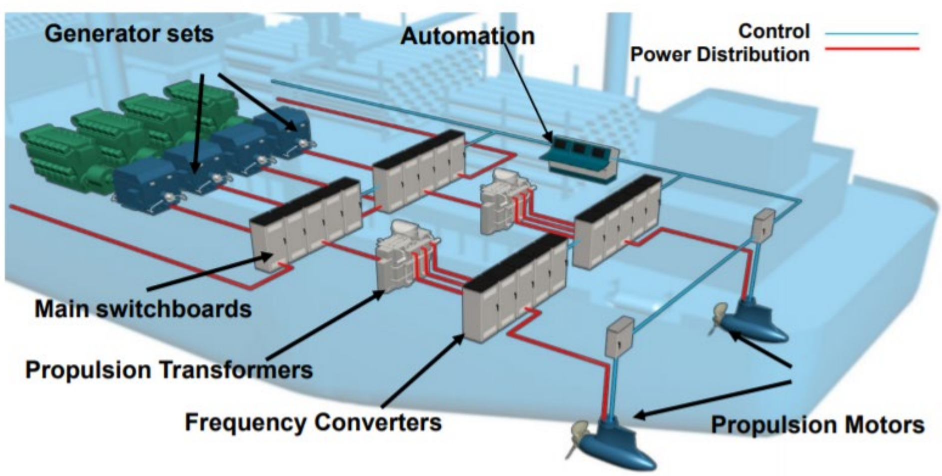

Figure 3: Electric Propulsion

The benefit of a diesel-electric system is that the number of prime movers (generator engines) running at any given time can be optimized to meet the instantaneous power demand. For example, a diesel-electric towboat traveling down-river to pick up a tow can meet its minimal power requirements with a single generator engine running at a high-efficiency load level. When it begins to push the heavy tow back up-river, it can engage all four generator engines to meet the demand. In a conventional vessel, the initial low-power transit would have required both main propulsion engines to run under-loaded and inefficiently. Diesel electric propulsion improves the efficiency of a vessel in operating ranges outside of the optimal range of a mechanical drive system. Electric propulsions systems can provide overall efficiency gains, but it is important to determine the total operational cycle of the vessel over a long period to properly understand and quantify said gains.

Taking this concept to the next level, we can add energy storage (batteries, etc.) to the equation. When diesel electric systems are combined with energy storage, the benefits of diesel electric systems continue to improve. For typical marine applications, the use of Lithium Ion batteries (Li-ion) can help by adding spinning reserve, peak shaving, and zero emission operations to increase the overall efficiency of the vessels.

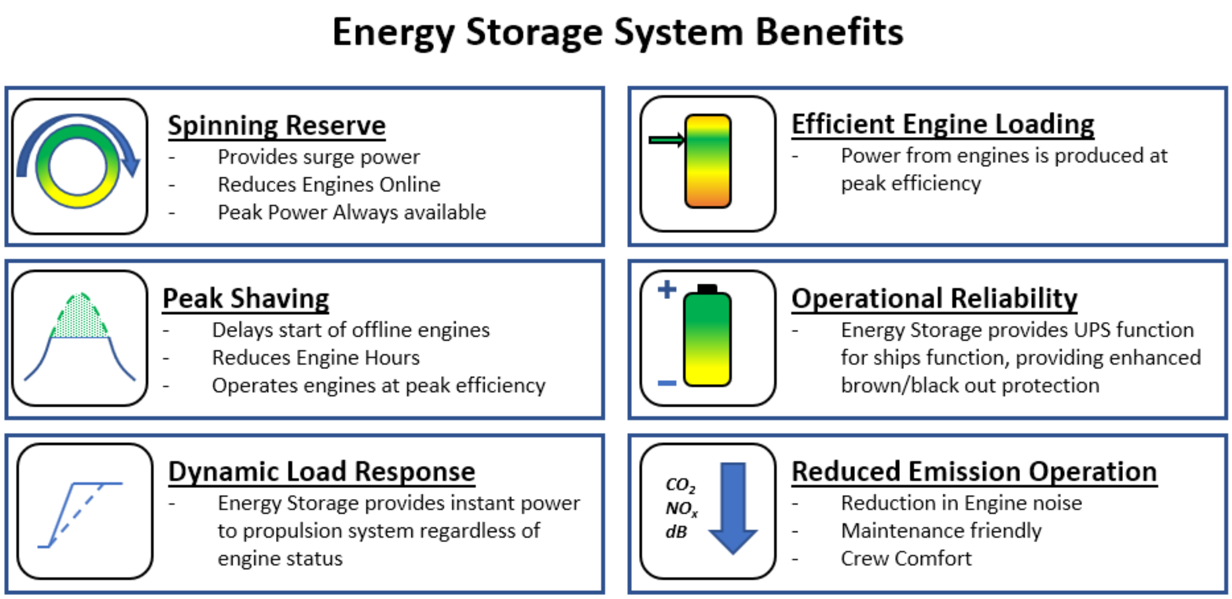

Figure 4: Energy Storage Benefits

These benefits allow the operator to have multiple prime movers but only run the ones necessary for the job at hand. In simple terms, because the batteries can provide full power when needed (Dynamic Load Response), generators can be taken off line when not needed (Spinning Reserve and Peak Shaving). This allows the operator to run a reduced number of generators at an efficient engine loading when the vessel does not need full power. By running fewer prime movers at efficient engine loadings, the operator is able to burn less fuel and thus reduce emissions when less than full power is required.

Diesel electric propulsion systems also provide benefits beyond fuel savings. During the design process, consideration should be given to items like redundancy of propulsion systems, urea consumption and storage, and engine maintenance.

As noted above, the diesel electric option shines with respect to redundancy and safety. With any engine able to provide power to either propulsion motor, an operator can minimize the impact of a prime mover failure. On a mechanical system with two engines and shafts, the loss of a prime mover results in the loss of 50% of the propulsion and an entire shaft. On a diesel electric vessel with four generators and two shafts, the loss of a generator results in the loss of 25% of the maximum available power but the remaining power is still available to both shafts. Similarly, with the loss of a generator on a mechanical system, the vessel now has no back-up power for house and auxiliary loads. Alternatively, the diesel electric system can provide power for the house and auxiliary loads from multiple power generation sources.

Using multiple Tier III generators removes the requirement for Tier IV engines which require the use of SCRs or EGRs to meet the higher tier emissions requirements. If a vessel is using urea for SCRs with a typical DEF dosing rate of 5%, a new vessel design has to accommodate a urea tank, the SCR, and the additional exhaust piping. A diesel electric system with multiple smaller generators that fall below the size requirements for Tier IV can alleviate these requirements.

Further, maintenance is improved as a diesel electric vessel will typically only have one type of prime mover (generator) on board. A diesel electric system can have multiple common generators allowing for a reduction in the number and type of spare parts and equipment required. Also, most vessels do not require full power much of the time. This allows for rotation of the generators which helps keep the engine hours (and thus the maintenance) to a minimum and can even allow for planned or emergent maintenance on a specific generator while the others are running.

For more information on these topics, see the following white papers available on our websites, www.bristolharborgroup.com and www.shearer-group.com: “Energy Storage Life Cycle Cost Study” and “Inland Towboats and Diesel Electric Propulsion”, both by Joshua Sebastian, P.E.

Power Delivery

The final piece of the puzzle involves improvements in delivering this efficiently produced power to the water. A simple improvement that many of our clients utilize is proper propeller specification or even custom propeller, nozzle and stern appurtenance design utilizing the same CFD tools noted above.

However, even larger modifications in the type of propulsors can lead to large efficiency gains. A great example of this is the adoption of the use of Azimuthing Stern Drives (ASD’s, commonly known as z-drives) on inland towboats. Inland towboats have traditionally been built using main engines connected to reduction gearboxes connected to long drive shafts passing through the towboat hull to a propeller held in place by a large support strut and large rudders in front of and behind the propeller. The advantages of using z-drives on inland towboats are decreased installation time, increased fuel efficiency, increased trip time efficiency, decreased major maintenance downtime, and higher customer satisfaction. Savings in fuel and trip time from ten to thirty percent have been demonstrated in both theory and actual towboat operation. Results from a controlled experiment using unit tows yielded 28% fuel savings and 11% trip time savings as shown in the following white paper available on our website: www.shearer-group.com: “Inland Towboats: The Next Generation” by Greg Beers, P.E. and Ed Shearer, P.E.

Experience:

BHGI recently acted as the primary design consultant for a small passenger vessel project incorporating energy storage and electric propulsion in an electric-hybrid system. BHGI worked with a hybrid systems integrator to perform a duty cycle analysis and optimize the hybrid system for operational requirements and design constraints of the vessel. The vessel operates primarily in an all-electric mode with batteries providing power to electric propulsion motors and no engine running onboard. The high duty-cycle and limited space of a small passenger vessel mean that battery capacity comes at a premium, and the vessel will recharge often. In the event that frequent shore-charging is not accessible, a generator provides this capability onboard the vessel itself. Periodically throughout the working day, the generator will take over the propulsion load for a short time and simultaneously recharge the batteries. During these periods, the generator engine runs at a constant, high-efficiency load level, diverting all power not needed for propulsion to recharge the batteries. Whenever possible, the vessel docks and recharges the batteries from shore power, utilizing the energy generated by clean, land-side power plants. The electric-hybrid design increases the fuel efficiency of the vessel, reduces emissions, and treats passengers to a clean, quiet ride in all-electric mode.

BHGI has also designed a debris collector for the USACE that employs this technology. The *DRIFTMASTER II* is a 148' x 39' catamaran that utilizes a diesel electric propulsion system with energy storage. The design incorporates 3 MW-hr of battery capacity. The completed vessel will be placed in service with the New York District and will be used by USACE in support of its drift collection and emergency response missions.

TSGI is currently working with one owner to explore the option of a battery powered fleeting boat. By analyzing the operating profile of the vessel, we are able to determine the optimal size of the energy storage. During the design of TxDOT's next ferry serving the Galveston-Bolivar route, much consideration was given the propulsion system. The overarching concern throughout the process was providing the safest and most capable platform to provide service for the next 40 years. Originally, the vessel was to include two large main diesel engines providing power to the double ended ferry. After analyzing the route and option schedule, TxDOT eventually decided that a diesel electric with energy storage offered them what they were looking for: a vessel with lower operating costs than their current vessels as well as better performance and increased operational safety for their passengers. The vessel is designed to operate with both the batteries and generators running, but can also provide full speed passage with batteries alone or with the generators alone to provide essentially two complete propulsion systems for redundant operation.

The improvements offered by diesel electric and energy storage technology are not just limited to the passenger fleets, which is where most of the diesel electric and energy storage vessels are found currently. We have studied the operational profiles from a number of vessels from four different owners in different parts of the inland river system. What we found after analyzing the operational profiles is that many of the vessels have profiles that will benefit from the inclusion of diesel electric and energy storage to reduce fuel and maintenance costs. Fuel costs on some of the vessels were projected to go down by 15% and maintenance costs by more than 30% by reducing engine operating hours.

Lessons Learned:

The single largest lesson learned by BHGI and TSGI while designing and analyzing vessels with regard to the concepts above is the need for proper and thorough analysis of the operating profile of the vessel. This is similar to how LNG vessels are designed. As noted above, BHGI and TSGI have experience with LNG vessel design. These pressurized and cryogenic vessels are more like rockets than oil barges. A thorough understanding of their operating profiles is of paramount importance to their successful design. Vessel designs implementing the ideas above for improving efficiencies require a similar level of analysis and engineering in order to successfully realize the targeted improvements in efficiencies which can include reductions in operating costs, maintenance costs, and in some cases, capital costs.

BHGI's design of the electric-hybrid small passenger vessel described above pushes electric vessel technology into a new sector of the industry. Coast Guard regulations for Subchapter-T vessels with electric propulsion and onboard battery storage are still under development, and previous electric vessels in the U.S. have fallen into different regulatory categories. One of the key innovations of the small passenger vessel is a consolidated twin-screw drivetrain served by a single battery bank and a single generator. Previous twin-screw electric vessels have featured independent and parallel drive trains for each screw, requiring two generators and two separate battery banks. By combining the battery banks and using a single generator, the small passenger vessel achieves savings in space, weight, efficiency, maintenance, and flexibility of the hybrid system. In order to validate the consolidated drive-train design, BHGI worked with the Coast Guard to establish standards of redundancy and reserve power that achieve an equivalent level of safety with existing Subchapter-T vessels. The consolidated drivetrain opens up new possibilities for small commercial vessels to adopt electric-hybrid technology, and BHGI is currently working on concept designs to leverage the capabilities of the system.

BHGI and TSGI are firm believers and users of the latest technology to create more efficient vessel designs. However, we also understand the importance of grounding our analytic efforts in the real word. Said simply, we “trust but verify” the tools in our tool chest.

Future:

Electric vehicles are a growing feature of the global transportation network, and electric vessels are poised to become increasingly prevalent as legislative and social pressures create incentives for technological progress and green transportation. This progress still requires significant capital investment in most cases, but the potential benefits of early adoption are heightened as regulators face pressure to update industry standards. The main challenge facing electric vessels is the high cost, size, and weight of energy storage systems. Battery technology is advancing, but the systems currently available put tight limits on the range of an electric vessel before it must recharge. Applications where shore power or alternative means of recharging are readily accessible present the most likely areas for electric technology to gain a major foothold in the near future. BHGI and TSGI are currently developing concepts for inland vessels and short-route ferry vessels utilizing electric propulsion and battery storage. Electric fleet boats could house enough batteries to complete a normal operational cycle before returning to the dock for several hours to charge. Electric ferries can be optimized for a given route and schedule, either relying on shore power to charge between transits or using a high-efficiency generator to extend the range and run all day before recharging overnight.

Electric vessels are an investment that will increase in value as technology improves. As shore-side power generation becomes cleaner and fossil fuels become more restricted, increasing environmental benefits and financial incentives are passed on to the vessel every time it charges at the dock. Vessels linked to the developing land-side electric grid are able to harness the benefits of national energy advancement. Electric energy storage systems are inherently modular, battery technology is developing rapidly. When installed batteries have reached the end of their usable lifespans, they are replaced with updated models that increase the performance and efficiency of the vessel at every major overhaul. BHGI and TSGI designs combine the latest in green power technology with a vision for the future of electric marine transportation.

Some other areas for improvements that BHGI and TSGI are currently working include the measured reduction in emissions for vessels utilizing the concepts outlined in this paper, specifically as they might relate to new and imminent port requirements such as harbor emissions caps. We are also investigating the use of augmented and autonomous control of vessels to further improve their efficiencies. As noted in the beginning, these new technologies are full of opportunities to improve the efficiency of marine vessels, and BHGI and TSGI remain committed to exploiting them to their fullest potential.