DIESEL-ELECTRIC HYBRID TUGBOATS USING LITHIUM-ION BATTERIES

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Diesel-Electric Hybrid Tugboats Using Lithium-Ion Batteries

Abstract

by

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Diesel internal combustion engines have long been the dominant power source for tugboats. Because of the high power needed for towing jobs, conventional tugboats use engines that are relatively large for the size of the tug. These large engines provide all of the propulsive power to the tug, despite being severely oversized for low power operations like transit and idle. Hybrid configurations allow for the main engines to be turned off when not towing by using an alternate source of propulsion. In the case of the *Carolyn Dorothy*, for example, the main engines are disengaged from the driveline via a clutch and the propellors are turned by electric motors powered by diesel generators. This configuration reduces fuel consumption by nearly 25%, just by using diesel power more effectively. By the year 2030, lithium-ion batteries will reach a cost per kWh, weight per kWh, and size per kWh at which operators will want to utilize hybrid configurations with lithium-ion batteries in place of a diesel generator, further reducing fuel consumption and the enormous costs associated with diesel fuel. Since Logan Clutch Corporation are manufacturers of clutches, a critical component in hybrid configurations, the company should vigorously pursue opportunities in hybrid tugboats over the coming years.

Introduction

Tugboats have been around well over a hundred years serving to save disabled vessels, maneuver large vessels in tight spaces, and providing propulsion to vessels without their own, among other duties. Their importance in harbors as well as deeper waters means they service industries such as shipping, fishing, offshore oil drilling, offshore windfarms, and many more. With so many industries depending on tugs, owners must ensure that their vessels are reliable and powerful. As such, diesel engines have long been the status quo for power, and redundancy has been the status quo for reliability.

Because of the power needs of tugboats during heavy towing operation, for the foreseeable future diesel engines will remain operators' preferred option for main propulsion. Since a typical tugboat has thousands of horsepower of main engines that are constantly running yet only needed during towing operations, tugboats are an application that especially needs a viable hybrid configuration so that the main engines can be shut off when not needed to save fuel and reduce emissions. Hybrid configurations that allow the main engine to be shut off do currently exist. In these situations, low-power propulsion is provided by an electric motor powered by the onboard diesel generator sets (gensets)[1]. While this configuration does reduce fuel consumption, the power is still provided by diesel fuel.

With fossil fuels seeing increased scrutiny for their contributions to elevated CO2 levels in the atmosphere as well as highly fluctuating costs, investing in hybrid tugboats should reduce uncertainty for operators. Finding alternative sources of electrical power for hybrid tugs should reduce that uncertainty even further. Competing technologies to

[1] In the marine industry, essentially all gensets are diesel; for this paper any mention of gensets can be assumed to mean diesel generator sets.

reduce the reliance on diesel engines have been investigated for decades. In particular, fuel cells have received a lot of attention and investment as one of the most promising technologies. In May of 2022, the Shenzhen State Fuel Cell Corporation received a $1 billion valuation thanks to its success manufacturing solid-oxide fuel cells used in several commercial vehicles in China [1]. Adoption of fuel cells will require significant investment, particularly in infrastructure for hydrogen refueling stations. As an environmental benefit, production of hydrogen via electrolysis using electrical energy generated via solar or wind creates an energy cycle devoid of carbon. In this manner, hydrogen becomes a type of energy storage. Another similar alternative fuel that can be electrically generated is ammonia. Work is being done to scale up clean ammonia production as well as to develop the systems that will use the ammonia fuel. There are two competing ideas—ammonia engines and ammonia fuel cells [2]. While promising, these technologies are relatively young and hence are several years away from reaching any large-scale adoption.

Lithium-ion batteries, however, are rapidly approaching a point where they will outperform diesel in multiple parameters. Lithium-ion batteries have already reached large-scale adoption for a variety of applications, from smart phones to electric cars. In these applications, these batteries are acceptable, allowing smartphones to last over a day on a single charge with a lifespan of a few years and allowing some electric vehicles to drive as far as you can with a tank of gasoline. But the power demands on a tugboat require a different set of parameters to be met. The nature of the vessels being out on the water possibly miles from other watercraft requires a particular focus on safety and reliability, even more than for electric land vehicles, when hundreds of thousands of dollars of equipment and multiple crew members are isolated on the water.

The obvious goal of a tugboat's power plant is to supply sufficient power for the application. The key is to achieve the desired power within the constraints of the remaining parameters. A typical conventional 28m tug could have two 2000kW main engines for propulsion and two 175kW gensets for deck equipment and "hotel" loads. A hybrid variation of this design replaces one of the 175kW gensets with a 560kW genset used to supplement propulsive power [3]. These engines are selected based on several factors including cost, weight, and size. Replacing any of these components with an alternative power source such as batteries would require similar consideration of cost, weight, and size.

The unique operating profile of tugs means the large main engines are only necessary during bollard pull conditions. In the conventional tug, the main engines are used whether towing or not. In the hybrid configuration, the 560kW genset can power an electric motor on the shaft of the driveline. When not towing, shutting off and declutching the main engines allow for the 560kW genset to provide propulsion via the motor. While both configurations are entirely diesel-powered, the hybrid design reduces fuel consumption by limiting the use of the main engines. Reducing the use of the main engines also implies less maintenance on the main engines—maintaining a 560kW genset is easier than maintaining a 2000kW engine. Since engine maintenance occurs based on the number of hours the engine runs, reducing the burden on the large engines extends their operating life.

By the year 2030, improvements to lithium-ion battery technologies will reach a point where every tugboat will want to replace some portion of their power system with a battery. These improvements will impact key performance parameters by reducing weight, size, and cost without sacrificing capability, reliability, and durability. Logan Clutch, as a manufacturer of power transmission equipment, should vigorously pursue hybrid applications in the coming years. By proving the capability of their clutches and gearboxes to handle hybrid applications prior to the year 2027, early adopters will feel confident in the product, allowing Logan Clutch to be a leader in the rapid growth of hybrid tugs and repowers of existing tugs as 2030 approaches.

Logan Clutch business overview

As manufacturers of mechanical power transmission equipment, Logan Clutch corporation is part of the Engine and Turbine Manufacturing Industry (NAICS code 33361A). The industry as a whole is $40 billion, while the mechanical power transmission segment is 11.5% of that at $4.6 billion. The industry is mature, with very little change in its share of the overall US economy and the number of establishments in the industry. For this industry, the 2021 IBISWorld report [4] notes that regulation, especially Environmental Protection Agency (EPA) requirements, will provoke both technological advancement of diesel engines and demand for new products. New developments include reductions in emitted particulate matter and higher thermal efficiencies. Though clutches do not directly impact an engine's satisfaction of EPA requirements, Logan Clutch can take advantage of the increased focus on environmental concerns since clutches contribute to reductions in emissions by serving as on/off switches for equipment powered by engines, hence reducing unnecessary loads on engines and increasing fuel efficiency.

Even though Logan Clutch is part of the Engine and Turbine Manufacturing Industry, the company's performance is driven by the 11 industries it serves, including marine, oil and gas, agriculture, and more. In one application, screw machines, the clutches operate as part of an electrical machine. In most of the other applications, however, the clutches are used as part of an internal combustion engine powertrain. As is evident by the rise of electric passenger cars, there is apparently a strong future in some applications for entirely electric equipment. Even higher-powered electric applications such as semi-trucks are in development. Internal combustion engines, however, remain the dominant power method for vehicles from cars to semis to boats and beyond. For

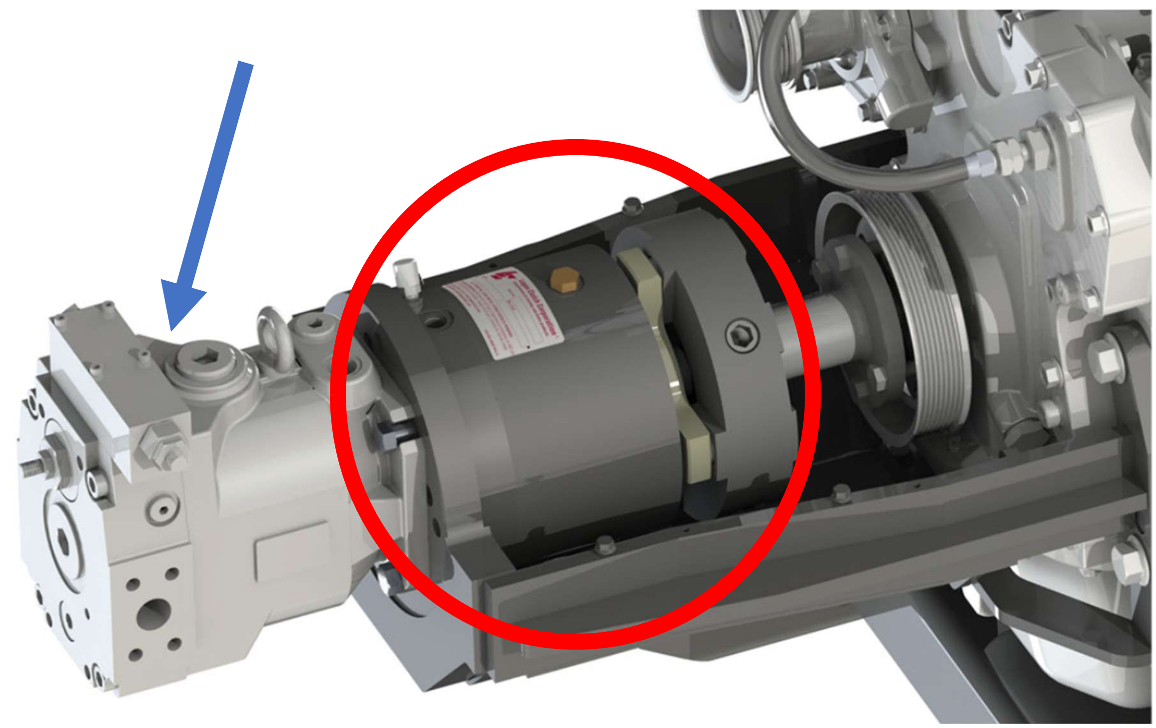

Figure 1, a clutch (circled in red) serves as an on/off switch for rotational motion from an engine (right) to a hydraulic pump (indicated by blue arrow) these applications, reducing the reliance on engines will require the integration of hybrid systems utilizing alternative power sources.

While passenger vehicles may be headed towards widespread electrification, Logan Clutch's diversification in industrial applications suggests that its future is still strong. Maintaining its position and achieving its growth goals will require a keen knowledge of what the mechanical power transmission landscape will look like in the coming years. The company is privately owned, but public estimates place the company in the $1 million to $25 million range. Without disclosing specific pricing information, conservatively $10,000 of Logan Clutch products could be used on a single tug. More likely, $20,000 of product might be used, and possibly more. Reaching just 50 tugs would mean between $500,000 and $1 million in new revenue, allowing Logan Clutch to meet reasonable growth goals through this specific market alone.

Logan Clutch has two products that are well-suited to reducing fuel consumption and emissions in the context of combustion engines. First, a clutch acts essentially as an on/off switch for equipment, as shown in Figure 1. Logan Clutch has several clutch product lines, each of which meets certain specifications depending on the application. Typically a clutch is mounted to a power take-off[2] source on an engine, but more generally a clutch serves to engage and disengage rotating components. Since in many industrial applications a single engine might power multiple pieces of equipment, reducing the load on the engine by disengaging pieces of equipment from the powertrain is critical to reducing fuel consumption and emissions. Second, the FlexaDrive is a pump

[2] A power take-off is any rotating component off of which equipment may be run, including an engine's main flywheel, but also components like the pulleys that automobile alternators are powered via

Figure 2, the FlexaDrive expands an engine's output options by providing additional power take-off sources (the two circled components in this model)

drive gearbox. The FlexaDrive fits between an engine's main flywheel and the main driven member, transferring full engine HP while providing additional power take-off locations, as shown in Figure 2. By expanding the number of power take-offs available, equipment designers can eliminate the need for multiple engines by taking advantage of the additional power take-offs available via the FlexaDrive. Further, the power take-offs can also serve as power take-ins. The engine can be declutched so that an alternate power source can drive the power take-in and hence drive the main driven component. In many high-power applications, the equipment only requires such high powers for a small percentage of its operating time, but the engines are constantly running. Since engines are less efficient under low power loads, constantly running the high-power engine at low loads is a waste of fuel. Instead, it would be better to shut off the high-power engine in favor of some smaller power source to maintain the low power functions. For example, passenger vehicles frequently come equipped with a feature that stops the engine at red lights, leaving operation of electrical components like air conditioning to the battery. This seemingly minor innovation can increase fuel economy in cars by up to 10% [5]. The FlexaDrive can serve to reduce fuel consumption and emissions by allowing the main engine to be turned off when less power is required, which can be supplied by some alternate power source like a smaller engine or a motor powered via battery.

Target Market

To ensure that it reaches or exceeds its growth goals, it is critical for Logan Clutch to pay attention to each of the markets it serves. Finding a market that Logan Clutch already serves that can take advantage of multiple products can help Logan Clutch pursue new opportunities in the market by leveraging existing sales channels. Logan Clutch can continue the company's usual sales strategies to customers in the market while simultaneously testing the waters of different products and applications. One such market is the marine market, and more specifically tugboats. Logan Clutch has clutches on tugboats around the world in a variety of uses, including supplying mechanical power to hydraulics systems, running firefighting pumps, and connecting winches to the power source. Additionally, Logan Clutch has seen use in hybrid applications. The *Campbell Foss* hybrid tug (now called the *Bering Wind*) was built in 2005 by Foss Maritime Company and ports in Long Beach, CA [6]. A Logan clutch is used to decouple the main engines from the driveshaft, allowing the main engines to be shut down while electric motors drive the propellors [7]. Another application was in partnership with Cleveland-based Great Lakes Towing and Shipyard, in which Logan Clutch's FlexaDrive was used on the tug *Michigan* [8]. The FlexaDrive gearbox allows electric motors to propel the boat without the motors being coaxial to the driveline.

US Market Analysis

According to the 2021 IBISWorld report [9], Tugboat and Shipping Navigational Services in the US (NAICS code 48833) is a $4.3 billion industry, of which Tugboat Services account for 62.9% or $2.7 billion. The report anticipates 2.3% annualized growth over the next 5 years to a total of $4.8 billion for the industry as a whole. If

Tugboat Services retains the 62.9% share of the market, the sector will grow to over $3 billion. Revenue in the industry is dependent largely on fuel costs as operators usually apply fuel surcharges to their services to absorb the highly volatile fluctuations of fuel cost. The report also notes that since water transportation is one of the most inexpensive shipping methods, increased trade activity leads to increased demands for tugboat services. After a decline in trade during the Covid-19 pandemic, the report suggests economic activity has bounced back, likely meaning a greater need for tugs. While the IBISWorld report only covers data for the US, the relationship of fuel costs and trade applies just as well to the international market.

Worldwide Market

According to commercial marine broker Marcon [10], the number of sea-going tugs in the world has increased from 18,749 to 20,543 between August of 2017 and November of 2021, indicating a CAGR of 2.17% over the time period. Since some older tugs are retired each year, the number of new builds each year will be a bit higher than 2.17% to make up for the scrapped. Thus, it is expected that the number of new sea-going tugs built each year will be at least 445 based only on the CAGR. In the United States, the number of sea-going tugboats has actually decreased over the same time period, from 1535 to 1485. Note that these are sea-going vessels—the US no doubt has a multitude of tugs operating inland such as in the Great Lakes and on the Mississippi River.

A beachhead market for Logan Clutch is the country with the largest fleet of sea-going tugs, Indonesia, which has increased their number of tugs from 4151 to 5232 over the same period for a CAGR of 5.59%. Indonesia has by far the largest market for tugboats. Indonesia has over 25% of the world's total, as well as the youngest fleet with an average age of 12 years. The second largest fleet in the world is in the US, but that fleet is less than one third the size of Indonesia's. The biggest factor influencing the size of the Indonesian fleet is that it is an island country, composed of some 17,000 islands. Further, Indonesia is rich in natural resources, leading to a lot of interisland and international trade of oil and natural gas, coal, tin, copper, gold, and nickel [11]. Additionally coal briquettes and palm oil are the leading exports. Over the last 20 years, Indonesia's economy has rapidly grown to the 16th largest in the world by GDP. Specifically regarding tugboats, the size of the fleet is not just a de facto requirement based on trade volume, but also a de jure necessity as Indonesian maritime law dictates a specific number of tugs required to accompany ships of varying sizes in harbor environments:

- If a ship is between 70 and 150 meters it must use at least one tugboat with a minimum total pulling force of 24 tons of bollard pull;
- If a ship is between 150 and 250 meters it must use at least two tugboats with a minimum pulling force of 65 tons bollard pull; or
- If a ship is above 250 meters it must use at least three tugboats with a minimum total pulling force of 125 tons of bollard pull [12].

This strict usage of tugs was developed to ensure safe passage of vessels into and out of harbor. Even with these requirements, vessels are still susceptible to accidents as seen by the 5 accidents in the port of Cilacap in just an 18 month span [13].

Industry Needs

Historically tugs have utilized diesel engines directly driving propellors. But, according to shipbuilders Robert Allan, LTD [3], "tugboat operators are looking for ways to make their vessels more efficient and friendlier to the environment, to reduce costs, meet regulatory requirements, cater to market demands for cleaner operations, or simply to improve 'green' credentials." If these goals will be met, however, the demands of reliability and performance must be considered. Any alternative tugboat power configuration must be able to maintain the requisite reliability without increasing cost, weight, and size.

Tugboats

Tugboats are used to safely maneuver much larger vessels and to propel vessels that do not have their own propulsion, such as barges. As such, tugboats are powerful vessels in a relatively small package. For example, the Emma Maersk shipping boat has a length of 397m and a beam of 56m with a total power plant of around 100MW [14]. That's 4kW/m2 of boat. Compare that to the Alta June tugboat with a length of 23.8m and a width of 4.6m with a total power plant of 4.2MW [15]. That is 38kW/m2 of boat. Tugs require such high power density because they need sufficient power to handle such enormous ships like that Emma Maersk. This necessity leads to a design challenge. Tugs conventionally will directly drive their propellors via large main engines. While this design allows tugs to satisfactorily perform their towing jobs, it will be shown that towing jobs only account for about 22% of a tug's operation time.

The various operating modes of a tug are shore power, dock, standby, transit, barge move, and ship assist. In *Shore Power*, the tug is plugged into a power source and so all engines may be turned off. In *Dock*, the tug is docked yet still relying on one of its auxiliary engines to supply electrical power as needed. In *Standby*, the tug is out on the water but idling as it awaits a call. In *Transit*, the tug is moving between jobs or docks. In

Barge Move, as the name suggests, the tug moves barges, large vessels that don't typically have their own propulsive engines. In *Ship Assist*, the tug helps large ships into and out of port. While these last two operations are similar in that they require significant power, the fact that barges don't propel themselves means that more power is typically needed—hence the distinction.

Tug emissions

In 2010, researchers at the University of California, Riverside College of Engineering-Center for Environmental Research and Technology compared operation and emissions of the conventional tugboat *Alta June* to its hybrid sister tug *Carolyn Dorothy* [16]. Both tugs are dolphin class tugs operated by Foss Maritime Company in the ports of Los Angeles and Long Beach. The operating profile of the Carolyn Dorothy is nearly identical to that of the Alta June, with the most significant difference being in the use of shore power. The hybrid tug spends 18% of its time under shore power with

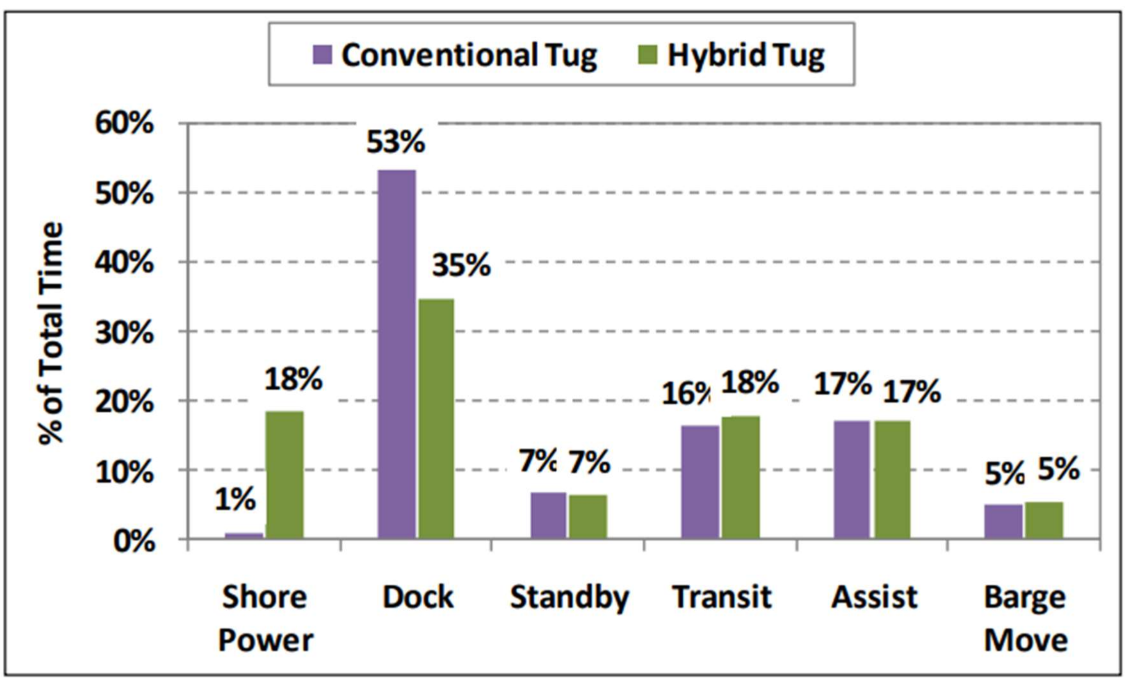

Figure 3, percentage of total time spent in each operation for the conventional Alta June and hybrid Carolyn Dorothy [16] dock operation for 35%. Like the Alta June, the Carolyn Dorothy spends 7% in standby, 17% in assist, and 5% in barge move. The remaining mode, transit, takes up 18% of its time. As with the Alta June, these percentages were pretty consistent during the month long study, fluctuating by just a few percent in each category. The operating profiles of each tug are summarized in Figure 3.

Because of the nearly identical operating profiles of these two tugs (if shore power and dock are considered one category), the comparisons between the tugs' emissions and fuel consumption are straightforward. In particular, the operators reported fuel savings of roughly 25% in the hybrid vessel over the conventional tug over an 8-month span. The researchers were able to confirm the operators' word by showing the reduction in emitted CO2 to be about 26% percent. They further segmented their analysis to include the hybrid tug operating without the use of its batteries. Overall findings are shown in Figure 4 with additional data regarding emitted particulate matter (PM) and nitrous oxide (NOx). Perhaps the most remarkable result is the significant reduction in

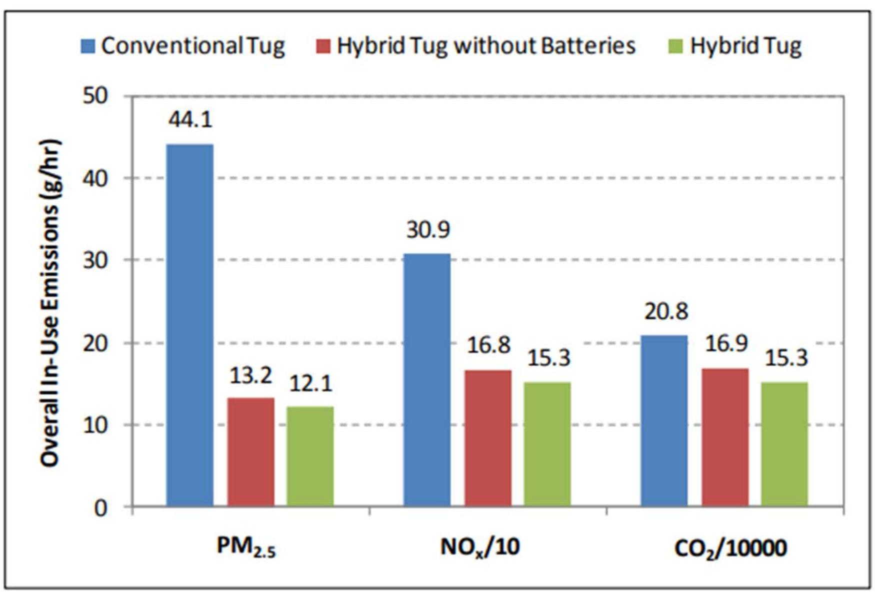

Figure 4, emissions profile of the conventional tug Alta June, the hybrid tug Carolyn Dorothy (without considering its batteries), and the hybrid Carolyn Dorothy (with considering its batteries) comparing the hybrid tug without batteries to the conventional tug. Though the batteries clearly contributed to the reduction in emission and fuel consumption, the hybrid configuration was the most significant reason for the reduction. The overall power plant is smaller in the hybrid tug, but by simply allocating each component of the power plant more appropriately the hybrid tug performs basically identical work to the conventional tug as seen in the operating profiles. The ability to shut down the main engines dramatically reduces emissions and fuel consumption.

The Alta June utilizes two 1902kW CAT 3512C main engines, each mechanically driving one propellor. Since the main engines are the only source of power to the propellors, any time that the vessel is moving or maneuvering, both main engines are required to be operating. Two 195kW John Deere 6081 auxiliary engines serve as generators to electrically power the hotel and equipment. Figure 5 [3] shows a schematic of this configuration, called Diesel Mechanical (DM).

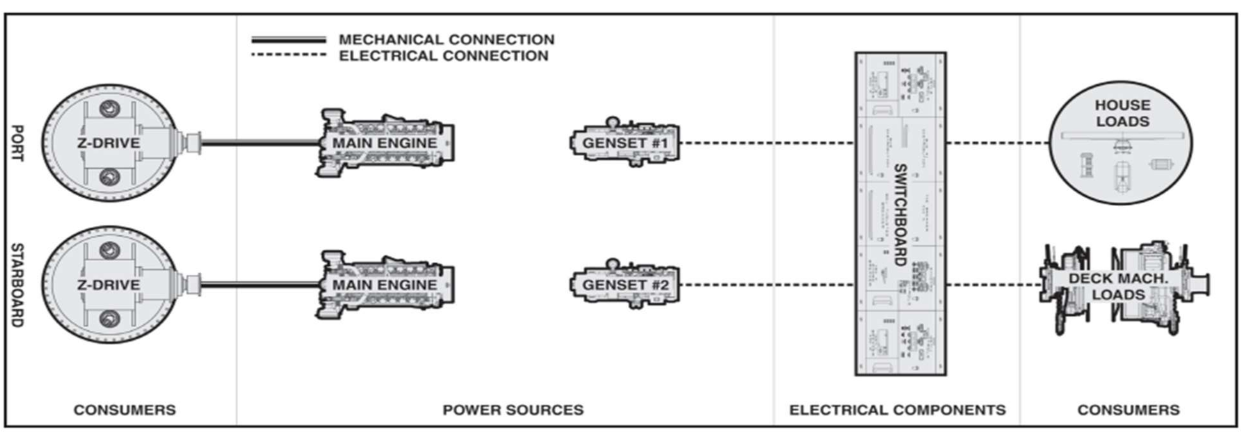

Figure 5, showing a diesel mechanical scheme in which the main engines each directly drive a propellor and the gensets supply electrical power to other components [3]

Table 1, showing under which operational modes each of the conventional tug Alta June's engines are used

Operational Modes	ME #1 CAT 3512	ME #2 CAT 3512	AE #1 JD 6081	AE#2 JD 6081
Shore Power	Off	Off	Off	Off
Dock	Off	Off	On	Off
Standby	On	On	On	Off
Transit	On	On	On	Off
Barge Move	On	On	On	Off
Ship Assist	On	On	On	Off

***ME**: Main Engine, **AE**: Auxiliary Engine*

Table 1 [16], shows the usage of each engine depending on which operating mode is being used. The combined 23% that the Alta June spends in standby and transit is an enormous waste of fuel since the main engines are working at small loads relative to their capabilities. Further, utilizing a generator while docked as opposed to using shore power means relying on diesel fuel for electricity rather than electricity from the grid. On a per kWh basis, diesel fuel is more expensive than grid electricity. As will be shown in the section **Diesel Costs vs. Electricity Costs**, though fuel prices and electricity prices have been increasing over the years, fuel prices have grown more rapidly than electricity prices [17], [18]. Hence, the price difference from running a generator rather than using shore power will continue to widen in the future.

The hybrid Carolyn Dorothy utilizes two 1342kW Cummins QSK50-M main engines, each mechanically driving one propellor as in the Alta June. Electrical power is provided by two 317 kW Cummins QSM11-M generators and two arrays of soft gel lead acid batteries, each storing 170.1kWh of energy at full capacity. Figure 6 [16] shows a schematic of a similar configuration known as Series Diesel Mechanical Electircal

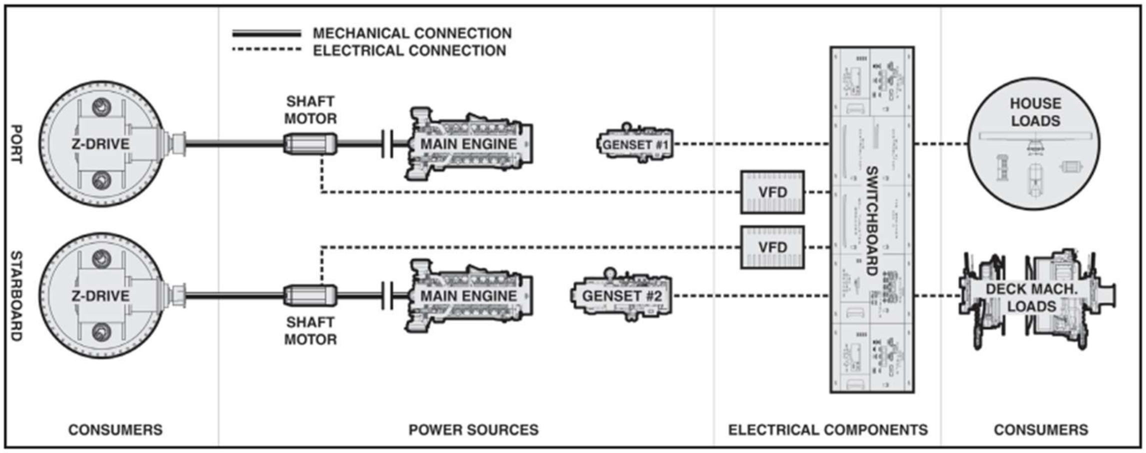

Figure 6, showing a series diesel mechanical electric hybrid scheme in which the main engines each drive a propellor but can be declutched so that electricity from the gensets can power shaft motors to drive the propellors

(SDME). The Carolyn Dorothy would look the same except with the addition of the battery arrays electrically connected to the switchboard.

The key difference that makes the Carolyn Dorothy a hybrid is the use of motor-generators mounted on the shafts between the main engines and propellors. This configuration allows the main engines to be turned off and declutched so that the batteries and auxiliary engines can drive the propellors. Further, since the motor also works as a generator, the batteries can be recharged when the main engines are driving the propellors. Additionally, when the propellor is freewheeling, regenerative power can also charge the batteries. Table 2 [16] shows the usage of each power source depending on which operating mode is being used. Note that this hybrid configuration includes the additional distinction *Fast Transit*—when speeds over 6 knots are required, both auxiliary engines are utilized.

Table 2, showing under which operational modes each of the hybrid tug Carolyn Dorothy's engines and battery are used

Operational Modes	ME #1 Cummins QSK50-M	ME #2 Cummins QSK50-M	AE #1 Cummins QSM11-M	AE#2 Cummins QSM11-M	Battery
Shore Power	Off	Off	Off	Off	Off
Dock	Off	Off	On	Off	On
Standby	Off	Off	On	Off	On
Transit	Off	Off	On	Off	On
Fast Transit	Off	Off	On	On	On
Barge Move	On	On	On	On	On
Ship Assist	On	On	On	On	On

***ME**: Main Engine, **AE**: Auxiliary Engine*

The researchers concluded that the batteries, while contributing in part to the success of the hybrid, were not the defining feature of this configuration. The biggest factor was the ability to turn off the main engines and use the generators for transit. Taking this idea a step further, the ability to turn off all engines can reduce emissions and fuel consumption even more. In the section **lithium-ion batteries**, it will be shown that these batteries will reach a point in their technological advancement when they will outperform generators in terms of weight, size, and cost.

Other Tugboat Power Configurations

As discussed above, a SDME tugboat engine configuration reduces emissions and fuel consumption by utilizing electric motors powered by onboard generators, thus allowing the main engines to be turned off. A natural extension of this configuration would eliminate the mechanical linkage from the large main engines to the propellors, opting instead for large main *generators*. In this configuration, known as Diesel Electric (DE), each generator can be turned on and off as needed so that only the appropriate amount of power is being generated at any given time. It turns out, however, that this setup is not only impractical, but also consumes more fuel than both the DM and SDME configurations. Robert Allan, LTD is a naval architecture and marine engineering company. In order to analyze different power configurations of tugs, the company developed their *RAptures* program (Robert Allan Ltd. Powering Tugs for Real Energy Savings) [3]. In their analysis, they conclude that "the electro-mechanical conversion losses outweigh the efficiency penalty in running the main engines at a lower load level". Essentially, if a tug has large main engines, it is best to shut them off when they are not needed and to use their power mechanically when they are needed.

The analysis by Robert Allan, LTD covers a lot of the same ground as the research by the team at the University of California, though their SDME configuration does not include any battery packs. Their DM configuration utilizes two 2000kW main engines and two 175kW generators. Their SDME setup uses two 2000kW, one 560kW generator, and one 175kW generator. Without batteries, the shaft motors do not need to operate as generators. The DE configuration described above is split into two setups. The Diesel Electric—Running Standby (DERS) configuration utilizes two 2200kW generators, one 560kW generator, and one 175kW generator. No mechanical power is transferred from the generators; instead all propulsion is delivered through two 2000kW motors driving the propellors. The phrase "Running Standby" indicates that when bollard pull is anticipated the large generators will be running, waiting to be used. This option stands in contrast to the other setup, Diesel Electric—Cold Standby. Figure 7 shows the schematic of both diesel electric setups. The phrase "Cold Standby" indicates that generators are only turned on exactly when needed. In other words, if a generator is only producing surplus system power, that generator will be turned off until the exact moment

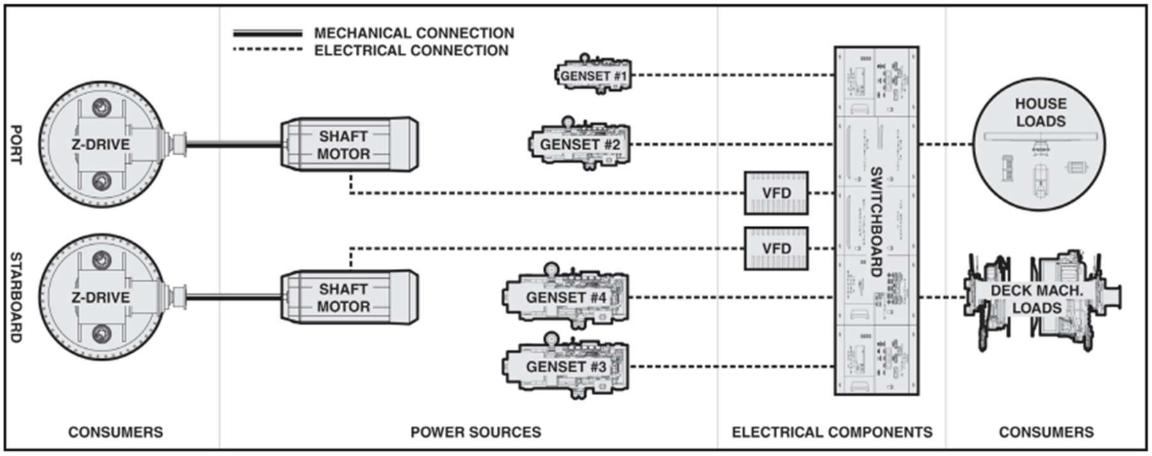

Figure 7, a diesel electric scheme in which all power is electricity produced by gensets that in turn power the shaft motors

it is needed again. The authors note that this configuration is not practical since the responsiveness of turning on and shutting off an engine is not strictly immediate. When piloting any sort of vessel, responsiveness is critical in proper maneuvering. They include this configuration for comparisons sake, explaining that “the comparison gives an indication of the potential savings in fuel, and underscores how batteries can have a beneficial role to play in providing a means to respond to short-term power fluctuation without the need to start up a genset each time”.

Diesel Costs vs. Electricity Costs

Both the cost of diesel fuel and the cost of grid electricity have increased over the last 20 years. But, diesel fuel cost has been increasing more rapidly, and on a per kWh basis grid electricity is becoming cheaper than diesel fuel. Figure 8 shows the ratio of the price of diesel per kWh to the price of electricity per kWh. Note that this graphic assumes 38kWh/gallon of diesel and a 50% efficient engine, which is generous since diesel engines typically don’t achieve such efficiencies. While both diesel and electricity fluctuate in price, after the year 2004 diesel is almost always more expensive than electricity, with the only exceptions occurring occasionally during the summer months.

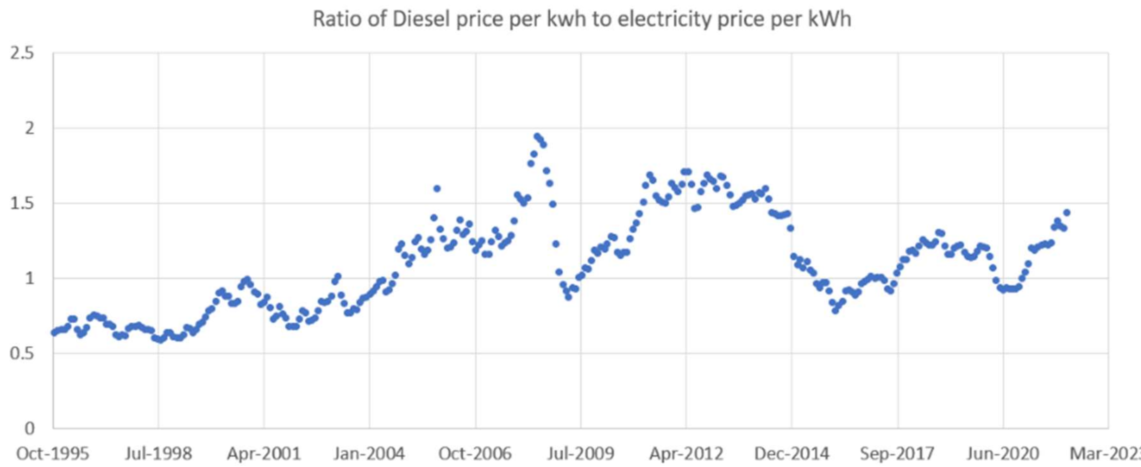

Figure 8, ratio of diesel fuel price per kwh to electricity price per kWh, data from [17], [18]

Lithium-ion batteries

Cost

As noted, electrification of various facets of society is underway, perhaps most notably in the form of electric passenger vehicles. At the core of this change are lithium-ion batteries. The cost of lithium-ion batteries has decreased dramatically over the last

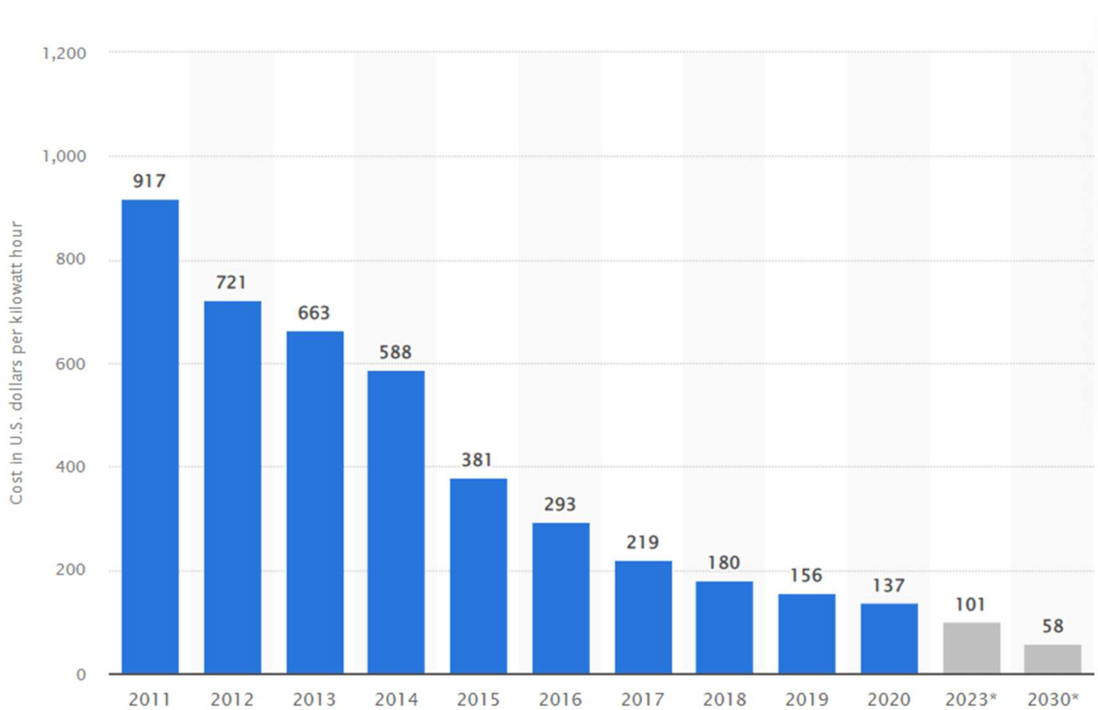

Figure 9, cost per kWh for lithium-ion battery packs from 2011 to 2020 with forecasts for 2023 and 2030 [19] decade, allowing electric vehicles to become more affordable to a greater number of consumers. According to data from Bloomberg [19], lithium-ion battery pack costs have dropped from $917/kWh in 2011 to $137/kWh in 2020. This data is reported in Figure 9 with the additional predictions that lithium-ion battery costs will reach $101/kWh in 2023 and $58/kWh in 2030. Bloomberg's forecast for the year 2030 is in agreement with the US Department of Energy's goal to reach $60/kWh by that time [20].

Energy storage

Not only has the cost of lithium-ion batteries contributed to their widespread adoption, but also the desirable energy storage capabilities have helped them to become perhaps the best performing battery option. Using the Granta EduPack Sustainability database [21], Figure 10 shows the specific energy and energy density of a selection of common battery technologies. Lithium-ion batteries outperform the alternatives in both

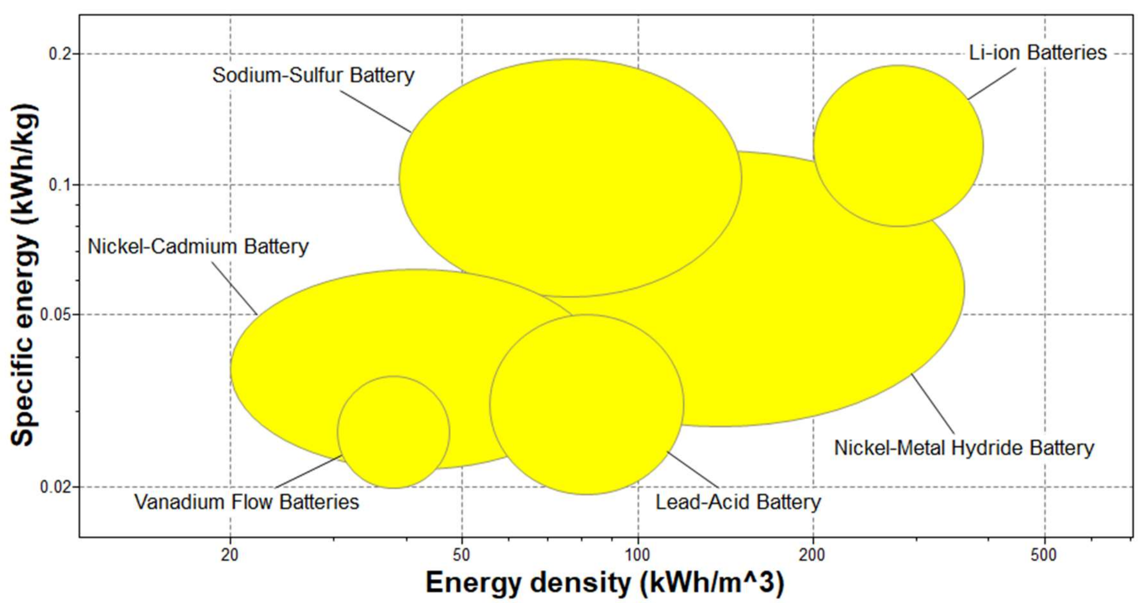

Figure 10, specific energy and energy density of a selection of batteries, Images used courtesy of ANSYS, Inc.

size and weight. Other estimates have the specific energy and energy density even higher. For instance, the Clean Energy Institute at the University of Washington estimates the specific energy of lithium-ion batteries to be 100-265Wh/kg and the energy density to be 250-670kWh/m^3 [22].

By the year 2030, the US Department of Energy has set the goal of reaching 500Wh/kg specific energy for lithium-ion batteries [20]. Noting that the conversion between specific energy and energy density is roughly a 2.5x multiplier from Wh/kg to kWh/m^3, the goal of 500Wh/kg specific energy means an energy density of 1250kWh/m^3. This goal is reasonable given the historical trends of energy density shown in Figure 11 from the US Department of Energy Office of Energy Efficiency & Renewable Energy [23]. This rapid increase indicates exponential growth. Extrapolating to 2030 shows an energy density of over 2500kWh/m^3, which corresponds to a specific energy of 1kWh/kg. While it is always difficult to predict the future of innovations, the

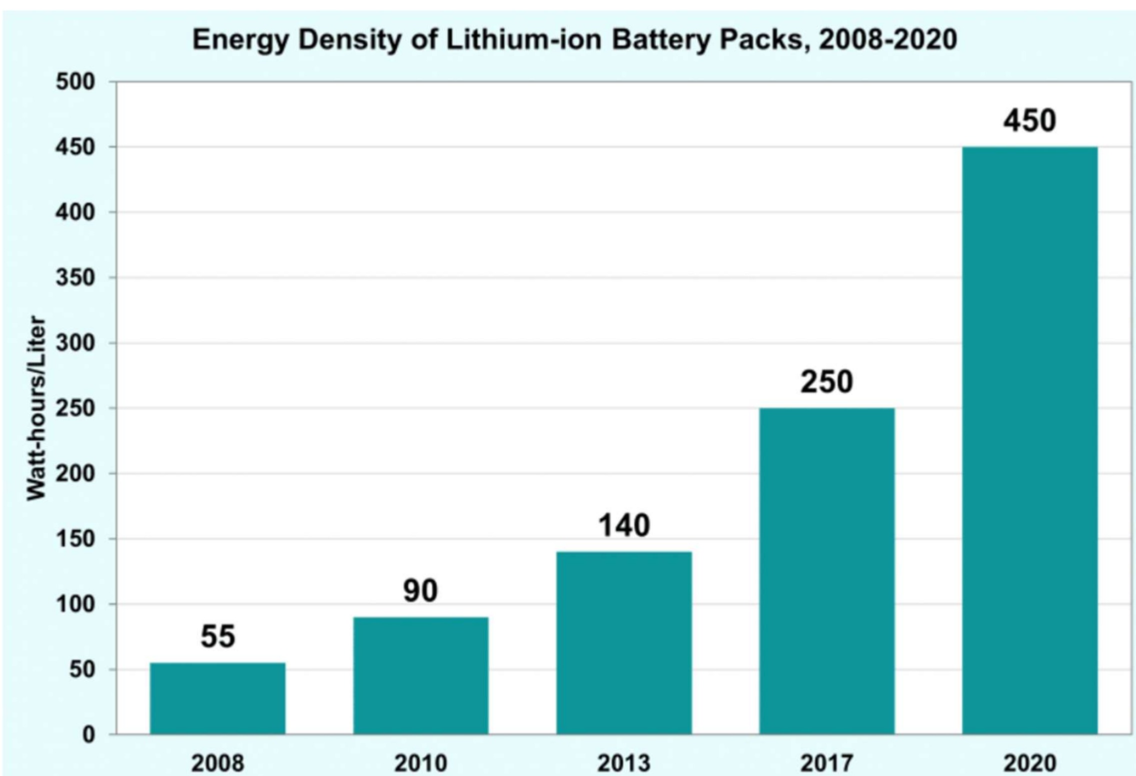

Figure 11, energy density of lithium-ion battery packs from 2008-2020 fact that historical data shows the possibility for such high performance in the future makes the Department of Energy's goals well within reach.

Other benefits

There are a few other noteworthy benefits to lithium-ion batteries over other battery designs. The University of Washington's Clean Energy Institute further supports lithium-ion batteries by noting several more performance benefits [22]. First, the ability of current lithium-ion batteries to deliver up to 3.6 volts allows them to deliver higher current than other batteries, making them more suitable for high-power applications than alternative batteries. Second, lithium-ion batteries are easier to maintain than the alternatives. Many other batteries require a full charge and discharge each cycle lest they degrade to a lower charging capacity. Lithium-ion batteries do not require that sort of care and so can be charged and discharged as needed.

Replacing a genset

A 350kW Kohler genset weighs 3086kg [24]. Assuming an average 50% load[3] at 46.9L/hr fuel consumption for 20 hours (an auxiliary engine runs for about that long on the hybrid Carolyn Dorothy), the genset produces 3500kWh at the expense of 938L of diesel fuel. To realize the same power from a battery, the battery must also be 3500kWh capacity. With the current specific energy of li-ion batteries between 100-265Wh/kg, the 3500kWh battery pack would weigh between 13,000-35,000kg. While this range is up to over 10x more massive than the diesel genset, on the low end its only about 4x more massive. Note also that there would still be two main engines and possibly a generator on

[3] 50% is an overestimate. On the Alta June, a generator operates at constant 10-12% load. On the hybrid Carolyn Dorothy, a generator only exceeds 50% load during transit operation, which is a relatively small proportion of its operating profile.

board, the batteries can easily be recharged from one of the other power sources. In this case, the battery wouldn't necessarily need the capacity to run for 20 hours, and thus the battery may be lighter. Assuming now that the battery only needs the capacity to run half as long at 10 hours on its own[4], the size becomes 1750kWh with a weight between 6500-17,500kg, nearing the weight of the genset it would replace. Further, with the US Department of Energy's goal to reach a specific energy of 500Wh/kg for li-ion batteries by the year 2030, reaching this goal would mean a 1750kWh battery pack will weigh just 3500kg, nearly the same as the genset it would replace. Note also that this disregards the weight of the fuel. The 938L of diesel fuel consumed by the generator weighs about 800kg.

The volume of the above Kohler genset is 4.72m^3. Using the estimated energy density range of 250-670kWh/m^3, the volume of a 1750kWh battery would then fall into the range of 2.6-7m^3, already possibly smaller than the engine it would replace. Using the 2030 goal of 1250kWh/m^3, the 1750kWh battery would take up only 1.4m^3, considerably smaller than the genset it would replace.

A smaller, 200kW version of the above engine is available for a list price of $88,000 on colburnpower.com. While it is difficult to find published pricings for each size of generator, the 350kW generator is certainly more expensive. The exact price, however, does not matter because even if it were free, by the year 2030 a battery will still make more economic sense. Using the US Department of Energy's target cost of $60/kWh for li-ion batteries by 2030 the 1750kWh battery pack would cost $105,000. While this cost is almost 20% higher than for the diesel genset, factoring in fuel costs will

[4] See section **battery capacity**

dramatically change the picture. Assuming the 46.9L/hr fuel consumption as above running for 20hr/day for 360days/yr, the 350kW genset will consume over 337,000 liters of fuel annually, generating 1.3GWh of electricity. At a cost of over $1.342/L, annual fuel costs will exceed $450,000. In the United States, the average cost of electricity is $0.1042/kWh. Li-ion batteries charge at an efficiency of nearly 100%. Even assuming 95% charge efficiency, roughly 1850kWh would be needed to charge the 1750kWh battery for a total cost of $192.77/charge. Charging twice each of the 360 days of operation yields a total cost of about $138,000/year to charge 1.3GWh. After a single year, the battery plus charging will cost $243,000 compared to $538,000 for the genset plus fuel.

Battery capacity

In the above example, the assumption that the battery capacity only needed to be half of the energy output of the genset plus 20 hours of fuel was based in part on using the onboard generator or the main engines to charge the battery. As a hybrid configuration, the example vessel necessarily has motors on the propellor drive shafts. As seen in the Carolyn Dorothy, these motors can also serve as generators. So during the 22% of time (just over 5 hours) that the main engines are on, they can easily serve to recharge the batteries. While the cost calculation in the previous section does not account for this recharging, it shows that there is can be a backup in case the batteries run low on power. Further, the Carolyn Dorothy spends 18% of its time (just over 4 hours) connected to shore power and 35% of its time (just under 8.5 hours) docked. In the case of the Carolyn Dorothy, when the vessel is docked the tug switches between using its batteries and its generator. If the battery charge falls below 60%, the generator will turn on to charge the batteries and power the hotel until the batteries reach 80% charge. Once the batteries reach 80%, the generator turns off and the batteries return to supplying power for the hotel load until their charge falls below 60% and the cycle repeats. With this power management system, the researchers found that 80% of the time at dock and 30% of the time in standby are powered solely by the batteries.

One other big assumption was that the generator operates at 50% load on average. This value was deliberately overestimated so that the required battery capacity would need to be larger. Testing other possibilities as shown in Table 3 still demonstrate that batteries should be the superior choice by 2030. Since fuel consumption is the driving factor of the cost, reduced fuel consumption means the generator cost is reduced. But it also means that the size of the battery replacement is also reduced, so no matter the average load on the generator, the battery replacement will still pay for itself in under a year. Analyzing the case of 25% load, with fuel costs of $278,277 compared to charging

Table 3, calculations of the cost savings using a battery pack to replace a 350kW genset for the year 2030

Battery Replacement for 350kW Generator Assuming Different Average Loads						
Load	Battery Replacement Size (kWh)	Battery Cost	Generator plus Fuel Weight (kg)	Battery Weight (kg)	Generator Volume (m^3)	Battery Volume (m^3)
25%	875	$ 52,500.00	3581	1750	4.72	0.7
50%	1750	$ 105,000.00	3893	3500	4.72	1.4
75%	2625	$ 157,500.00	4245	5250	4.72	2.1
100%	3500	$ 210,000.00	4636	7000	4.72	2.8
Load	Yearly Fuel Usage (L/year)	Yearly Fuel Cost ($/year)	Yearly Battery Charging Cost ($/year)	1 Year Generator plus Fuel Cost ($/year)	1 Year Battery plus Charging Cost ($/year)	1 Year Savings with Battery ($/year)
25%	207360	$ 278,277.12	$ 69,101.05	$ 366,277.12	$ 121,601.05	$ 244,676.07
50%	337680	$ 453,166.56	$ 138,202.11	$ 541,166.56	$ 243,202.11	$ 297,964.45
75%	485280	$ 651,245.76	$ 207,303.16	$ 739,245.76	$ 364,803.16	$ 374,442.60
100%	648720	$ 870,582.24	$ 276,404.21	$ 958,582.24	$ 486,404.21	$ 472,178.03

costs of $69,101, the expected payback time of the 875kWh battery with price $52,500 is just 3 months. With the rapid payback time, any qualms about a battery being slightly more expensive than a genset should be abated, especially since this calculation does not even consider the price of the genset.

The future of Li-ion

If the goals for Li-ion batteries in the year 2030 set by the US Department of Energy are reached, then the analysis shows how significant replacing just a single genset with a battery pack can be. According to Warner [25], the capabilities of lithium-ion batteries depend on the specific chemistries of the battery. Prasanth notes that reaching the goals "will require innovations both in the component materials used in the cell and in the engineering involved in fabricating the cell [26]." The author further notes that most of the incremental improvements over the last 30 years have largely been engineering accomplishments, with components and operation generally remaining the same. The battery consists of several necessary components, each of which could be the focus of improvement. The anode (typically the negative battery terminal) and cathode (positive) are where the chemical reactions take place, and hence where the lithium-ions live. The lithium containing compounds are deposited onto a substrate. When the compounds are on the substrate, the resulting component is called an electrode. The electrodes are kept electrically apart by a separator, and an electrolyte is added. The electrolyte allows the lithium ions to pass back and forth from anode to cathode. The entire apparatus is contained in an appropriate enclosure—altogether the device is called a cell [25].

Of these components, the Prasanth suggests that the cathode is the main contributor to possible improvements to battery energy density [26]. The energy density is a function of the battery's capacity and potential. Prasanth suggests that doubling the capacity of the positive electrode can improve cell energy density by 57%, while similar improvements would require over 10 times a capacity increase in the anode. As such, research is currently investigating cathode materials that are more oxidizing (and hence produce greater potential) and materials that can more effectively move electrons (and hence yield larger capacity). Researchers have especially been investigated layered materials, such as the manganese-based layered cathode materials via molybdenum surface modification worked on by Shao [27]. The lithium-rich manganese-based materials have been promising for high capacity but have shown poor cycling. The molybdenum surface modification helps to solve this issue.

Surface modifications have been suggested for a few years, such as in *Future Lithium-ion Batteries* by Ali Eftekhari [28] in 2019. Eftekhari classifies the cathode materials as either lithium-rich or nickel-rich. Cathode materials have their own set of performance parameters such as irreversibility, oxygen loss, energy density, and voltage drop during cycling. Between the two classifications of cathodes, the nickel-rich materials (180-230 mAh/g) have lower discharge capacity than lithium-rich (250-300 mAh/g) but tend to outperform lithium-rich in the other performance parameters. Eftekhari suspects that the nickel-rich cathodes will play a role in the improvements to lithium-ion batteries in the coming years. Unfortunately, this prediction goes against the US Department of Energy's goal to "Develop cobalt- and nickel-free cathode materials and electrode compositions that improve important metrics such as energy density, electrochemical stability, safety, and cost and outperform their current commercial, imported counterparts" [20].

Table 4, a selection of layered cathode materials and some performance parameters

Material	Doping method	Cycling voltage (V)	Initial discharge capacity (mAh g^{-1})	Capacity retention (%)	Cycles	C-rate
$LiNi_{0.6}Mn_{0.2}Co_{0.15}Al_{0.05}O_2$	Coprecipitation	2.5–4.3	145	80	140	1
$LiNi_{0.6}Mn_{0.2}Co_{0.15}Sn_{0.05}O_2$	Coprecipitation	2.5–4.3	160	80	155	1
$LiNi_{0.6}Mn_{0.2}Co_{0.15}Fe_{0.05}O_2$	Coprecipitation	2.5–4.3	156	80	148	1
$LiGa_{0.05}Co_{0.95}O_2$	High pressure	3.0–4.7	215		1	0.02
$LiGa_{0.1}Co_{0.9}O_2$	High pressure	3.0–5.0	197		1	0.02
$LiGa_{0.25}Co_{0.75}O_2$	High pressure	3.0–5.1	132		1	0.02
$Li(Ni_{0.5}Co_{0.2}Mn_{0.3})_{0.99}Mo_{0.01}O_2$	Hydrothermal	2.5–4.5	154	97	50	8
0.01%Al–$LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$		3.0–4.3	168		50	0.07
$Li_{1.2}Ni_{0.13}Co_{0.13}{-}xMn_{0.54}AlxO_{2(1}{-}y_{)}F_2y$	Coprecipitation	3.0–4.5	250	88.2	150	0.5
$LiAlyCo_1{-}yO_2$ ($y = 0{-}0.5$)	Coprecipitation	2.0–4.4	182	61	9	0.125
$LiCo_1{-}xFexO_2$ ($x = 0.2$)	Solid reaction	3.0–4.4	164	43	2	0.025
$LiCo_{0.995}Fe_{0.005}O_2$	Re-anneal	3.2–4.3	143	87	50	0.1
$Li_{1.2}Ni_{0.13}Co_{0.13}Mn_{0.44}Cr_{0.1}O_2$	Sol–gel	2.0–4.8	224	93.7	50	0.1
$Li_{1.2}Ni_{0.13}Co_{0.13}Mn_{0.49}Fe_{0.05}O_2$	Sol–gel	2.0–4.8	230	90.4	50	0.1
$Li_{1.2}Ni_{0.13}Co_{0.23}Mn_{0.44}O_2$	Sol–gel	2.0–4.8	248	88.8	50	0.1
$LiCr_{0.1}Ni_{0.9}O_2$	Sol–gel	3.0–4.5	185	95.1	50	0.5
$LiCr_{0.2}Ni_{0.8}O_2$	Sol–gel	3.0–4.5	155	90.3	50	0.5
$LiNi_{0.6}Mn_{0.2}Co_{0.15}Al_{0.025}Fe_{0.025}O_2$	Self-combustion	2.5–4.4	189	89.9	10	0.05
$Li_{1.08}Ni_{0.92}O_{1.9}F_{0.1}$	Solid reaction	3.0–4.3	200	63	100	1
$Li(Ni_{0.5}Co_{0.2}Mn_{0.3})_{0.97}V_{0.03}O_2$	Solid reaction	2.7–4.4	170.5	88.5	50	1
$LiNi_{0.59}Co_{0.2}Mn_{0.2}Mg_{0.01}O_2$	Coprecipitation	2.8–4.3	177.1	90.0	100	1
		2.8–4.5	179.7	87.7	100	1
$Li_{1.19}Ca_{0.005}Ni_{0.13}Co_{0.13}Mn_{0.54}O_2$	Sol–gel	2.0–4.8	273	82.5	100	0.2

Table 4 shows a vast selection of different layered cathode materials and some performance parameters [28]. While this list is not exhaustive of every single cathode, it is still noteworthy that each of these options contains nickel, cobalt, or both. Further, the author notes that innovation in cathode materials has been happening. But as certain characteristics are reached, other components need to keep up with the innovation. Specifically, these cathode materials have begun reaching higher voltages along with higher capacities.

The next piece of the puzzle then is to ensure that the electrolyte material can handle the higher voltages. Otherwise the entirety of the elevated capacity cannot be achieved. For as much work is being done to develop better cathodes, electrolytes are similarly receiving a lot of attention. Sashmitha and Rani note that solid polymer electrolytes might be the most effective thanks to “high safety, no leakage, wide electrochemical stability window, mechanical flexibility, and thermal stability” [29].

Solid polymer electrolytic material has the advantage of eliminating the separator as the polymer serves as both electrolyte and separator. Within the topic of polymer electrolytes, different polymers are investigated as well as the various lithium salts used, inorganic fillers, and solvents.

More specifically, researchers have shown particular attention to the cathode material LiNi0.8Co0.1Mn0.1O2 (NCM811) thanks to high discharge specific capacity. The downside to NCM811 is poor cycling and rate capacity. Wan and Chen experimented with a dithiol-based electrolyte additive to improve the performance of NCM811 [30]. Their promising results have shown a discharge capacity retention rate of 75.59% after 200 cycles compared to just 15.11% without the additive. Yang et al. have proposed their own additive, 3-(Trifluoromethyl)benzoylacetonitrile [31]. Their findings show a more stable cathode-electrolyte interface which helps improve cycling as well as better thermal performance, thereby acting as a better flame retardant. Further, Zhang et al. have tried adding ethoxy(pentafluoro) cyclotriphosphazene with lithium difluoro(oxalate)borate [32]. Their experiments show capacity retention up to 84.2% after 100 cycles.

Conclusion

This document is an active document for planning for Logan Clutch Corporation sales strategies. Diesel-electric hybrid tugboats are already effective in dramatically reducing fuel consumption by roughly 25% and harmful emissions by even more. A clutch is a critical component to accomplish the hybrid configuration since the main engines must be disengaged from the driveline. While operators have not yet fully embraced hybrid tug designs, the advent of lithium-ion batteries with low cost and high energy density will yield even more significant reductions in fuel consumption. The uncertainty in diesel costs furthers the benefit of switching to batteries for some portion of a tugs power plant. Because of the trajectory of lithium-ion battery technology and the already significant fuel savings of hybrid tugs over conventional tugs, Logan Clutch should ensure their clutches and FlexaDrive gearbox are capable of handling hybrid applications. Providing reliability that operators expect will allow Logan Clutch to capitalize on the impending switch to hybrid tugs. By leveraging existing sales channels both at home and abroad, particularly in Indonesia, Logan Clutch can strengthen its position in the marine industry.

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