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## **ENERGY STORAGE ANALYSIS TO INCREASE LARGE SHIP FUEL EFFICIENCY**

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### **ABSTRACT**

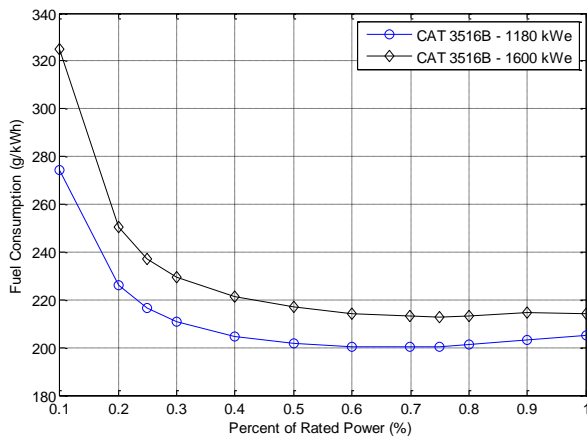
The marine transportation industry is a significant contributor to global emissions of CO<sup>2</sup> and other pollutants. Although marine emission standards have become increasingly stringent, increasing fuel efficiency remains the primary objective in terms of further reducing emissions and overall marine energy use. In this paper, a hybrid powertrain is investigated as a means of increasing fuel efficiency for a modern, 100 m class, passenger vessel. The hybrid powertrain includes an Energy Storage System (ESS) based on sodium sulfur (NaS) batteries and commercially available Caterpillar diesel engine-generator sets. The ship's power load profile is based on annual averages for similar vessels. A control strategy and simulation models are developed and implemented in Simulink to analyze the power and energy flows in the hybrid powertrain. The Simulink model is used to compare the base scenario of a ship without energy storage to a hybrid scenario employing a 7.5 MWh NaS battery pack with related control strategy. Annual fuel consumption is the primary measure that is used to assess efficiency. Unlike hybrid powertrains for light-duty surface vehicle transportation, which achieve efficiency gains on the order of 10-20% [8, 9, 10], the hybrid powertrain for a large ship is estimated to lower annual fuel consumption by approximately 2%. The surprisingly small level of fuel savings is explained largely by the granularity of marine power systems, which include multiple generators that can be switched on and off to maximize fuel efficiency.

### **INTRODUCTION**

With fuel costs rising and environmental concerns growing, every facet of the manner by which we consume energy in our society has been the target of increasing scrutiny. Land transportation systems are the current focus of most research efforts, but over 90% of the world's freight is transported by ship, a segment of the marine industry that consumes around a half billion tons of fuel each year alone [3]. These concerns are compounded by the fact that grades of marine diesel fuel have 30-100 times more sulfur content compared to land-use diesel fuels. In addition, an estimated 645 mega-tonnes per year of CO<sup>2</sup> is emitted from all marine vessels, as well as other pollutants such as nitrous-oxides (NO<sub>x</sub>) and particulate-matter (PM) [4].

Large (~100 m) scale passenger ships operate under propulsion loads averaging multiple megawatts, and thus, must use combinations of multiple diesel generator sets (gensets). A genset is comprised of a diesel engine (e.g., here, a 1600kW, V-16, 4-stroke diesel) with the output shaft fixed to the input of an electric generator. The generator then provides the necessary power directly to the electric propulsion motors and ship hotel loads. According to the necessary load profile, several gensets may be combined to provide the total power in order to meet the ship's load. Thus, it is required that each generator operate at the same voltage and frequency, which, in turn, demands that the diesel engines operate at a constant rotational velocity, and that each one operates at the same load percentage; meaning the ratio of current load to maximum load for each machine must be the same. The granularity resulting from combining multiple gensets with different power ratings allows a great

deal of control over generators' operating set points (% of full load), as total capacity can be manipulated by selecting which machines to operate for a specific load. This granularity places a great deal of importance on optimization in the genset selection process. In this paper, the gensets consist of 4 Caterpillar units, all operating at 50 Hz, 1500 rpm, and 400 Volts: 2 Marine 3516B gensets rated at 1250 kW (1180 kWe) and 2 Marine 3516B gensets rated at 1660 kW (1600 kWe). Detailed operational data for each of these two units were obtained from the manufacturer [3 and 4]. The most pertinent information used in this paper is the fuel consumption data for both of these generator sets, which are illustrated in Figure 1.



**Figure 1. Fuel consumption data for Caterpillar marine diesel engine generator sets (at 50 Hz, 1500 rpm, 400 Volts) indicates there are preferred regions of power operation for lower consumption. [3 and 4]**

The intent of this report is to outline the potential for fuel savings by supplementing the suggested gensets with an energy storage system, namely, a sodium-sulfur (NaS) battery pack. Sodium-sulfur is a relatively new battery technology selected for its efficiency, energy density, ability to sustain charge without losses and other qualities for utility-scale energy storage systems [1]. This report will provide a comparison of power and energy flows, fuel consumption rates, and other details associated with the base scenario (the selected 4 gensets operating without battery assistance) and a “hybrid” configuration (with battery assistance).

### THE BASE SCENARIO

The base scenario is the selected genset configuration (two 3516B gensets rated at 1180 kWe and two 3516B gensets rated at 1600 kWe) meeting all ship power demands. The ship's duty cycle consists of 9 modes of varying duration and varying power demand, of which the details can be seen in Table 1. The indicated time distributions were applied on a monthly basis, such that each mode was visited for the indicated percent of time in a month, and that duty cycle was repeated 12 times. This duty cycle is a summary of the annual averages resulting from operation a specific vessel and is used for all simulations throughout the report. It should be noted that a load profile

was assumed for a vessel that performed multiple tasks. This type of an assumption was needed to quantify the effect of the storage technology. The analysis approach is general, but different load profiles and different storage technologies are expected to lead to different quantitative results.

For the power required by each mode, several alternatives exist with respect to genset combination selection. As long as a given configuration has the capacity to provide at least the necessary power, it is a viable option. However, Figure 1 shows that certain load percentages will provide much higher efficiency, indicated on the graph as a lower number of grams of fuel that are consumed for each kilowatt-hour (g/kWh) demanded. Thus, for the base scenario, an optimization routine was run for each mode, comparing the resulting fuel consumption for each potential combination, and selecting the minimum. The results of this optimization are shown in Table 2. Here, we have indicated the percent load for each of the gensets in the selected configuration, as well as the total fuel used for that mode. The modes vary for different operational needs such as in-port, cruising, full-speed, mapping, etc. The fuel consumption rate is included as an indication of efficiency for a given mode. This rate, multiplied by the total time spent in each mode, yields the fuel consumed in that mode over the course of a year. Summing this column yields the total annual fuel consumption for the assumed power requirements and load profile. The total is 5195.2 m<sup>3</sup>/yr, where m<sup>3</sup> is the volume of diesel fuel in cubic meters.

**Table 1. The ship load duty cycle is based on averages from yearly operation and indicates modes requiring high power or long duration.**

Mode	Power Requirement (kW)	Average Percent of Annual Time (%)
1	365.4	10
2	705.7	10
3	1765.0	1
4	5207.6	4
5	3107.6	25
6	2086.4	5
7	2743.4	5
8	3147.0	15
9	2373.0	25

**Table 2. Performance results for base scenario illustrating modes of operation at high fuel rates and high consumption.**

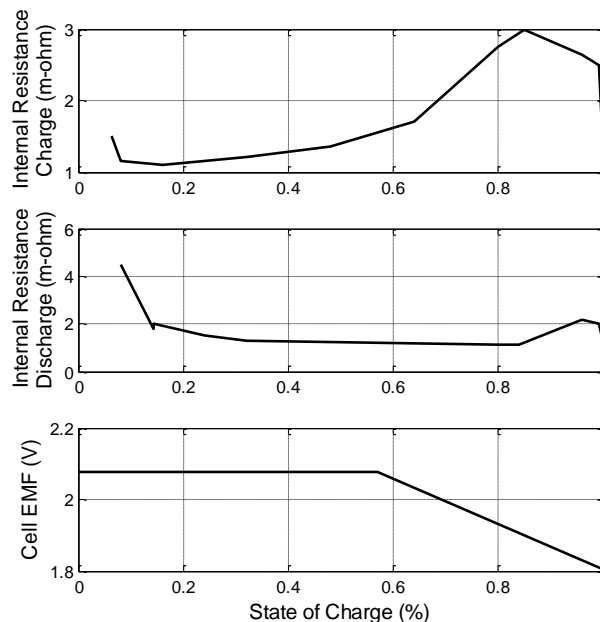
Mode	Fuel Rate (m <sup>3</sup> /hr)	Time In Mode (hours)	Total Fuel Used (m <sup>3</sup> )	Genset % Full Load	GenSet Sizing (genset kW rating)
1	0.0915	876	80.2	31%	1×1180
2	0.1683	876	147.4	60%	1×1180
3	0.4216	87.6	36.9	75%	2×1180
4	1.3025	350.4	456.4	94%	2×1180 + 2×1600
5	0.7622	2190	1669.3	79%	2×1180 + 1×1600
6	0.5045	438	221.0	88%	2×1180
7	0.6716	438	294.2	69%	2×1180 + 1×1600
8	0.7722	1314	1014.7	80%	2×1180 + 1×1600
9	0.5822	2190	1275.1	60%	2×1180 + 1×1600

One initial conclusion from these data is that the optimization routine results in operation of configurations utilizing the 1180 kWe gensets (furthermore referred to as kW, as this report focuses on electric power conversions) whenever possible. It can be seen in Figure 1 that for any load percent, the 1180 kW unit consumes between 10 and 20 g/kWh less than the 1600 unit.

### THE SODIUM SULFUR BATTERY PACK

The battery used for the energy storage ship model is a combination of twenty 52 kW modules (Type G50) similar to those developed by Tokyo Electric Power Company (TEPCO) and NGK Insulators, Ltd. Each of these modules is comprised of 320 cells in series. The effective internal resistance and electromotive force (EMF) generated by each cell is dependent on its State-of-Charge (SOC), and these relations can be seen in Figure 2. The internal resistance of the cell is dependent on whether the battery is charging or discharging, as indicated. These NaS modules are individually enclosed, and their operating temperature is assumed to be regulated at a constant 320°C. Module specifications were used for power and capacity ratings to allow compensation for any effect this active heating would have on system performance. Thus, 20 modules were combined in parallel, each rated at 52 kW and 375 kWh, yielding a 1042 kW battery pack with 7,500 kWh of stored energy operating around 640V. For comparison purposes, this

system would occupy approximately 47m<sup>3</sup> of space and weigh 70 tonnes, although this weight does not affect system performance as it is designed to be included in the required ship ballast [2 and 7].



**Figure 2. The internal resistance for charging and discharging and electromotive force vary as a function of the state-of-charge for a NaS Cell at 320°C (2)**

This analysis does not account for any effects that may result from the rise in internal resistance that occurs as a result of cell-deterioration from cycling. Test data indicates that these values may rise just over 0.1 m-ohms after the first 100 full charge-discharge cycles, whereas the focus here is on fuel savings comparisons for a single year which comprises the equivalent of approximately 20 battery charge-discharge cycles. By comparing to Figure 2, it can be seen that even such a small rise is negligible. These data are important from a life cycle analysis perspective. Until comparisons and analysis are extended significantly beyond the scope of a single year, however, cell deterioration has insignificant impact on performance or results. Additionally, all battery power must be transferred through power electronics whether being charged from the gensets or discharged to the propulsion system and ship distribution boards. A net 5% one-way loss is assumed for these conversions.

### BATTERY AND GENERATOR SET CONTROLLER

The system controller necessarily orchestrates both genset loading and battery load simultaneously. With a battery sized to 1042 kW (almost the scale of an 1180 kW genset) we have the capacity to manipulate operation to a large extent. Optimization of the base scenario shows us that operation with the 1180 kW genset is preferable. Beyond that, we begin by utilizing the optimum genset load percent. The data contained

in Figure 1 show that peak efficiency is achieved at 76% load, which is our target load for control purposes. To take advantage of this target, we initially divide the given duty cycle load by 0.76. The result is the *ideal* genset capacity to supply the power the ship requires. For example, we can arrange all potential combinations of those 4 gensets in order of increasing power capability. In that case, a number could be assigned corresponding to each configuration, from 0 to 7, as in Table 3. Rounding the ideal genset capacity (the duty cycle load divided by 0.76) to the capacity of the closest genset combination gives us an initial configuration suggestion.

**Table 3. Listing of potential combinations of 2x1180kW and 2x1600kW Caterpillar gensets and granularity of total power capability listed in increasing total power output.**

Configuration No.	1180 (1)	1180 (2)	1600 (1)	1600 (2)	Total Power Available (kW)
0	0	0	0	0	0
1	1	0	0	0	1180
2	0	0	1	0	1600
3	1	1	0	0	2360
4	1	0	1	0	2780
5	0	0	1	1	3200
6	1	1	1	0	3960
7	1	0	1	1	4380
8	1	1	1	1	5560

For this model, the system communicates both the required load and the initial genset configuration into the battery controller. The battery controller has three modes based on SOC value, each with two modes within it. There is a low-SOC, charge-only mode, defined by a lowest allowable SOC value; a mid-range of SOC defined by a mid-SOC value that is effectively our target SOC; and a high-SOC mode defined by a SOC that is above either of those limits. To avoid any extremely inefficient genset usage we must also define a lower limit to the allowable percent load that the gensets can see. The controller must then determine which configuration to use, along with the load percentage on the gensets and the battery load.

This rule-based strategy is embedded in a controller as script Matlab code, represented as pseudo-code in Figure 3. In the first range, the “SOC<lowest limit” indicates that we have reached the lower limit of battery operation. In this mode we do not want our SOC to drop any further and only allow it to

charge. The limits indicated in Figure 3 are variables to be tuned for optimal operation. If the genset load percent is less than the target (76%) we can use the battery as a load to charge it and raise the genset load percent to a more efficient region. Thus, by combining battery charge and discharge operations, we can keep the batteries and gensets operating in their window of highest efficiency. If we are already operating above ideal efficiency, we turn the battery off and wait for a better time to charge it.

**SOC < lowest limit**  
 If: load percent < target load  
     Charge battery with remaining capacity, raising load percent to target  
 Otherwise: Use genset to match load, battery off

**SOC < middle limit**  
 If: load percent < lowest allowable load  
     Use genset to match load, battery off  
 Otherwise: Run genset at target load and battery charges or discharges to follow load demand

**SOC > limits**  
 If: load percent < lowest allowable load  
     Turn genset off, use battery to provide load  
 Otherwise: Run genset at target load and battery charges or discharges to follow load demand

**Figure 3. Illustration of the rule-based control strategy that was used such that the battery maintains constant, peak efficiency from the gensets.**

The middle range is defined by what can be considered our target SOC. Above this value is the range where we have enough charge built up in the battery to operate as we like to ensure maximum efficiency. Below it, we have substantial SOC, but would like to favor charging. In this range we initially evaluate whether we are below the acceptable range of genset load percent operation. In this case, we define the battery load to be 0, and force the genset to handle the load. Desired operation of this nature is not initially obvious, but if possible, it accomplishes two things: it establishes the defined limit for this range as the target SOC, and prevents the battery controller from aggressively switching between charging and discharging on the target SOC line. This benefit will be clarified once the functionality of the upper bound is defined. In all other cases, the controller operates the selected genset configuration at 76% and the battery follows the load as necessary around that value, effectively as a load leveling device.

The last range is for all SOC values above the selected target. Here we want to take advantage of our available SOC to ensure absolute minimal fuel consumption. In the same case as before where the load percent is less than the minimum allowable, we will always discharge the battery such that the gensets can be turned off. This rule is effective in creating our desired tendency to discharge back to the target SOC for this

region. Again, our “otherwise” operation is defined as: run the genset that was selected as being closest to 0.76 at that target load percent and use the battery to adjust to follow the load.

What we have effectively done is defined that we want to choose the most appropriate genset combination, have it run at 76% (which is variable) and have the battery follow the difference between that and the actual load. By intentional coincidence, this sets up a neutral operation for the battery as far as an even amount of charging and discharging. The lower power modes where the gensets are running inefficiently can then be used to disrupt that balance depending on what the current SOC is. When SOC is high, we use the battery to cover the load, when SOC is low we use the gensets to match the load and increase this load to a more efficient region by charging the battery and in between we remain somewhat neutral. If the middle battery mode is set to discharge in this case, the SOC will typically rest and fluctuate around the lower limit. If it is set to charge, the SOC will rise to the target, then immediately discharge to below the limit, then charge back up, etc at a rate of around +/- 800kW.

This control strategy is logistically very simple. But the real performance factors are the limits and initial condition set, including: initial SOC, target genset load percentage, lower SOC limit, target/mid SOC limit and minimal acceptable genset load percent. Moving the range of SOC operation around in the spectrum does not have as obvious an impact as one would hope. Internal resistances and cell EMF depend directly on these values and greatly affect operation, fuel consumption and most importantly the rate at which the power demand will

affect SOC. Lower SOC’s have generally smaller internal resistance values and operation at high SOC has a drop-off in EMF, seemingly indicating the most efficient region. However, a lower EMF means the current used is greater to meet the power demand, which causes a more rapid change in the battery SOC within those limits, meaning varying rates of transition between the battery operating modes at different times. Additionally, losses due to internal resistance are very small, particularly compared to power electronics losses. The interplay of all of these factors is dictated by the selected limits of operation, especially the target SOC. Thus, various values for these limits were tested, with the best performing results for the specific control strategy reported, as well as the sensitivity of those results in a later section.

### SIMULATION

In order to clearly depict and perceive battery functionality and compare fuel consumption, we will use the same duty cycle shown in Table 1, where yearly load averages are projected onto each month, and that is repeated for each month, yielding the duty cycle shown at the top of Figure 4. The second and third plots illustrate the correlation between energy storage system function and load variation, as well as verifying that we have a control strategy operating in a balanced, charge sustaining manner, such that each month is an identical repetition. Thus, we may focus in on one month for clarity of comparison purposes.

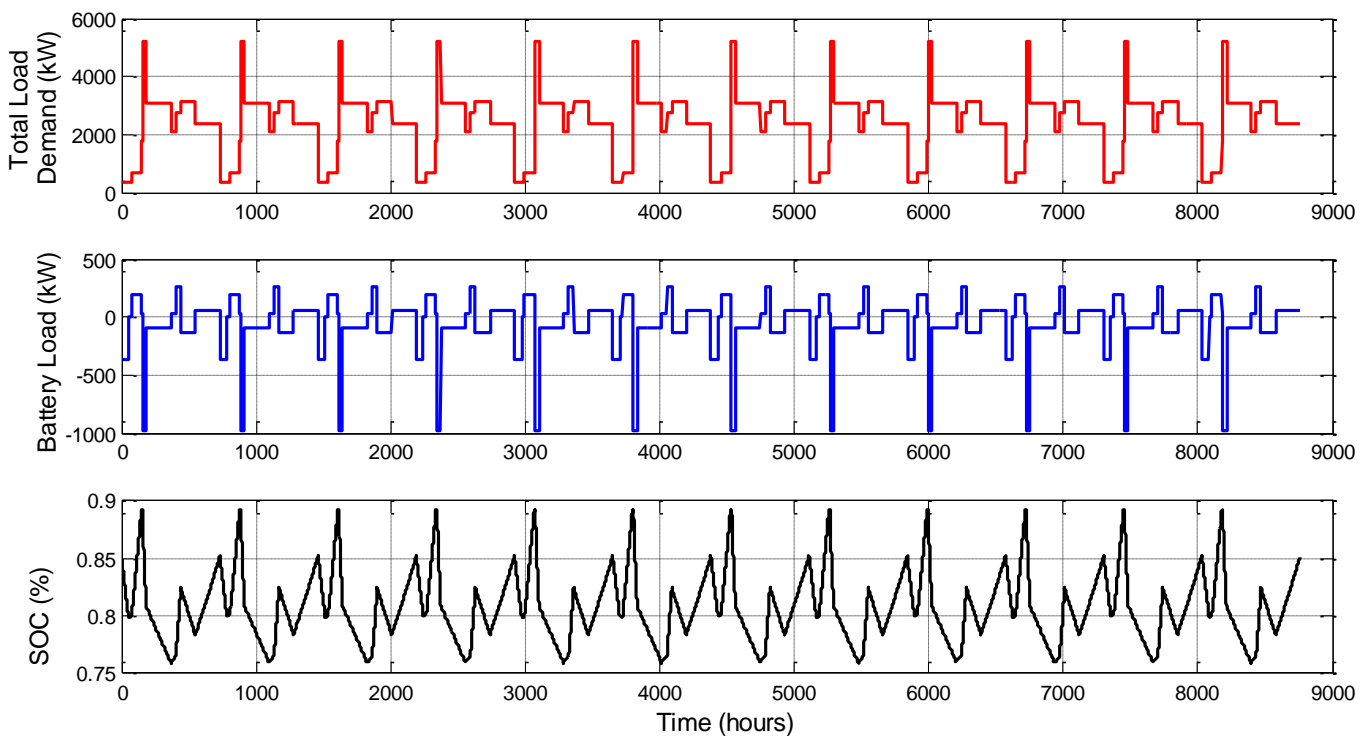


Figure 4. Total ship load, battery load and state-of-charge variation for year-long simulation of the hybrid system model demonstrates steady, cyclic operation.

Figure 4 illustrates the primary operational parameters of concern for a year-long simulation of the hybrid model. This configuration, implementing the described battery model and operated as outlined in the control strategy definition in Figure 3, yields an annual fuel consumption of 5102 m<sup>3</sup>/yr, which is a 2% savings over the base scenario of 5195 m<sup>3</sup>/yr. This result is indicative of the best attainable performance for that specific control strategy. For the explicit set and order of rules defining a control strategy of the format used here, only select combinations of control variables (SOC limits, targets, etc.) will yield charge sustaining operation. The best performing scenario indicated here (5102 m<sup>3</sup>/yr) represents the lowest fuel consumption of all control variable combinations that create a charge sustaining control strategy. A complete list of the variable control parameters and the combination used in the best performing scenario is shown in Table 4. This control strategy demonstrates successful, balanced operation in that SOC does not approach and settle on 1 for any period of time, nor does it approach and settle on the Lower SOC Limit of 0.4. These requirements, their relation to control variable selection and coordination with the control strategy rules are further discussed in the Control Sensitivity section. Here, the simulation will be further explored to more clearly illustrate control strategy operation using a comparison to the base scenario.

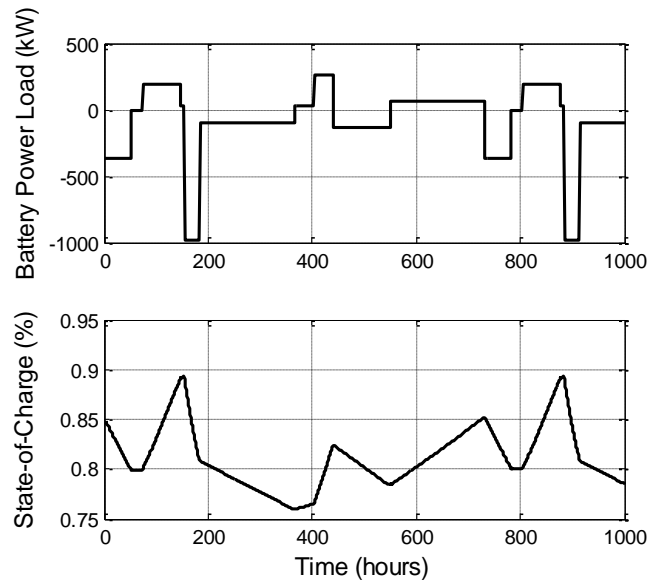
**Table 4. Values for control strategy variables yielding the most efficient charge-sustaining operation.**

Operational Parameter	Value (%)
Initial SOC	0.85
Target Genset Load	0.76
Lower SOC Limit	0.4
Target/Mid SOC Limit	0.8
Minimum Genset Load	0.4

Taking the first 1,000 hours of this simulation shows a little over one cycle (the first cycle ends at 730 hours), as in Figure 5, which shows the battery load and SOC variation for that period. A positive battery load indicates that it is charging. At around 50 hours we can see the SOC settle on our target value of 0.8. The fact that the battery then turns off is what “centers” the SOC fluctuation as the battery is discharging up to that point, then rests until load demands change, as it does with each cycle.

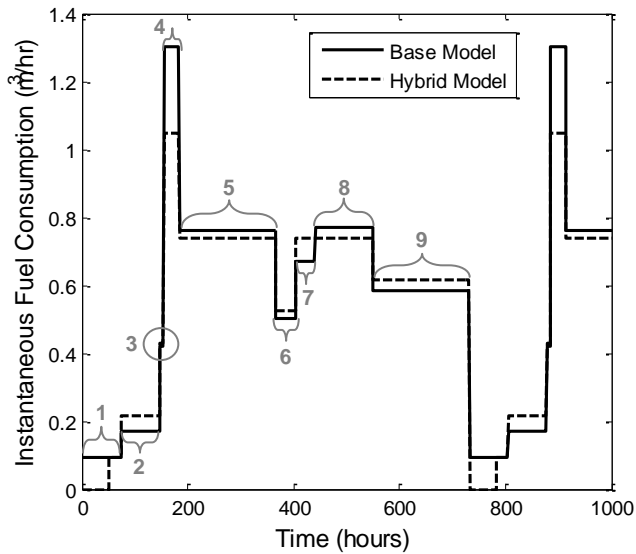
The load that the gensets see determines their rate of fuel consumption. Referring to Figure 1, we can see that the fuel consumption units are g/kWh, expressed as a function of load (kW). Thus, for a given load and a given genset there is a specific g/hr, or m<sup>3</sup>/hr. The way the energy storage system

works is to increase this rate when it yields more power per unit fuel and store it, or else decrease the total load on the generator sets, thereby decreasing consumption. Figure 6 illustrates the instantaneous fuel consumption for both the base model and this hybrid model, superimposed on each other. This overlay most clearly demonstrates the impact of load variation through battery use on fuel consumption. There are several instances where base fuel consumption exceeds that of the hybrid model and vice versa. However, the most significant change is when the hybrid powertrain consumes less fuel in modes 1 and modes 4; these are the first mode of the cycle where hybrid consumption is zero, and the peak where base model consumption is far greater.

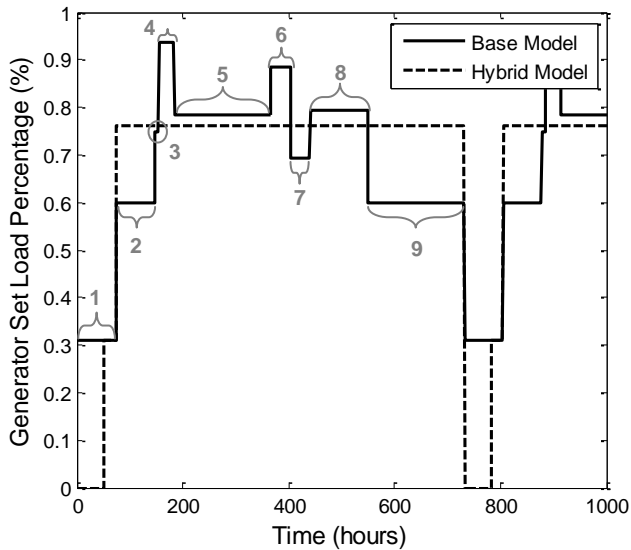


**Figure 5. Correlation between battery load and SOC variation for the optimal configuration.**

These fuel savings are attributed to the “free” power provided by the battery, which reduces the load and therefore consumption, as well as the improvements in efficiency that result from doing so by keeping the load centered on 76%. Figure 7 shows the actual load percent that the gensets see for both hybrid and base models. Clearly, the hybrid model is fully set on achieving 76% steady state genset operation, except in the case of loading below the defined limit, in which case genset load percent is zero. However, referring back to Figure 6, we can see that there are configurations where the base scenario yields better economy due to the fact that it is using more optimal gensets, which is further shown in Figure 8. This difference is because the control strategy is focused on optimal load percent operation (at 76%) over utilization of the smaller, more efficient gensets; thus suggesting regions with the potential for reduced fuel consumption. However, these changes would have an impact on the amount and the timing of battery recharge, which has effects on battery operation in other modes in order to be charge sustaining. Thus, any potential gains are not obvious nor without potential consequences.



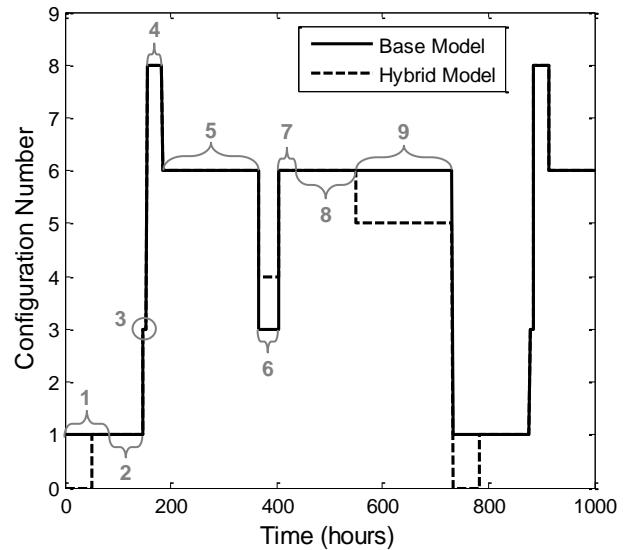
**Figure 6. A comparison of the instantaneous fuel consumption rates for the hybrid case and base model, which highlights regions of highest impact, with corresponding operational modes indicated.**



**Figure 7. A plot of genset load percentages for both the hybrid and base model fully depicts the constant load operation of the control strategy, with corresponding operational modes indicated.**

Using the representation presented in Table 3, we can additionally plot which configuration is being utilized at a given time for both models in comparison, as in Figure 8. This representation further illustrates some of the differences and benefits between the two configurations. Configurations 1, 3 and 6 represent utilization of the more efficient 1180 kW

genset, as indicated by the base model configuration plot. However, the hybrid system needs to use these modes to correct SOC. For instance, mode 9 represents one of the longest periods, or modes, of constant operation. Thus, operation in this region is going to have a large impact on the net results. The control system is figuratively unaware of this duration and defines its operation based on the fact that the SOC is above the target. If it were operating in the more optimal configuration number 6, the genset load percent would be greater than the target, allowing only the potential to charge, thus indicating a region that would develop tendencies to deviate from charge sustaining behavior.

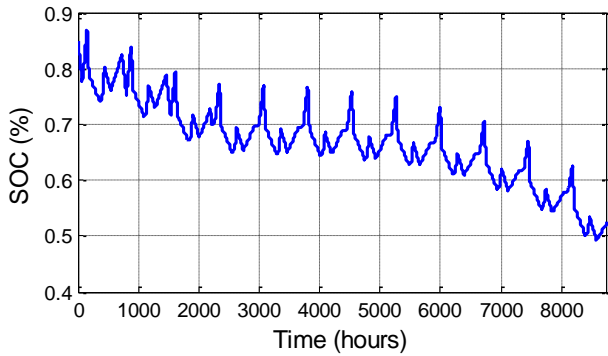


**Figure 8. Genset configuration being used for the base scenario as compared to the hybrid model, where we see regions that compromise more efficient genset combinations for more efficient load percents, with corresponding operational modes indicated.**

## CONTROL SENSITIVITY

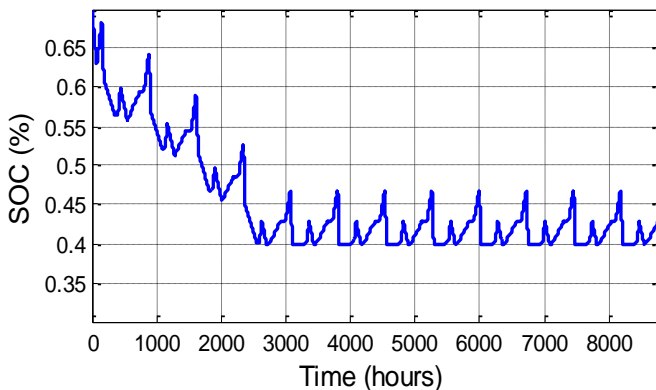
As was previously alluded to, operation of a given control strategy is particularly sensitive to the parameters which bound its operation, namely, initial SOC, target genset load percentage, lower SOC limit, target/mid SOC limit and minimal acceptable genset load percent. The system is equally sensitive to any changes made in the rules that define the control strategy. Figure 9 shows the exact same control strategy as used in the previous hybrid case, with all the same parameters, except the target SOC is changed to 0.7. The resulting control strategy is an example of non charge sustaining control. Initial operation depletes charge as expected down to the 0.7 target SOC. However, as we see the charge start to settle on 0.7 at around 3000 hours, in the next iteration it has dropped just enough that the cycle cannot return it to that point and so begins a gradual decline. Additionally, this non-ideal behavior impacts fuel consumption as the net

result from this simulation is 5136 m<sup>3</sup>/hr, despite the slight advantage it has of over-discharging.

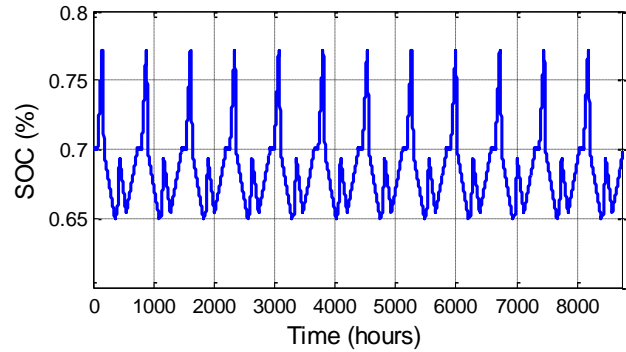


**Figure 9. Demonstration of how SOC is not sustained using the same control strategy with a different target SOC value.**

Figure 10 demonstrates what is meant by approaching and settling on a particular value. This is, again, the same control strategy as before with the exact same parameters except a target SOC of 0.6 and an initial SOC of 0.7. Settling on these values produces even poorer results as now the gensets are in sub-optimal configurations with no energy storage power available (fuel consumption here is 5207 m<sup>3</sup>/hr). Hence, it is important to pick the target SOC thoughtfully. However, any target SOC value is theoretically sustainable, given the right initial conditions and, at most, a modification of the control strategy. For instance, if the desired target SOC is 0.7, as in Figure 9, we can modify the control strategy to eliminate the middle SOC range provision for zero battery load, then the battery will charge in this instance. If we then change the initial SOC to 0.7, we have a charge sustaining control strategy once again. Figure 11 shows the year-long SOC fluctuation for this configuration which yields 5133 m<sup>3</sup>/yr.



**Figure 10. Yearly state of charge variation for the same control strategy operating in a different region of battery capacity.**



**Figure 11. Results of modifying control strategy to create a charge sustaining battery controller that operates at a different desired target SOC.**

## CONCLUSIONS AND FURTHER RESEARCH

The most obvious conclusion drawn from this analysis is the potential benefit of 2% fuel savings per year. At the time of this analysis, diesel was approximately 850\$/m<sup>3</sup>. This price yields a net cost of \$4.4M each year in fuel alone, and thus a 2% savings in fuel has the potential to save \$88,000 per year. Thus, any fuel savings in the case of such huge power demands can have a substantial impact. However, a 2% variation is a figure that could result from any fluctuation in annual load distribution, or, more importantly, by alternative diesel genset selection. These minimal benefits are coupled with the fact that a 7.5 MWh battery pack will have very large capital costs (although specific pricing information for NaS batteries and others of this scale is not generally available to the public).

Despite these financial aspects, the fact remains that even with genset operation strictly confined to its peak efficiency of 76% load, the gains in efficiency are small. These minimal gains are the result of the granularity provided by large-scale ship propulsion system design in that it utilizes multiple diesel gensets, and is in contrast with light-duty vehicles for land-based transportation, where adding in storage with electric motors improves efficiency significantly. Additionally, the diesel gensets used here have a much larger region of near-peak efficiency. Thus, the granularity allows the ship's power system enough refinement in load percent designation that additional variation provided by a battery pack, even if sized at 1000 kW, has little impact.

Alternatively, numerous benefits in performance are attained that are not easily quantified without much more detailed information. The system controller essentially operates, in this analysis, as a load-leveling device. The gensets see a very smooth, constant load of 76% all of the time (or they are off). In the base scenario the diesel gensets must be operated to provide all power to the ship, and thus meet all fluctuation in load, including highly variable ship loads such as lighting, HVAC, pumps, anchors, kitchen needs, and so on, in addition to propulsion system needs. Operation of this nature must necessarily have harmful effects of rapid-cycling the

gensets sets through their load capabilities, such as wear, electrical system noise, required power electronics, and potentially even small impacts on fuel economy, that this avoids. Additionally, research vessels require noise-free electric power for instrumentation and other sensitive electronic devices. Thus, the integration of an energy storage system into a ship propulsion system offers significant load-leveling and power quality benefits, which might have concomitant maintenance benefits, but does not produce sufficient efficiency gains through load manipulation as in terrestrial gasoline-electric hybrid vehicles to make it attractive. Instead, it demonstrates the dominating importance of careful generator set selection with respect to the design of fuel-efficient passenger ships.

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