4-2016

Capacity optimization of battery-generator hybrid power system: Toward minimizing maintenance cost in expeditionary basecamp/operational energy applications

Jude C. Onwuanumkpe
Purdue University

Recommended Citation

Onwuanumkpe, Jude C., "Capacity optimization of battery-generator hybrid power system: Toward minimizing maintenance cost in expeditionary basecamp/operational energy applications" (2016). *Open Access Theses*. 804.
https://docs.lib.purdue.edu/open_access_theses/804

Graduate School Form
30 Updated 12/26/2015

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By JUDE C. ONWUANUMKPE

Entitled

CAPACITY OPTIMIZATION OF BATTERY-GENERATOR HYBRID POWER SYSTEM: TOWARD MINIMIZING MAINTENANCE COST IN EXPEDITIONARY BASECAMP/OPERATIONAL ENERGY APPLICATIONS

For the degree of Master of Science

Is approved by the final examining committee:

ERIC DIETZ
Chair

JOSEPH PEKNY
Co-chair

MARK FRENCH
Co-chair

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy of Integrity in Research" and the use of copyright material.

Approved by Major Professor(s): ERIC DIEZ

Approved by: KATHRINE NEWTON 4/29/2016

Head of the Departmental Graduate Program Date

CAPACITY OPTIMIZATION OF BATTERY-GENERATOR HYBRID POWER SYSTEM: TOWARD MINIMIZING MAINTENANCE COST IN EXPEDITIONARY BASECAMP/OPERATIONAL ENERGY APPLICATIONS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Jude C. Onwuanumkpe

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

May 2016

Purdue University

West Lafayette, Indiana

To my family, whose sacrifices, patience, and understanding throughout the past two years allowed me to focus and deal with challenges of this project.

ACKNOWLEDGEMENTS

I would like to acknowledge the overwhelming support, guidance, and mentorship I received from my graduate advisors, Dr. Eric Dietz and Dr. Joseph Pekny. I also appreciate assistance from Mr. Tim Raney in the U.S. Army Combined Arms Support Command (CASCOM), Steve Iverson, Doreen Sorensen, Elias Anaya, and the R&D team at Cummins Power Generation. I am also grateful to the Purdue Military Research Initiative (PMRI) and the Purdue Homeland Security Institute (PHSI) for enabling my pursuit of unique research opportunities that are tailored and relevant to my profession. These programs ensured that I received professional development concurrently with my academic endeavors, so that one did not suffer because of the other. I am also grateful for the guidance provided by the senior staff in the Department of Chemistry and Chemical Engineering at the U.S. Military Academy—COL Robert, COL Burpo, and LTC Clancy. Last but not least, I owe a great deal of gratitude to my wife and two young children who have borne the brunt of sacrifices that we have had to make along this journey. Thank you all.

TABLE OF CONTENTS

Page

Page

APPENDICES

Page

LIST OF TABLES

Appendix Tables

LIST OF FIGURES

Figure Page

Appendix Figures

LIST OF ABBREVIATIONS

AMMPS	ADVANCED MEDIUM MOBILE POWER SOURCE
ARCIC	Army Capabilities Integration Center
B-G HPS	Battery-diesel Generator Hybrid Power System
CASCOM	Combined Arms Support Command (CASCOM)
COP	Combat Outpost
DG	Diesel Generator
DOD	Depth of Discharge
EOCV	End-of-Charge Voltage
EODV	End-of-Discharge Voltage
FOB	Forward Operating Base
HPS	Hybrid Power System
MEHPS	Mobile Electric Hybrid Power Sources
M&S	Modeling and Simulation
SOC	State of Charge
TEP	Tactical Electrical Power
TQG	Tactical Quiet Generator
USMC	United States Marine Corps

GLOSSARY

Battery: a device that converts and chemical energy into electrical energy and vice versa.

Capacity (Ah): total hours of charge available when a battery is discharged from 100% SOC to a cut-off SOC at a certain discharge current.

Charge/Discharge Current: also known as “C-rate”; the maximum safe current at which a battery can be charged or discharged continuously without damaging the battery or reducing its capacity.

Contingency Operations: operations that involve hostilities and require military action.

Contingency Basecamp: locations that support military operations in an expeditionary environment, and provide the support and services necessary to sustain operations.

Combat Outpost (COP): a type of military contingency basecamp that can sustain a small group (less than 200 soldiers) for extended periods of time in a remote environment. COPs have short cycle life and provide protection, shelter, sanitation, and dining. Infrastructure is likely to provide portable generator, temporary wiring, water storage, crude toilets and shows. Energy systems tend to be inefficient, and therefore present significant improvement opportunities.

Cycle Life: the number of charge-discharge cycles a battery can experience before it can no longer meet specific performance criteria. This is dependent on the frequency and depth of the cycles, as well as other battery conditions such as temperature and humidity. Shallow discharge cycles extend cycle life.

Deployability: ease of movement to the battlefield of a military equipment.

Depth of Discharge (DOD): an expression of battery capacity that has been discharged at any given time as a percentage of maximum capacity.

Emergency Operations Center (EOC): a central command and control facility responsible for carrying out emergency preparedness or disaster management functions such as information gathering and analysis, and coordination of field service operations.

Energy (Wh): total Watt-hours available when a battery is discharged from 100% SOC to a cut-off SOC at a certain discharge current.

Forward Operating Base (FOB): A type of contingency basecamp that generally support a battalion or larger size population. FOBs typically have temporary or semi-permanent structures, electrical power grids, water, sewage systems, and operational, administrative, housing and recreational facilities that require energy for lighting, heating, and air conditioning.

Low load Operation: the operation of a diesel generator at engine loads below 40% of its maximum-rated power capacity.

Operational Energy (OE): Also referred to in this work as "expeditionary energy". The energy and associated systems, processes and resources required to train, move, and sustain forces and systems for military operations.

State of Charge (SOC - %): an expression of a battery's capacity at any given time as a percentage of its maximum capacity.

Tactical Electric Power (TEP) – A range of electrical power output (0 to 200 kilowatts) that satisfies the power requirements of an expeditionary force. TEP meets electricity demand of mission-critical C4ISR and life support systems employed by tactical military echelons (brigades, battalions, companies, and platoons).

Transient Load Operations: operation of a diesel generator under variable load condition or sudden changes in load demand, which causes engine torque deficit and speed change.

Voltage (V): potential difference between battery terminals—known as "terminal" voltage when a load is applied, and "open-circuit" voltage when no load is applied. Voltage varies with SOC and rate of charge/discharge.

Wet-stacking: formation of carbon deposits and soot due to incomplete combustion of fuel inside the cylinder of an internal combustion diesel engine.

ABSTRACT

Onwuanumkpe, Jude C. M.S., Purdue University, May 2016. Capacity Optimization of Battery-Generator Hybrid Power System: Toward Minimizing Maintenance Cost In Expeditionary Base Camp Applications. Major Professor: Eric Dietz

Low and transient load conditions have been shown to have deleterious impact on the efficiency and health of diesel generators (DGs). Extensive operation under such loads reduces fuel consumption and energy conversion efficiency, and incrementally contribute to diesel engine degradation, damage, or catastrophic failure. Unfortunately non-ideal loads are prevalent in contingency basecamps that support contingency operations in austere environments or remote locations where grid electricity is either non-existent or inaccessible. The impact of such loads on DG exacerbates already overburdened energy logistics requirements. There is a need, therefore, to eliminate or prevent the occurrence of such non-ideal loads. Although advances in diesel engine technologies have improved performance, DGs remain vulnerable to the consequence of non-ideal loads and inherent inefficiencies of combustion. The mechanism through which DGs mitigate non-ideal loads is also mechanically stressful and energy-intensive. Energy storage could provide load-levelling capability that is more ameliorative than modern DGs' load-following capability. Thus, this research investigated the idea of using batteries to prevent DGs from encountering non-ideal loads, as a way to reduce basecamp energy logistics requirements. Results show that if optimized for dynamic loads, a battery-diesel generator system allows for more than 50% reduction to generator runtime and maintenance cost.

CHAPTER 1. INTRODUCTION

1.1 Introduction

Expeditionary basecamps enable life support, communications, and command and control functions of contingency operations—emergency response and disaster-relief activities, humanitarian aid missions, and military combat operations. Such basecamps are usually isolated from a reliable power grid by combat threats and safety hazards. In the absence of accessible electricity infrastructure, contingency basecamps rely on diesel generators (DGs) and a steady supply of fuel for electric power, without which many functions and capabilities would be lost in the technology-intensive 21st-century operating environment.

The sustainment of basecamp power requirements is a major logistical undertaking that comes with extraordinary financial and human costs. Efforts to minimize those costs are also a major effort that continues to yield positive results. Innovation in combustion engine technology and intelligent control electronics has led to significant improvement in the efficiency, reliability, and durability of diesel generators. This is evident in the performance of the recently fielded Advanced Medium Mobile Power Source (AMMPS) family of military generators.

Performance enhancements notwithstanding, DGs remain susceptible to the negative impact of non-ideal load conditions. Extended DG operation under low and transient loads exacerbate inherent limitations of internal combustion engine (ICE) science and manifest in increased basecamp energy logistics requirements. This research seeks to contribute to continued effort to find solutions that might lower or eliminate the impact of non-ideal load conditions on DGs. Solutions exist which not only enable DGs to deal with non-ideal loads, but also ensure that they do not encounter such loads at all.

1.2 Problem Statement

Vulnerability of DGs to the impact of non-ideal load exacerbates or at least contributes to basecamp energy logistics burden. A major challenge to meeting tactical electric power requirements are still center on energy conversion, despite recent improvements to combustion technology. Although diesel generators provide reliable, high-quality power, their energy-conversion efficiency is less than 50%, which is lower than the efficiency of many other energy conversion technologies (DOE, 2006). The efficiency decreases when DGs are subjected to non-ideal operating conditions. DGs subjected to extended periods of low-average and drastically-fluctuating power demand consume more energy per power output, and are more prone to damage or essential function failure (Tufts, 2014). They require more frequent resupply of fuel, repair parts (Table 1.2), maintenance man-hours, and increased costs.

Table 1.1 Diesel generator parts susceptible to damage related to non-ideal loads (Tufts, 2014)

-	Cylinder	-	Crankcase bearing
-	Fuel pump	-	Head gasket
-	Piston ring	-	Lubricating oil and filter
-	Piston ring seals	-	Fuel and filter
-	Cylinder liner	-	Fuel Injector nozzle

Non-ideal load conditions are prevalent in military basecamps. During certain phases of contingency operations, the tempo of basecamp activities—including command & control, life support, and force protection functions—is very dynamic. This manifests in a basecamp load profile that is characterized by wide fluctuations. Operational readiness requirements and planning practices—such as the requirement for redundant generators—also contribute to the existence of non-ideal conditions. Engineers at Cummins Power Generation—a major DG manufacturer—note that stringent power-quality requirements necessitate overdesign of military DGs. These factors inevitably contribute to the prevalence of conditions that subjects DGs to suboptimal utilization, and increases basecamp energy sustainment costs, which include the risk of maintaining supply lines through enemy territory and difficult terrain.

Modern DGs are equipped with advanced combustion technology features—electronic fuel inject, variable engine speed, power control electronics--which enable improved performance. AMMPS DGs, for example, can probably handle non-ideal load conditions better than their predecessors; however, the process through which they achieve that feat is not immune to consequences. Research suggests that the mere existence of non-ideal loads, and the mechanics of adjusting to those conditions, also take a toll on generator's operating efficiency and long-term health. Furthermore, the degree advanced combustion technologies address wet-stacking and other engine problems associated with suboptimal DG operation is not yet known. Cummins engineers concede that the wet-stacking solution equipped in AMMPS DGs—an artificial engine temperature control—does not completely eliminate wet-stacking potential (interview citation). DGs remain vulnerable to a compendium of faults related to low and transient conditions (Appendix A). These realities compound the logistics burden of sustaining energy requirements of contingency basecamps.

Research Question

Diesel generators' vulnerability to deleterious impact of non-ideal load conditions remains a significant technological problem, the ultimate solution of which may require not using DGs at all. The long-term solution may indeed require complete transition away from combustion-based technologies, and towards renewable energy technologies. Unfortunately a perception that renewable technologies currently do not meet weight, size, and cost standards limits their use in contingency basecamp applications. An alternate solution may lie not only in enabling DGs to handle low and transient loads, but also in ensuring that they do not encounter such loads at all.

Reduction of basecamp energy requirements (fuel, maintenance, etc) achieved from minimizing DG usage may exceed that achieved by engine performance enhancements. Introducing an energy storage capability may be the most effective way to inoculate DGs from the effects of non-ideal load conditions. A battery would not only provide additional load that forces DGs to run at greater efficiency, but also provide power capacity that can be used to reduce DG usage. To the extent that these potential benefits exist, there is value in investigating how those they might be realized. This research therefore seeks to contribute to that investigation by asking and answering the following question:

> How can the components of battery-diesel generator hybrid power system (B-G HPS) be rightsized to (a) eliminate the generator's vulnerability to the negative

impacts non-ideal load conditions which are prevalent in contingency basecamps, (b) minimize engine wear caused by prolonged exposure to low and transient loads, and (c) reduce generator maintenance cost and the overall burden of basecamp energy logistics?

1.3 Significance

The performance and benefits of a B-G HPS depend on right-sizing its components and employing it under optimal conditions. Results and findings in this study provide insight that could encourage hybridization of the military's vast inventory of diesel generators using increasingly reliable and affordable off-the-shelf batteries. It may also help set conditions for an eventual transition to renewable hybrid technologies while enhancing the investment in existing combustion-based power systems.

1.4 Scope

The scope of this research is limited to expeditionary power infrastructure, particularly small military basecamps and tactical sites that provide support for contingency operations. Energy requirements in such basecamps are more challenging to manage and sustain. DGs employed there are predictably more susceptible to underutilization and all the attendant consequences of non-ideal load conditions. This research builds on the USMC's Mobile Electric Hybrid Power Source (MEHPS) program, which prescribes a range of storage capacity for the 3kW and 10kW AMMPS DGs (USMC Expeditionary Energy Office, 2013). If its components are appropriately sized for a given load profile, the duty cycle of a battery-DG hybrid system would mimic an ideal cycle (Figure 1.1) with short generator runtime, short battery charging time, and long discharge time. Such a cycle would minimize generator runtime, frequency of maintenance, and maintenance cost over time. This research will analyze performance of using MEHPS capacity prescriptions with respect to maintenance cost, fuel consumption, and energy-conversion efficiency over 90-day mission cycle.

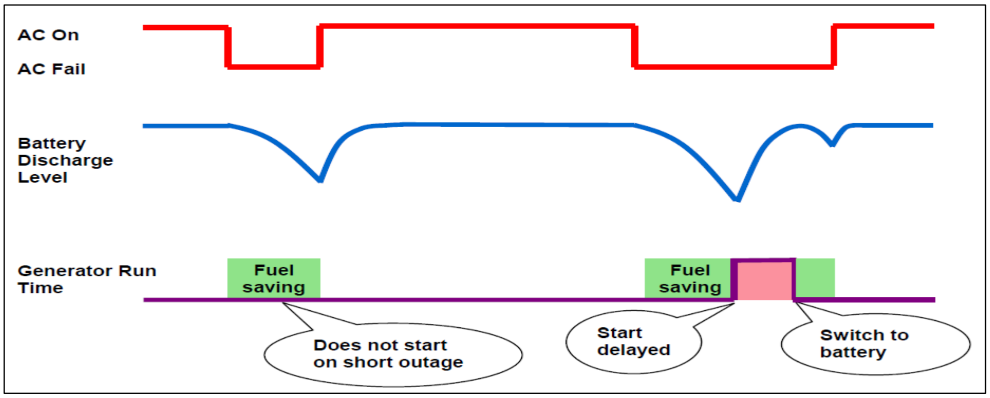


Figure 1.1. Ideal Duty Cycle (Sloane, 2008)

1.5 Assumptions

The following assumptions are necessary for completion of this study:

- Hybrid generator components (battery, diesel engine, inverter) operate at high efficiencies and near perfect conditions
    - Battery does not experience significant chemical degradation over time.
    - Energy losses by electronic control devices are negligible
- Available basecamp load data sufficiently replicates low and transient loads.
- Battery is subject to degradation or reduced capacity in temperature extremes.
- Hybrid system is already located at a basecamp and is not subject to battery transportation safety requirements.

- Battery at the start of operation has at least 90% of charge
- Generator capacity is large enough to service load and charge battery simultaneously at the battery's maximum charge rate.
- Hybrid system, in default mode, controlled autonomously/passively by battery state-of-charge.
- Battery is sized so that the sum of its capacity at minimum state-of-charge (SOC) average load over a duty cycle is less than or equal to generator's rated capacity.

1.6 Limitation

The limitations of this study include:

- Analysis of hybrid system is limited to loads and battery capacity ranges prescribed for the MEHPS program.
- Analysis considers a limited sample power demand data for each category of generator size.
- Analysis considers system parameters established for the MEHPS program.
- Analysis uses one specific cell chemistry or design.
- Optimization is based on minimization of excess power production, energy waste, generator runtime, and maintenance cost.
- Battery model does not include temperature and capacity fading effects
- Since AMMPS generators are newly fielded, there is no service history or record of damages that can provide data to qualitatively measure the frequency and impact of low and transient load conditions.

1.7 Delimitations

The delimitations of this study include:

- Hybrid Power System (HPS) does not include renewable generation sources such as wind turbines and solar photovoltaic (PV) cells.
- Hybrid system is simulated for operation at standard atmospheric conditions.

1.8 Summary

This research attempts to identify the optimal capacity of a battery that may be used in conjunction with a diesel generator to provide electric power for contingency operations in austere environments. Batteries would force generators to run at full capacity and more efficiently, thus reducing frequency and impact of LL and TL generator operations. Right-sizing the components of a hybrid power system is a classic design problem that can be solved experimentally through optimization. Therefore, the research studies four scenarios establish a general guideline for tailoring a hybrid generator solution to a specific power demand profile. The research seeks to improve storage capacity estimates established by the Marine Corps MEHPS program. Results might yield a less broad, more targeted estimates that would facilitate design and production of energy storage device that is tailored to unique basecamp applications.

CHAPTER 2. REVIEW OF RELEVANT LITERATURE

This section discusses review of research literature on topics related to the motivation, scope, and question posed in this research. The main areas covered include effects of non-ideal load conditions on diesel generators, general cycling behavior of modern high-capacity rechargeable batteries, as well as computational and simulation-based experimental methods used study hybrid power systems. The review focuses on aspects of the topics that are relevant for application to modeling, simulating, and analyzing battery-generator hybrid power systems.

2.1 Diesel Generator Operation under Non-Ideal Load Conditions

The term “diesel generator” refers to a set of two devices—an internal combustion diesel engine and a permanent-magnet alternator—that work tandem to produce to electrical power. During the combustion part of process, the diesel engine continuously ignites a mixture of air and fuel under high temperature and pressure induced by compression of a piston within the engine’s cylinders. This converts the fuel’s chemical energy content into kinetic energy, which the alternator consequently converts to electric power through electromagnetism. The efficacy of this process depends on several variables related to load level, which Tuft (2014) defined according to Table 2.1.

Table 2.1. Definition of Low-load conditions (Tufts, 2014)

0 – 25%	Extreme low load
25 – 40%	Low Load
40 – 80%	Regular generator operation load
80 – 90%	High load
90 – 100%	Extreme high load

Tufts (2014) linked a compendium of diesel engine problems (Table A.1) to operation under low load conditions. Low loads, according to Tufts, deteriorates two key parameters—temperature and pressure—that contribute most to deteriorate DG engine's combustion efficiency. As Tufts described in detail,

> "Temperature the most important parameter in the combustion process because of its exponential dependence on chemical reaction rate (p. 9)… Low load operations of a diesel engines cause lower cylinder pressures, and thus lower temperature, which can result in ignition problems and incomplete combustion. Low cylinder pressure has mainly a negative effect on the cylinder temperature, but also deteriorates the piston ring sealing efficiency as piston rings rely on the gas pressure in the combustion chamber to work properly. Incomplete combustion will lead to increased soot formation and aggregation of unburned fuel in the cylinder…"(p. 83)

Tufts noted that low loads negative impact other parameters that contribute to combustion efficiency—rate and geometry of fuel injection, timing of valve openings to allow intake of fresh air and exhaust of combustion gas products from the cylinder, and the physical integrity of cylinder components—piston rings, piston crown, liner, and oil ring (Tuft, 2014, p. 15). With prolonged exposure to low loads, the initial chain of events described above cascades to many other problems that eventually lead to significant DG engine failure.

Similar sequence of deleterious consequences can result from transient loads, which refer to sudden change in power demand that causes drastic fluctuations in the voltage and frequency output of a diesel generator alternator. Diesel generators are built to different standards and capacity to maintain power quality amidst load fluctuations; thus there is no universal threshold of transient load that is considered detrimental. Nevertheless, Rakopoulos & Giakoumis (2009) representation of DG's response to load change, as well as findings from diesel engine damage cases (Figure A.1), shows that load changes are indeed consequential. The dependence of the energy-conversion process on load factor—the ratio of power demand to supply—suggests that diesel generators are always susceptible to inefficiencies and other forms of performance tax imposed by non-ideal loads.

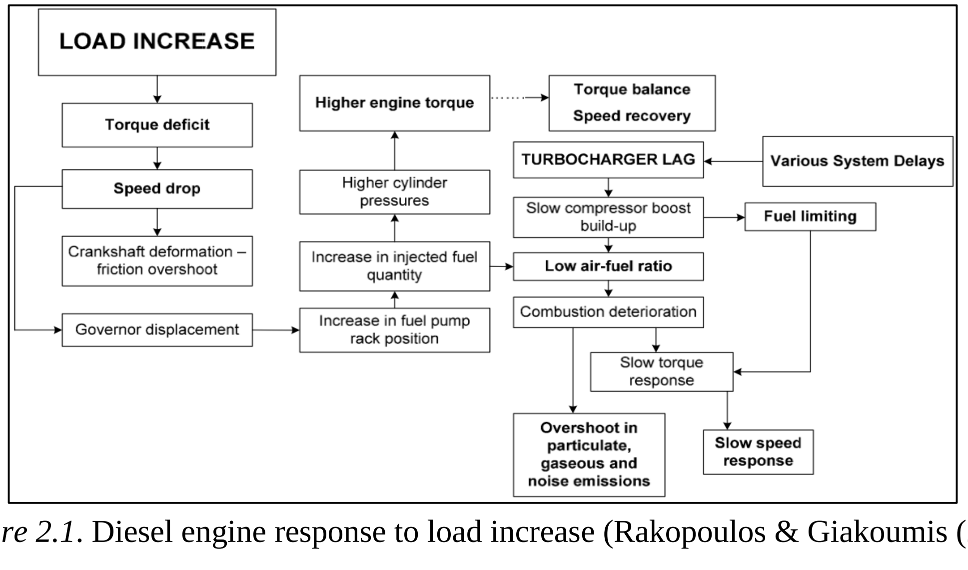


Figure 2.1. Diesel engine response to load increase (Rakopoulos & Giakoumis (2009)

Additionally, Allen (1993) observed that engine loading is one of several factors that contribute significantly to formation and accumulation of carbon deposits, and consequent degradation of combustion efficiency. Additionally, Buhaug (2003) posited that the accumulation of lacquer—a resinous substance formed from condensed fuel bi-products of combustion—tends to occur in non-ideal load conditions that also promote incomplete fuel combustion. Woodyard (2009) also attributed long period of load variation, along with other factors, to lacquer formation, which causes smoothing or glazing of cylinder liner surface and increases consumption of lubricating oil.

2.2 Prevalence of Non-Ideal Load and DG Underutilization in Military Basecamps

Reports and analysis of military basecamp operations in Iraq and Afghanistan found that low and transient loads (Figure 2.2) were prevalent in small, semi-permanent basecamps such as combat outposts (COPs) and Fire Bases (FBs) (ARCIC, 2010; USMC, 2013). The U.S. Army's Capability Integration Command observed that power demand at such basecamps "vary greatly…and are more difficult to resupply and sustain" (ARCIC, 2012). A USMC study also found that less than 1% of 767 electric load samples were serviced by diesel generators (DGs) operating at more than 75% of their rated capacity. The same study found that approximately 80% of those loads were serviced by generators operating at less than 55% of capacity (USMC Expeditionary Energy Office, 2013).

The prevalence of low loads and extent of generator underutilization in military basecamps suggests that DGs employed there experienced wet-stacking and other combusted-related problems associated with operation under non-ideal conditions. Most of those were older generation models known as Tactical Quiet Generators (TQGs), and did not have load-following capability—the ability to toggle engine speed to match power demand—or combustion control electrics that allow for better performance. Recently fielded AMMPS DGs are equipped with advanced features—variable-speed engine, electronic fuel inject, power control electronics—which, according to design literature and manufacturer tests claims, enable them to deal with non-ideal load conditions better than their TQG predecessors (Hess, 2002; ORNL, 2002; Tolbert, Peters, Theiss & Scudiere, 2003). However, a robust damage record or service history has not been established to measure their resistance to wet-stacking under actual basecamp operating conditions.

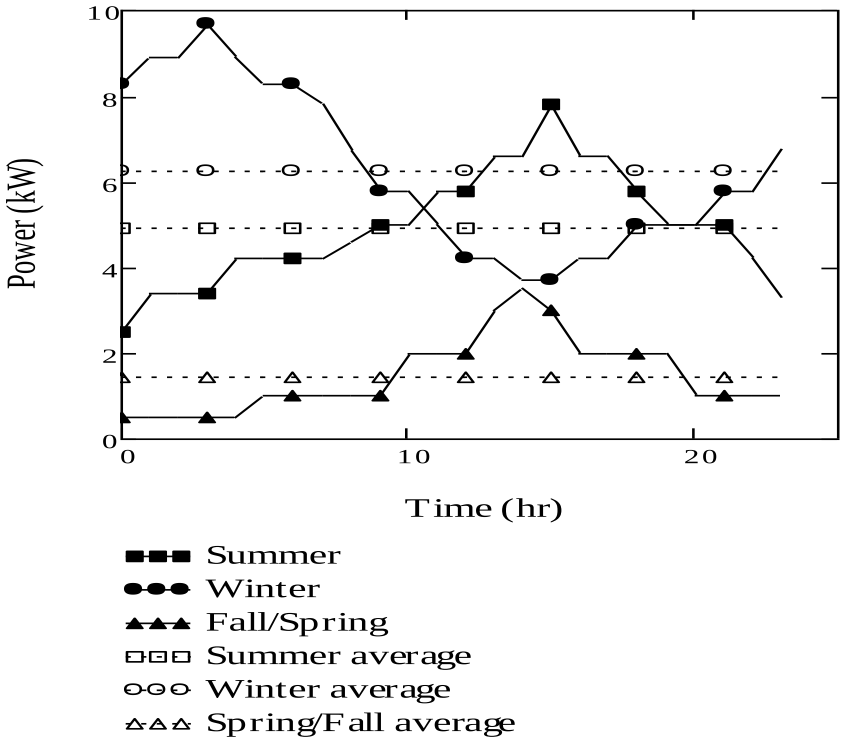


Figure 2.2 Sample seasonal load profile of a USMC basecamp

2.3 Potential Benefits of Energy Storage

Advances in high capacity batteries over the last decade have spurred massive price reduction and proliferation in automobile applications, as well as in grid/utility-scale stationary energy storage services (Manghani, 2015). This development trend is compelling evidence of the increasing reliability of modern rechargeable batteries, especially those based on Lithium ion (Li-ion) chemistry. The trajectory of progress may have also influenced recognition of potential benefits of energy storage to military basecamp applications. A 2010 U.S. Army Power and Energy Strategy white paper proposed the following goals for future base capabilities (ARCIC, 2010, p. 9-11):

- “12 hours of silent power to support COP-level life support and C4I functions
- “Minimize or replace current hydrocarbon energy systems”
- “Establish expeditionary grid for charging batteries”
- “Eliminate generator by 2030”
- “Import and/or export power to civilian systems” and achieve “security through improving conditions and civic engagement.”

These long-term goals indeed illustrate recognition of the potential benefits that batteries could provide. Despite the improvements, however, acceptance of batteries as a prime power source in contingency basecamp applications continue to be limited by portability, cost, and safety concerns, as well as stigmatized perception of their reliability. In fact, a 2014 U.S. Army study advised discontinuation of then on-going expeditionary energy storage R&D efforts on the basis that they were cost-prohibitive compared to new diesel-generator programs (CASCOM, 2014). The study specifically noted that future commitments to such efforts would require “radical advances in size, weight, and power ratios” (p. 26).

2.4 Circuit/System-Level Characteristics of Rechargeable Batteries

Indeed even the best battery technologies in existence today have scientific limitations. Just as diesel engines’ performance depends on load conditions, battery performance also depends the effectiveness of its electrochemical response to cycling conditions, which are defined by several parameters, including load profile. Interplay of those parameters determines the amount of energy the battery can store, how long it takes to store the energy, and the time and amount of power that the battery can output. It also determine the battery’s useful cycle life—the number of complete charge-discharge cycles the battery can undergo. Maximizing performance requires making tradeoffs and striking a balance between the impacts of multiple variables.

Modern rechargeable batteries are complex systems with chemical and electrical properties. In an electric circuit, batteries act as a power source and sink, dual roles that both depend on conditions external and internal to the battery. Concerns about the viability and cost-effectiveness of employing them for TEP stem from the degree to which those tradeoffs are not only understood, but deemed acceptable. Unfortunately many aspects of rechargeable batteries’ science is complex and not intuitive. Nevertheless, a rudimentary understanding can serve the purpose of maximizing the potential benefits of energy storage as part of a hybrid power system. To integrate a battery into a hybrid power system, the relationships between its internal state variables (DOD, SOC, open-circuit voltage, internal resistance) and system-level variables must be understood. Knowledge of how these parameters affect performance—measured in terms of charge and discharge time, storage capacity, power output, and cycle life—enables analysis that might inform successful and optimal employment of batteries.

Fortunately, several research works have created a comprehensive body of knowledge of rechargeable batteries. Doyle and Newman’s extensive work on first-principle modeling of lithium ion batteries provide fundamental understanding of their circuit behavior. They show in Figure 2.4 that a battery’s cell voltage decreases during discharge in proportion with discharge current (Doyle & Newman, 1993, p. 49). They also show that power’s output at any current depends on its DOD or SOC at any point during a discharge cycle. Figure 2.5 shows, for example, that at a current of 60Amps, power output is much lower at 80% DOD than at 1% DOD (Doyle & Newman, 1993, p. 1531). In Figure 2.6, Ning, White, and Popov (2006) present typical Li-ion charge and discharge cycle, which shows that cell voltage typically maintains a plateau and drops precipitously after a period of time.

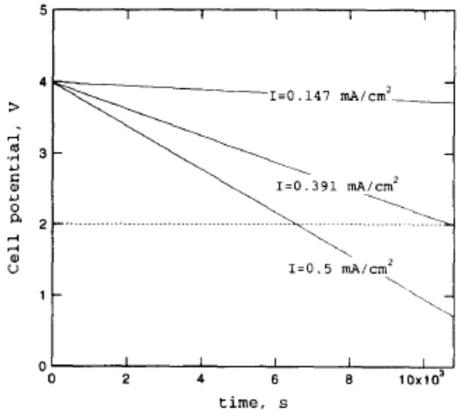


Figure 2.3 Relationship of discharge current to cell voltage

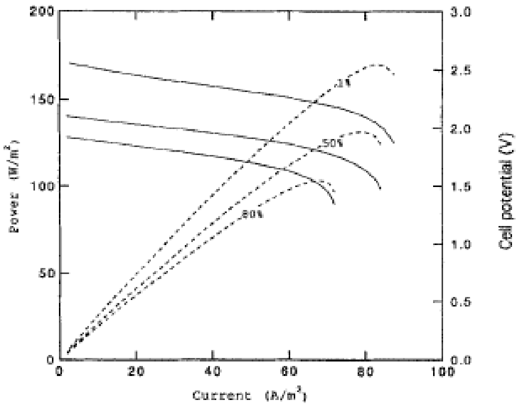


Figure 2.4 Relationship of battery power output to DOD.

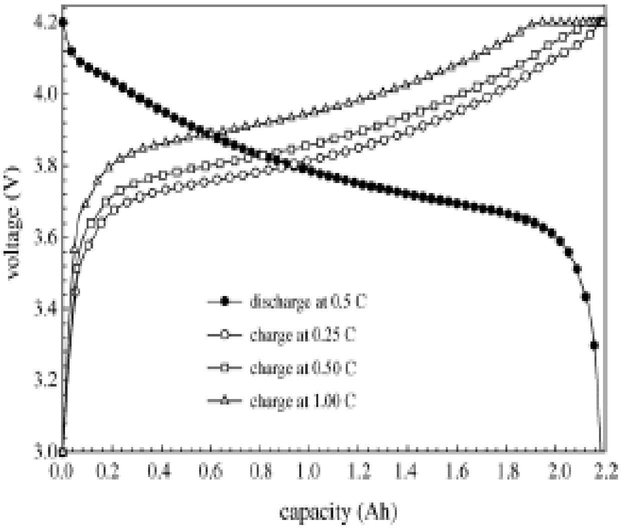


Figure 2.5: Typical Li-ion cell charge/discharge curve
(Ning, White, & Popov, 2006)

Other studies contribute to understanding battery characteristics and behavior by suggesting ways to optimize performance. Rahimian, Rayman, and White (2011) propose that “the optimum charge rates are the minimum charge currents at which the constraints for useful life are satisfied (p. 8). Broussely et. al (2005) found that found that charging Li-ion batteries to high SOC at elevated temperature increases their internal resistance, and consequently leads to reduction in charging capacity. Park et al (2007) demonstrate that charge time and impedance are inversely related to charge voltage in li-ion batteries (p 895). At higher voltages, Li-ions have greater energy and can move faster between electrodes; thus charging at higher voltage takes less time to complete. Haran, Ramadass, White, & Popov (200) also found that temperature increases the incidence of side-reactions at electrodes and contributes to battery capacity fade.

Additionally, according to Methekar, Ramadesigan, and Braatz (2010), “the method in which battery is charged can significantly alter its efficiency, safety and life time cycle”(p. 143). Zhang (2006) also found that a battery’s cycle life “strongly depends” on how it is charged (Figure 2.7). Zhang also established definition of “slow” and “fast” charging with respect to battery capacity. For Li-ion batteries, Zhang found that charging at 1C is not only fast but also increases the capacity fade (Zhang, 2006). Zhang, Xu, and Jow (2006) reported that beyond a certain charge rate (0.4C for grahite-LithiumCoO2 batteries), increasing charge current did not significantly shorten charge time; instead it aggravated other conditions that are detrimental to the battery’s health.

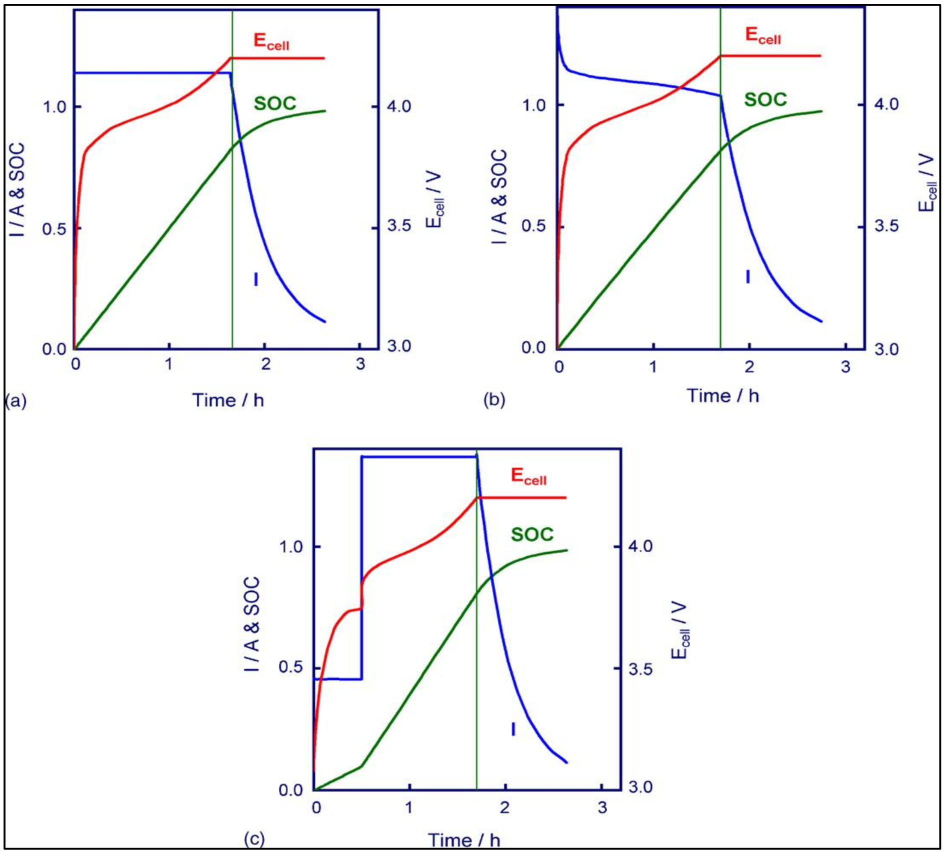


Figure 2.6: Li-ion battery charging protocols (Zhang, 2006). (a) Constant Current-Constant Voltage; (b) Constant Power-Constant Voltage, (c) Multistage Constant Current.

2.5 Modeling and Simulation

The nature of the question posed in this research necessitates a non-traditional experiment approach that relies on the aide of computer information technology. A traditional approach would use actual hybrid system components and real-time loads to obtain performance data needed to conduct analysis; however such resources neither exist at the disposal of the researcher, nor are necessary, given that the research goals can be accomplished with modeling and simulation software. Such information technology tools provide sufficient alternative to the expense and challenges of solving real-world problems via experiments. As Grigoryev (2015) notes, it is often impractical and sometimes impossible to conduct experiments with real objects because “building, destroying, and making changes may be too expensive, dangerous, or impossible” (p. 7). Summarizing the purpose of modeling, Grigoreyev states held that “modeling is about finding a way from the problem to its solution through a risk-free world where we’re allowed to make mistakes, undo things, go back in time, and start over again (Grigoryev, 2015, p. 8).

To conducting an experiment with a model is to requires execute of the modeling process, which Borschchev and Fillipov (2004) describe as follows:

> “The modeling process include the process of mapping the problem from the real world to the world of models, the process of abstraction, model analysis and optimization, and mapping the solution back to the real system” (p. 1)

The process also includes choosing one of several modeling methods that can be divided into two broad category of computer models—analytical and simulation models. Grigoreyev (2015) notes that that are two major types of computer models: analytical and simulation. Analytical models use formulas to define a problem and can be solved with common computation/data management tool such as Microsoft Excel. Some problems, however, are too complex, have intricate, non-intuitive dependencies and involve too many time-dependent or causal variables (Grigoreyev, 2015, p. 9). Those type of dynamic problems are usually require significant computational resources to solve analytical, if even possible, but are more approachable with simulation models, which Borschchev and Fillipov (2004) describe as “a set of rules…that define how the system being modeled will change in the future, given its present state” (p, 1).

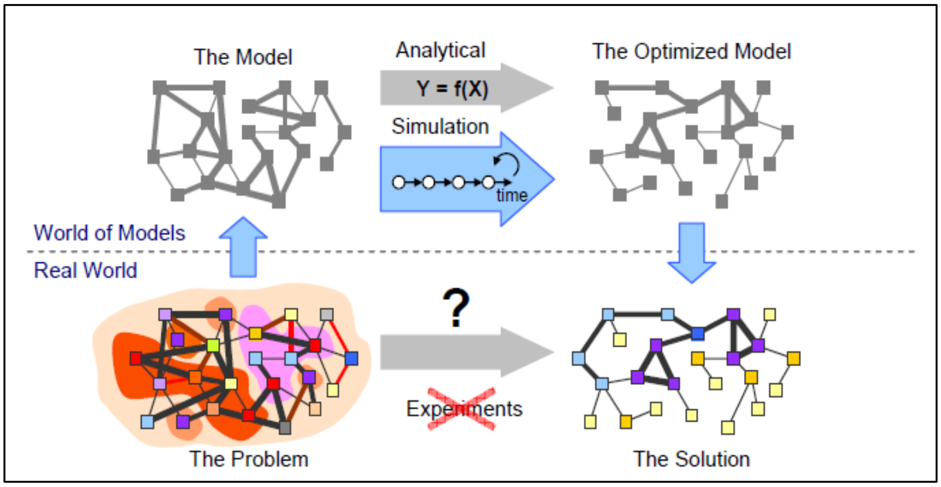


Figure 2.7 Analytical vs Simulation Modeling (Borshchev & Fillipo,

2.6 Hybrid Power System (HES) Optimization Studies

Optimization is the process of iteratively solving a problem several times under various conditions in order to identify a “best” solution based a certain criteria. An optimal solution is obtained by analytically or numerically evaluating an objective function—a mathematical/analytical expression or some rendering that define relationships between the problem’s dependent and independent variables—multiple times. An optimum solution is determined either by following a specific search algorithm, or simply comparing simulation results with established optimization criteria. The process often involves complex computations and a large amount of data, and is therefore tedious without an automated tool with sufficient computing resources (time and computer processor capacity). Efficiency, accuracy requirements may also drive need for additional resources.

2.7 Analytical Computation-Based Studies

The following studies provide examples of the aforementioned optimization approach. Diaf et al (2007) used this approach to minimize LCE in order to optimize size of a residential PV/wind system in Corsica Island. Agarwal, Kumar, and Varun (2013) optimized component sizes of a PV/DG/battery HES in Uttar Predesh, India by integrating a unique optimization algorithm into a C-programing computational tool to minimize LCC and COE. The mathematical model developed in this study comprise of 35 total parameters. 10 of the parameters model the system's storage component and are independent of battery chemistry.

Furthermore, several studies incorporate one or a combination of stochastic algorithms to improve computational efficiency. According to Hong and Lian (2012), the use of Markov-based genetic algorithm (GA) in optimization of an HES located on Orchid Island, Taiwan greatly reduced computational resources. Bilal et al. (2011) also used genetic algorithm to minimize LCE and COE for optimization of a PV/wind/DG/battery system located in northwestern Senegal. Additionally, Borhanazad et al. (2014) applied particle swarm optimization (PSO) algorithm in the size and operation-scheme optimization of a HES in Iran. Wang and Singh (2007) also applied a derivative of PSO, known as constrained mixed-integer multi-objective particle swarm optimization (CMIMOPSO), to optimize a complex HES.

2.8 Simulation-Based Studies

Many other studies analyzed HES with numerical methods embedded in modeling and simulation (M&S) tools (Bernal-Agustin & Dufo-Lopez, 2009). These tools also used parameters, decision variables, and objective functions, but in a less primitive format. They also make higher order (more complex and more numerous) computations less tedious. M&S tools allow flexibility and automation capability which make them well suited for optimizing both size and operation control of hybrid systems. The earliest variation is HYBRID—Hybrid System Simulation Model, developed by the National Renewable Energy Research Lab (NREL) and the University of Massachusetts. Baring-Gould, Green, and van Dijk (1996) reported the use of second generation HYBRID2 for optimization of a wind-diesel-battery hybrid power system located in Froya, Norway. Furthermore, Khare, Nema, and Baredar (2015) used the Hybrid Optimization Model for Electric Renewable (HOMER) simulation tool, in conjunction with particle swarm algorithm (PS) to optimize a renewable energy system in Sagar, India. HOMER enabled researchers to “fine-tune” various system parameters (generator loading, battery depth of discharge, and rate of recharge) and thereby determine optimal size and operational control strategy for the hybrid system. Kusakana and Vermaat (2013) also used HOMER to study the impact of adding a battery storage system to a diesel generator (DG) in two cases—a rural household and a base transceiver station.

Larkin (2014) used AnyLogic to model a B-G HPS in form of a stock supply chain (Figure 2.9a). AnyLogic is a java-based M&S tool permits the use of one or a combination of three modelling frameworks: system dynamics (SD), discrete event (DE), and agent base (AB) (The AnyLogic Company, 2014). Result of the study, however, is far from ideal as the system's duty cycles are short and frequent (Figure 2.9b). This suggests that the modeled battery is not appropriately sized for sample the load. Nevertheless, Larkin(2014) provides a good conceptual start point for this current research. Also, Bazan and German (2012) adapted AnyLogic to their i7-AnyEnergy simulation tool, using SD to model energy flows, and state charts to model power control decisions. Pruckner and German (2013, 2014) alssed AnyLogic to build a hybrid simulation model for large-scale electricity generation systems that includes pumped hydro storage. Both studies modeled a hybrid system and power dispatch control with SD (Figure 2.10a and 2.10b, respectively).

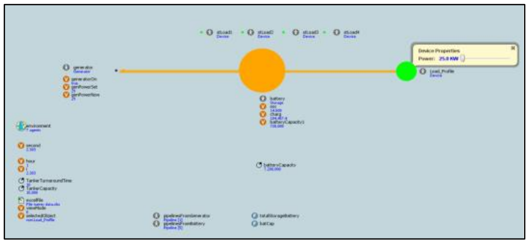


Figure 2.8a. Supply Chain model of a HPS (Larkin, 2014)

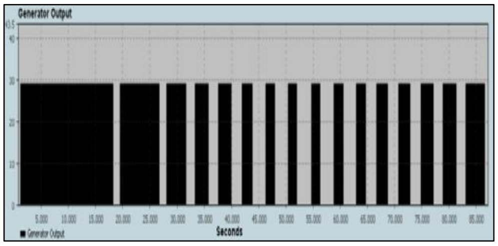


Figure 2.8b. Larkin Hybrid Generator Duty Cycle

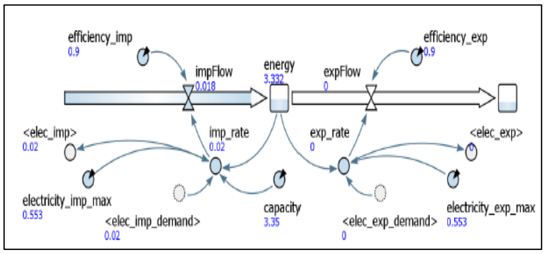


Figure 2.9a SD model of energy flow

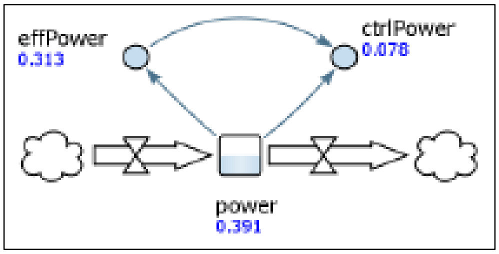


Figure 2.9b: SD model of dispatch control

2.9 Military Hybrid Energy Programs

The idea of storing energy or hybridizing diesel generators is not novel. Several military research and development programs have explored it to varying degrees of success. These programs (Table 1.2) represent a continuous effort to not only reduce the burdens of basecamp power logistics, but also close capability gaps, mitigate risks, and shore up vulnerabilities in contingency operations. U.S. government R&D investments and focus in this area suggests that it is a matter of national/strategic importance, not only for the U.S. military, but also for American taxpayers (DoD, 2012; Hammick, 2012; Jagels, 2013a,b; U.S. Army, 2010, 2013).

Table 2.2 Legacy and Existing Military Hybrid Energy System R&D Programs

Program	Source
Reusing Existing Natural Energy from Wind & Solar (RENEWS) system	Jagles, 2013
Ground Renewable Expeditionary Energy System (GREENS)	USMC Expeditionary Energy Office, 2013
Transportable Hybrid Energy Power Station (THEPS)	Ellwood, Cycowski, Raney, & Panozzo, 2009
Deployable Renewable Energy Alternative Module (DREAM)	Ellwood, Cycowski, Raney, & Panozzo, 2009
Exprimental Forward Operating Base (ExFob) system	Lasswell, 2009
Mobile Hybrid Electric Power Systems (MEHPS)	USMC Expeditionary Energy Office, 2013
Solar Portable Alternative Communication Equipment System	USMC Expeditionary Energy Office, 2013

The R&D programs mentioned above combined generation from fossil fuel and renewable energy sources with storage. Although they were effective in reducing fuel consumption, their employment requires significant tradeoff in with respect to cost and power density. This present study excludes renewable generation devices, as Figure 2.11

depecits, and explores a battery-generator hybrid power system (BG-HPS). The performance and benefits of the system depend on right-sizing its components and employing it under optimal conditions. By answering the research question posed above, this study sought to determine optimal combination of battery and generator capacity, as well as other operating conditions that might minimize energy waste and reduce maintenance costs. The results might provide insight that could encourage hybridization of the military's vast inventory of diesel generators using increasingly reliable and affordable off-the-shelf batteries. It may also help set conditions for an eventual transition to renewable hybrid technologies while enhancing the investment in existing combustion-based power systems.

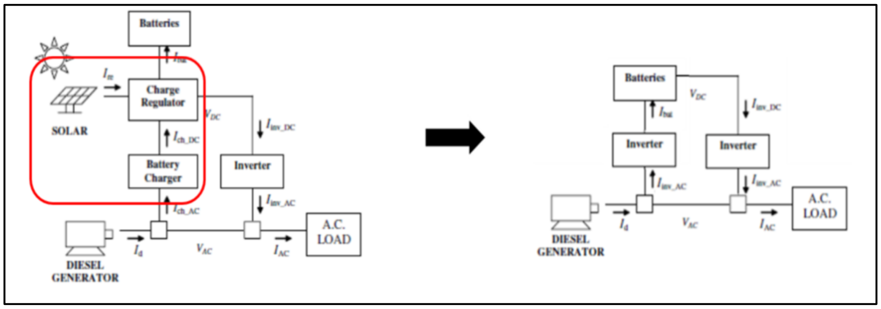


Figure 2.10 B-G HPS Design Concept (Dufo-Lopez & Bernal-Agustin (2005)

The problem tackled in this research is such that features of both analytical and simulation model can be employed to solve it. Characteristics and behavior of hybrid power system and its subcomponents have been developed and employed by several studies. Table 2.1 and Table 2.2 list models of hybrid system features and functions that are incorporated in this research.

Table 2.3. Generator Component Model

Parameter	Model	Source
Hourly Fuel Consumption	3kW: $0.2\ \mathrm{LF(t)} + 0.132$ 5kW: $0.328\ \mathrm{LF(t)} + 0.164$ 10kW: $0.528\ \mathrm{LF(t)} + 0.238$ 15kW: $0.948\ \mathrm{LF(t)} + 0.25$ where $\mathrm{LF(t)} = \text{Load Factor} = \frac{\mathrm{P_L(t)}}{\mathrm{P_{G,}}}$	Regression analysis using AMMPS Fuel Consumption chart USMC MEHPS RFP (2015)
Power Output	$\frac{P_G}{0.8} * LF(t)$ All AMMPS rated at 80% loading	Diesel Engine Theory Dufo-Lopez & Bernal-Augustin (2005)
Energy Content of consumed Fuel	Energy Content of JP-8: 18,400BTU/lb Density: 7.00lb/gal 1khW = 3412.14BTU	MIL-DTL-46162E (November, 2012)
Power Conversion Efficiency	$\frac{\text{Power Output} * \Delta\mathrm{t}}{\text{Energy Content of Consumed Fuel}}$	Dufo-Lopez & Bernal-Agustin (2005) Yang et al. (2008) Iverson, 2007
Excess Runtime due to generator inefficiencies OR Runtime equivalent of fuel consumption and power conversion inefficiencies	*Due to power-conversion inefficiency* $\frac{\text{Gen Power Output} - \text{Load}}{\text{Load}} * \Delta\mathrm{t}$ *Due to fuel-consumption inefficiency* $\frac{\text{Energy content of consumed fuel} - \text{Load}}{\text{Load}} * \Delta\mathrm{t}$	Tazvinga et al. (2013) Kaabeeche & Ibtiouen (2014)
Total Runtime	Runtime + Average of Excess Runtime	

Table 2.4. Battery Component Models

Parameter	Model	Source
SOC (t)	$SOC(t-1)*(1-\sigma)+\frac{\left[P_G*\Delta t-\frac{P_L(t)*\Delta t}{\eta_{inv}}\right]*\eta_B*\boldsymbol{CRate}}{Cap_B}$: Charge $SOC(t-1)*(1-\sigma)-\frac{\left[\frac{P_L(t)*\Delta t}{\eta_{inv}}\right]}{Cap_B}$: Discharge	Kaabeche, Belhamel, Ibtiouen (2011) Gonzalez-De-Durana et al. (2009) Deshmukh & Deshmukh (2008) Ashok (2007)
Terminal Voltage	$V_{oc}-I_L(t)*$ Resistance, where $I_L(t)=\left(\frac{P_L}{V_{DC}}\right)\eta_B$	
Open-circuit Voltage	$43.796(SOC)^6 + 150.27(SOC)^5 - 203.96(SOC)^4 + 139.85(SOC)^3 - 51.336(SOC)^2 + 10.17(SOC) + 2.9108$	Regression Analysis of Nissan Leaf Battery-pack performance. Data of transient characterisics provided by Ectality under contract from US.DOE V. Vermeulen – ANL
Resistance	Discharging $0.0694(SOC)^6 - 0.3484(SOC)^5 + 0.6135(SOC)^4 - 0.5054(SOC)^3 + 0.2078(SOC)^2 - 0.0407(SOC) + 0.0044$ Charging $-0.0019(SOC)^6 - 0.0323(SOC)^5 + 0.0949(SOC)^4 - 0.0984(SOC)^3 + 0.0469(SOC)^2 - 0.0103(SOC) + 0.0021$	
Energy Change per time step	$\frac{1}{\Delta t}*[SOC_{max}-SOC(t)]*Cap_B$: ; Charging $[SOC(t)-SOC_{min}]*\frac{1}{\Delta t}*Cap_B$: Discharging	Schuhmacher (1993)
Power flow $P_B(t)$	$\frac{P_L/\eta_{inv}-P_{G,nom}}{V_{DC}}$: Charging $\frac{P_{G,nom}-P_L/\eta_{inv}}{V_{DC}}$: Discharging	Yang, Zhou, Lu, & Fang (2007)

2.10 Summary

It is clear that extensive work has already been done on optimization of hybrid energy system. Several authors have developed analytical and numerical tools to accurately model the components of HES and their interaction. Majority of existing literature report studies that try to improve performance of HES by either optimizing their component size or the manner in which the power produced by those components are harvested and controlled. Most HES include intermittent renewable energy sources whose efficiency depend on local meteorological conditions. Hence the mathematical models used to describe HES are often complex and comprise a large quantity of parameters and variables. Similarly, HES operation scheme can be complex and subject to several constraints, and assumptions. The studies reviewed herein provide adequate understanding of the challenges associated with modelling HES, as well as insight on experimental techniques to improve the performance through capacity and operation scheme optimization.

CHAPTER 3. METHODOLOGY

This chapter discusses the investigative and experimental approach used in this research. It also provides a detailed explanation of the parameters, and modeling and simulation tools, as well as criteria used for data analysis.

3.1 Research Framework

This research is a semi-empirical quantitative study of a battery-generator hybrid system (B-G HPS). The system's battery component has similar cell characteristics as the battery in the Nissan Leaf Hybrid Electric Vehicle (HEV), while the diesel generator component has similar power output and fuel consumption characteristics as TQG and AMMPS military generators. The system also includes a bi-directional AC/DC power inverter with known efficiency. The framework of the research entailed using computer software to model and simulate various sizes (capacities) of the system's battery and generator components. Performance statistics were collected for various load samples, then compared to a standalone generator's performance. For each load scenario, a battery-generator capacity combination that yields the lowest maintenance cost and other performance metrics is subsequently identified as optimal.

3.2 Experiment Design

Experiment design for this research followed two key trends observed from review of HPS optimization literature. The first is that most studies take a similar approach comprising of the following steps:

(1) Identify and categorize relevant parameters as dependent or independent variables.
(2) Formulate a mathematical expression for individual components of the system.
(3) Define an objective function that describes the dependent variable.
(4) Develop an optimization model using the objective function, design variables, and applicable constraints
(5) Test and implement the model by applying to a real-world load scenario.

Second, most HPS optimization efforts tried to improve the system by either optimizing the size of its components, or optimizing its operation and control strategy. Furthermore, most studies sought minimization of various cost functions such as life-cycle-cost (LCC), levelized cost of energy (LCE), and net present cost (NPC). This research proceeds in a similar vein to minimize maintenance cost by varying component sizes and control strategies.

The experiment design simply entails use of known or assumed values of various parameters to evaluate analytical models that define characteristics of a power system and its subcomponents. The resulting data is then used to conduct a comparative analysis of the performance of stand-alone generators and a BG-HPS against a given load profile. The experiment design also enables optimization without using conventional algorithm. Although crude and tedious, approach provides sufficient data to test the hypothesis that optimizing a B-G HPS for maintenance cost may yield a more refined estimate of generator-battery capacity combination than that proposed by the MEHPS program.

3.3 Identification of Parameters

Selection of relevant parameters for an object or system depends on the intended goal of analysis, as well as the level of detail or abstraction envisioned for an experiment. For the purposes of this research, parameters are outlined in Table 3.1 and include only those that describe behavior of system components as electric power source, sink, or transmission node. The generator is a power source, load is a sink, battery is both source and sink, and inverter is a transmission node. Parameters that describe these components include operational features and technical data specifications provided in manufacturer literature, or scientific theory, or intuition. Among them are independent (design) variables, constraints, and dependent variables. Battery parameters include only those that describe its electric-circuit behavior, and exclude cell microstructure or topology (i.e. electrode and electrolyte properties).

3.4 Objective Function and Simulation Model Design

The objective of this research is to identify optimal parameters of a B-G HPS, specifically power and energy-storage capacities, which minimizes maintenance cost for the system's diesel generator component. Equations 1 to 3 below define maintenance cost as an objective function that is several parameters.

$$\text{Generator Maintenance Cost} = \#\, services\ *\ \$/service \qquad (1)$$

where $$\#\, services = \frac{Total\ Runtime}{service\ interval} \qquad (2)$$

and $$Total\ Runtime = Hours\ on + Excess\ runtime \qquad (3)$$

It is apparent from the preceding equations that the objective function is minimized by minimizing generator runtime. For a stand-alone generator employed as primary power source, runtime is limited only by periodic shutdown for routine maintenance or by unanticipated failure. For a hybrid system, generator runtime is minimized by maximizing battery discharge/autonomy time. This is possible if the system is set for deep cycle operation, wherein the battery is discharged to its maximum safe limits, and the generator is used to either charge the battery or provide additional power when demand exceeds battery capacity. Under this rubric, the following is true:

$$Hours\ on = \ Battery\ Charge\ time \qquad (4)$$

or

$$Hours\ on = \ Duty\ Cycle - \ Battery\ Discharge\ time \qquad (5)$$

Given the multi-variable dependencies of battery operation, as outlined in preceding chapters, a comprehensive definition of the objective function proceeds as follows:

$$Maintenance\ cost = f(component\ capacities, battery\ charge\ and\ discharge\ \ rate, SOC, load, efficiencies, system\ control\ scheme) \qquad (6)$$

Equation 6 shows that the objective function actually depends on several parameters that are also defined as functions of time (Appendix C and Appendix D). With this design, it is clear that an analytical solution for the objective function would be extremely complex, if possible. The numerical approach taken in this research is also complex and requires several computation steps. However, the complexity is resolved by using sample data, assumptions and intuition informed by the research objectives, to constrain the problem and make computations more manageable.

3.5 Sample Set

The sample data used for this research include actual military basecamp load profiles (Table 3.1), as well as data that describes characteristic features of the generator and battery that make up the B-G HPS. The seasonal load profiles are those of a midsize U.S. Marine Corps basecamp in Iraq. Table 3.1 also includes static loads used by CASCOM to conduct the cost-benefit analysis of the MEHPS program alluded to in Chapter 2.

Table 3.1 Sample Load Profiles (kW)

Hour	Summer	Winter	Fall/Spring	COSFPS-static	Guard tower floodlights-static
0	2.5	8.3	0.5	7.5	2
1	3.4	8.9	0.5	7.5	2
2	3.4	8.9	0.5	7.5	2
3	3.4	9.7	0.5	7.5	2
4	4.2	8.9	0.5	7.5	2
5	4.2	8.3	1.0	7.5	2
6	4.2	8.3	1.0	7.5	2
7	4.2	7.8	1.0	7.5	2
8	4.6	6.7	1.0	7.5	2
9	5.0	5.8	1.0	7.5	2
10	5.0	5.8	2.0	7.5	2
11	5.8	5.0	2.0	7.5	2
12	5.8	4.2	2.0	7.5	2
13	6.6	4.2	3.0	7.5	
14	6.6	3.7	3.5	7.5	
15	7.8	3.7	3.0	7.5	
16	6.6	4.2	2.0	7.5	
17	6.6	4.2	2.0	7.5	
18	5.8	5.0	2.0	7.5	
19	5.0	5.0	2.0	7.5	
20	5.0	5.0	1.0	7.5	
21	5.0	5.8	1.0	7.5	
22	4.2	5.8	1.0	7.5	
23	3.3	6.8	1.0	7.5	

Table 3.2 Nissan Leaf Battery Cell Characteristics (Vermeulen, 2013)

Chemistry	Graphite-$LiMn_{1/3}Ni_{1/3}Co_{1/3}$+$LiMn_2O_4$)
EODV	3.5
EOCV	4.2
Nominal Voltage	3.75
Current Capacity (Ah)	1.5
Nominal Energy Capacity (kWh)	0.005625

Table 3.3 Diesel Generator Fuel Consumption Rates (USMC, 2015)

Load Factor (%)	Fuel Consumption rate (gal/h) at rated load factor			
	3kW TQG	5kW AMMPS	10kW AMMPS	15kW AMMPS
0	0.14	0.16	0.23	0.28
25	0.18	0.24	0.37	0.46
50	0.22	0.34	0.50	0.70
75	0.28	0.42	0.67	0.97
100	0.34	0.48	0.86	1.21

3.6 Criteria for Optimization

Selection of optimal component capacity in this research was based on comparison of maintenance cost between a stand-alone generator and for the B-G HPS, as well as other factors. As outlined above, the cost is a function of generator runtime, which, for the hybrid system, depends on battery charge and discharge time. Other factors such as fuel consumption and number of battery charge/discharge cycles were also considered. The non-linear relationship between the system capacity and the performance metrics imply that optimization required tradeoffs between all design variables; thus the study included sensitivity analysis. Adjustments of various design variables have different degrees of impact on the objective function. Moreover, while the employment of a battery as primary power source prevents continuous generator operation under non-ideal load conditions, it is likely that the generator's start-and-stop function is just as mechanically stressful to its engine as adjusting to load variability. Therefore, the goal of minimizing generator runtime had to beaccompanied by the goal of minimizing duty cycles, i.e. the start and stop frequency. The benefit of hybridization would be maximized by if the system spends more time discharging and doing useful work than this charging. That is, the system capacity must be such that total hours of battery discharge (silent operation capability) are at least twice the total charge time. Also, DG efficiency influenced optimization since it is directly related to the issue of engine vulnerability to non-ideal loads, which underpins motivation of this research.

3.7 Summary

This research is a quantitative study that employs within-subjects experimental design methodology, which allows for measurement and comparison of same subjects (dependent variables) from repeated treatments. With the aid of the AnyLogic computer software, the experiment models and simulates scenarios in which four different sets of B-G HPS provide electric power to a military base camp for a one year period. For each B-G HPS set, the experiment is repeated multiple times while changing operating conditions (independent variables). Analysis compares the measurements between the BG-HPS sets and generator-only baseline. Results of the comparison would lead to determination of a battery capacity at which optimal value of the measured dependent variable occurs.

CHAPTER 4. PRESENTATION OF DATA

This chapter presents data input and outputs from the simulations. One of the primary goals of this research is to paint a picture of the difference that energy storage can make to the performance of a generator operating in non-ideal load conditions. The preceding chapters established that a battery reduces fuel consumption and overall efficiency. Simulation and optimization results presented in this chapter show the extent of that reduction, as well as reduction in generator runtime and maintenance cost. Standalone generators and B-G HPS of various capacity combinations are simulated for various basecamp load over a 90-day contingency operation.

4.1 Input Parameters

Tables 4.1 and 4.2 list values (obtained from literature or otherwise assumed in accordance with research objectives) for all system parameters. These values also establish constraints to certain parameters that are design (independent) variables—generator capacity, load profile, and charge rate. Table 4.2 shows that each generator is restricted to load profiles whose peak is less than the generator's maximum capacity. For example, peak of the Fall/Spring load is 3.5kW. All military generators are nominally rated at 80% load factor, so that the maximum capacity of a 3kW-rated generator is actually 3.75kW. Therefore, the fall/spring load can be serviced by all four generators.

However, this is not the case for the summer and winter loads, whose peaks are 7.8kW and 9.7kW respectfully, and can only be serviced the 10kW and 15kW generators.

Table 4.2 also establishes lower and upper bound for battery capacity; nevertheless, simulation will also test battery capacities that are outside of these bounds to get a more comprehensive picture of the design space. Battery capacity to the left and right of those bounds may yield lower maintenance cost, greater fuel consumption savings, or less reduction in battery lifecycle. Furthermore, reference to “passive control” in Table 3.4 implies that the system is tied to and controlled autonomously by SOC. When the battery is depleted (SOC = 10%), or is insufficient to service load, the generator automatically turns on, and services load while simultaneously charging battery. Active control, which may be applied to a different optimization scenario, simply applies additional constraints to passive control by the commanding battery discharge according to specified schedule. Two categories of active control may be applied:

a. Tactical active control: additional discharge to ensure silent operations based tactical needs (noise and heat signature reduction required for force-protection or anti-surveillance posture)

b. Economic active control: additional discharge requirement to maximize fuel savings (ex: discharge during extended low-average demand, or when generator load factor is less than 50%.

In either passive or active control mode, system charges battery to maximum SOC (90%) before allowing the next duty cycle. Additional constraints could be applied to the objective function. Charging for the hybrid system could be constrained to a specific C-rate and DOD while all other parameters remain constant. This eases an otherwise tedious and time-consuming computation process using Microsoft Excel.

Table 4.1. B-G HPS Parameters

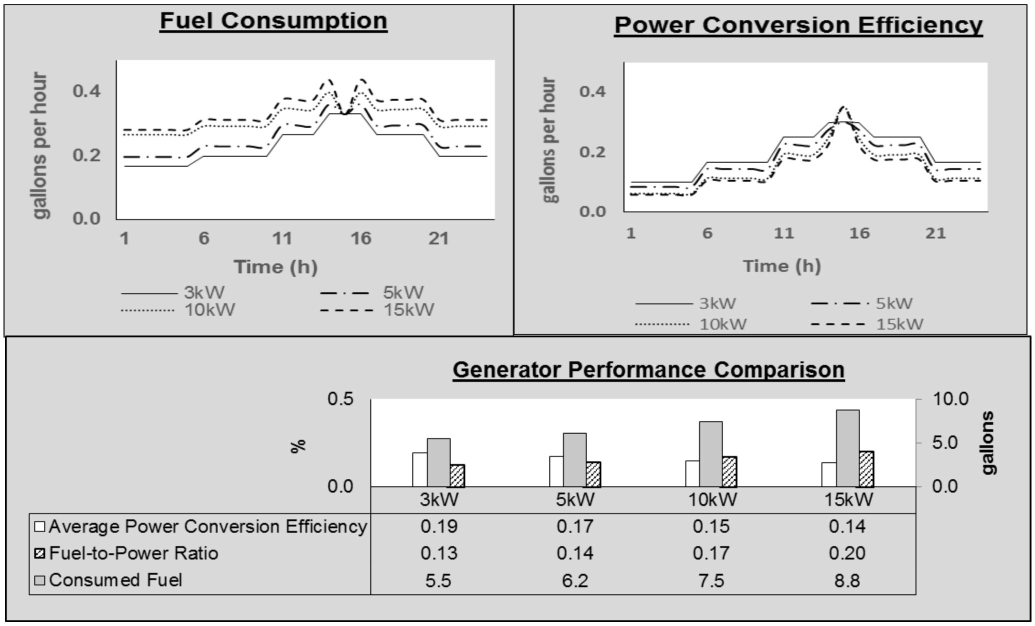
Component	Parameter	Values
Generator	Nominal Voltage (VAC)	120
	Load factor (%)	Time and load dependent
	Capacity (kW)	3, 5, 10, 15
	Maintenance Cost	$230/service
	Service Interval (h)	100
Battery	Capacity (kWh)	4.8kWh, 12kWh, 30kWh (MEHPS)
	Discharge Rate	Based on load
	Charge Rate	0.05C – 1C
	Nominal Voltage (VDC)	28VDC (MEHPS RFP)
	Depth of Discharge (DOD, %)	0- 80
	Minimum SOC (%)	10
	Maximum SOC (%)	90
	Initial SOC (%)	90
	Charge Efficiency (%)	90
	Discharge Efficiency (%)	100%
	Cut-off Voltage	EOCV and EODV for Leaf battery
	Self-Discharge/h	0.005%
Inverter	Efficiency (%)	92% (Yang et al., 2008)
System	Control Scheme	Passive

Table 4.2. Parameter Constraints

	Generator	Battery	Load
Capacity	3kW	4.8 – 12 kWh	Peak must be less than 110% of 3kW DG rated capacity
	10kW	12 – 30 kWh	Peak must be less than 110% of 10kW DG rated capacity
Control	On: SOC < min SOC Off: SOC < max SOC	Min SOC: 10% Max SOC: 90%	SOC-dependent passive control

4.2 Generator Model Validation

The generator model captures fuel consumption and other performance metrics well. . Dependence of generator performance on load condition is noted for all generators. Figure 4.1 shows that generators tend to perform best when servicing loads that yield high power factor; ie loads that approximate the generator's rated capacity. For example, for Fall/Spring load with 3.5kW peak, a 3kW generator consumed less fuel and generator's efficiency (19%) is low compared to standard DG efficiency (30 – 40%). This poor performance reflects the fact that the load's sustained average (1.4kW), which presents a less-than 50% load factor, is low and detrimental to the generator's performance. Similar trends were observed for summer and winter loads serviced by a 10kW genset.

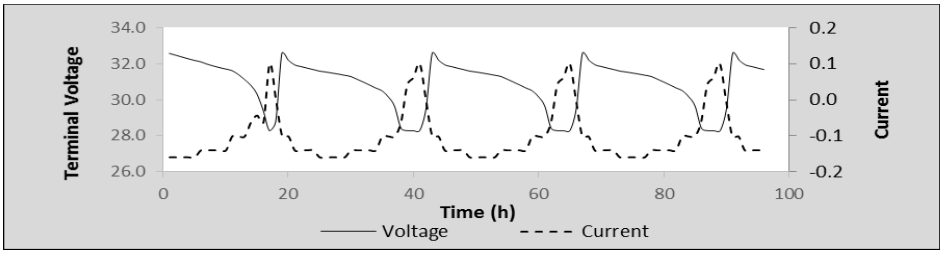


	3kW	5kW	10kW	15kW
☐ Average Power Conversion Efficiency	0.19	0.17	0.15	0.14
▨ Fuel-to-Power Ratio	0.13	0.14	0.17	0.20
☐ Consumed Fuel	5.5	6.2	7.5	8.8

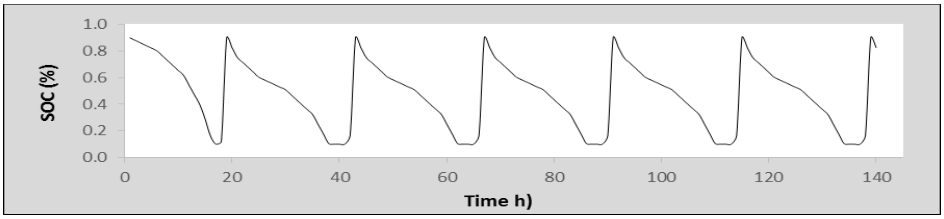
Figure 4.1 Generator Performance Model Validation

4.3 Battery Model Validation

As discussed previously, the battery used in this research have similar chemistry and cell characteristics as the Nissan Leaf HEV battery. Figures 4.2 shows simulation of the battery over a six-day summer load profile. The transient response is consistent with standard transient response of Lithium-based batteries, with minimal voltage drop throughout the duty cycle. For this particular simulation, C-rate is 0.5 and appears to be sufficient for fast recharge with a 5kW DG. The battery also exhibits good performance in terms of discharge time, providing over approximately 20-hours of silent watch.



(a)



(b)

Figure 4.2 Simulation of 12kW battery servicing the fall/spring profile load with a 5kW DG. (a) Transient response during charge and discharge; (b) State-of-charge.

4.4 Optimal C-Rate Selection

Further battery simulation and analysis in this research is conducted at C-rate of 0.5C. This decision was influenced by analysis of C-rate sensitivity to maintenance cost, and by review of lithium-ion battery life literature in chapter 2, which proposed that cycle life is optimized between 0.4C and 0.8C. C-rate is the rate of electron-packet or Coulomb charge flow (current)—expressed as fraction of battery capacity –that is required to completely charge or discharge the battery in an equivalent fraction of one hour. For example, at C-rate of 0.5, a 4.8kWh battery would discharge at 2.8kW per hour and would be completely depleted in 30 minutes. C-rate can also be measured by power through the relation (P = I V) if voltage is assumed to be constant. In this research, loads and generator output power are at a nominal voltage 120VAC. The battery receives rectified power for charging, and discharges power to an inverter at a nominal voltage of 28VDC. The simulation accounts for the energy losses associated with these power conversion steps. High C-rate (1C and above) means that a battery receives or outputs charge at greater intensity, which induces stress to its cell microstructure and as well as unfavorable chemical reactions. This is consistent with the sensitivity analysis in Figure 4.3 where it is apparent that maintenance cost remains flat between 0.2C and 1C for various capacity combinations.

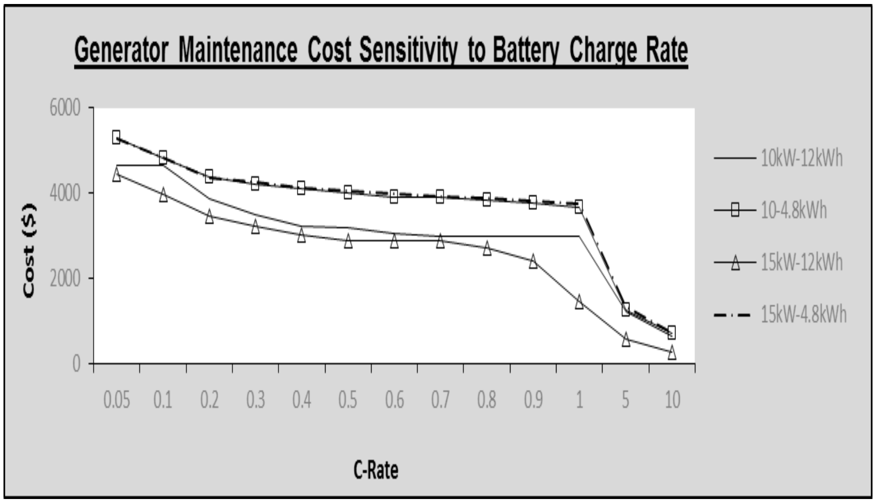


Figure 4.3 C-Rate sensitivity to generator maintenance cost

Battery life literature also established that C-rate is directly proportional to capacity fade. This is evident in Figure 4.3, wherein duty cycles (reduction in battery cycle life) increases with C-rate. It is also evident that C-rate is directly proportional to discharge time, and inversely proportional to charge time, so that the battery charges faster at high C-rate, and vice versa. This is intuitive and analogous to a water tank—the faster the flow in and out of the tank, the faster the tank will fill up and drain out. This will remain true if inflow and outflow water pressure is constant over time, and if inflow and outflow do not occur simultaneously. Under dynamic pressure, however, time required to fill or drain the tank will change in accordance with the magnitude of pressure change. This is another way of stating that charge and discharge are dependent on load.

4.5 Hybrid System Validation

Figure 4.4 shows simulation of a 10kW-12kWh B-G HPS employed for the summer load. Results show that the system, under passive control, tracks and responds to battery SOC. SOC never exceeds the minimum and maximum threshold of 10% and 90% respectively, although these thresholds are not reached during some parts of duty cycle. This non-uniformity represents inefficiency due to transient loads. The system's power output is also consistent with expected behavior. The battery's output (green line) closely tracks load (red line), and when the generator is on, it outputs enough power to sustain the load and charge the battery. Although the generator output (black line) exceeds demand, a significant proportion of the excess power is used to charge the battery. This guarantees that they generator runs at high load factor, which improves its power conversion efficiency and fuel consumption. These trends are consistent for all loads and battery-generator capacity combinations, with slight magnitude variations across C-rate range of 0.05-1C (see Appendix C).

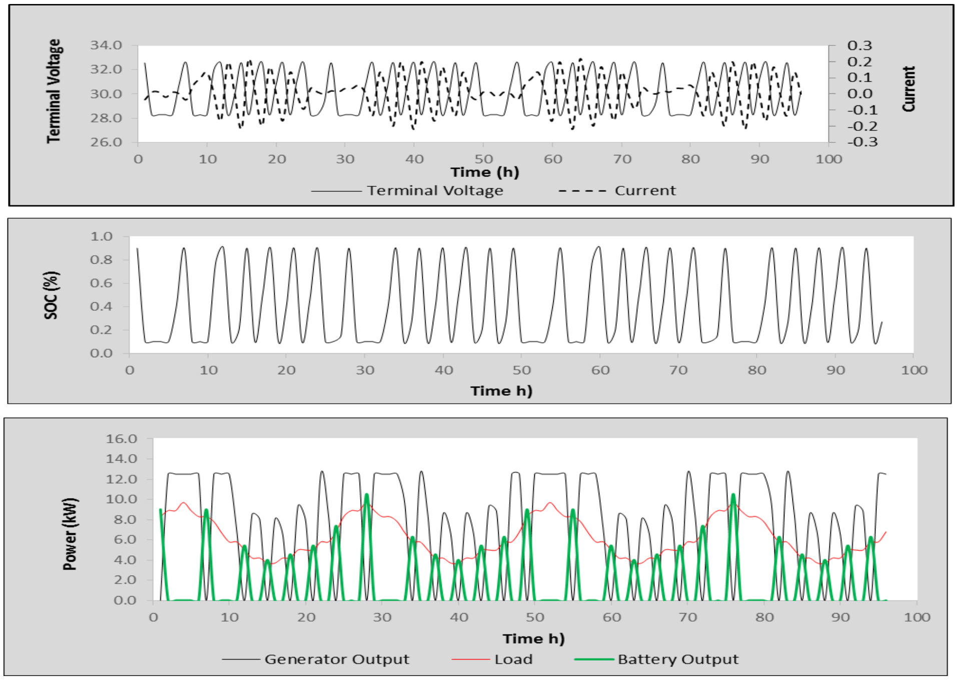


Figure 4.4 Simulation of 10kW-12kWh B-G HPS (top chart – battery voltage response, middle chart – SOC, bottom chart – power output).

4.6 Analysis for Fall/Spring Load

4.6.1 Stand-alone Generators

The Fall/Spring daily load (Figures 4.5a) is characterized by a 3.5kW peak, and 1.5kW average, and seven transitions (four increases and three decreases). Demand is below average during 14 hours of the day, and load factor for the 3kW generator (the smallest of all four tested generators) is below 40% for 14hours. The load is characteristic of non-ideal conditions that are detrimental to efficient and healthy DG operation. Figure 4.4b and c show standalone DG performance on the fall/spring load. It is obvious that the 3kW performs best on all metrics. Employing a higher capacity generator would be wasteful; however the 3kW generator leaves no room for flexibility.

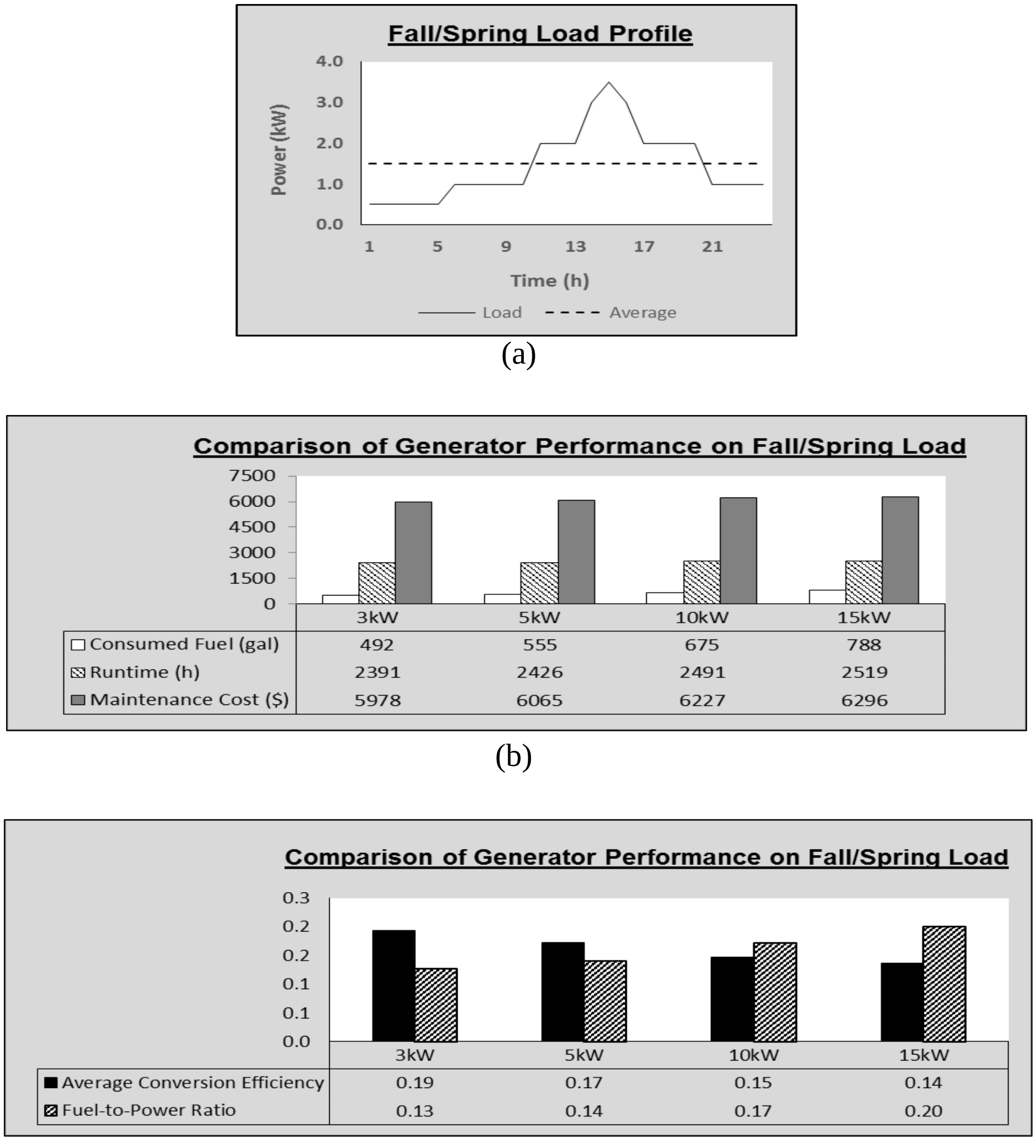


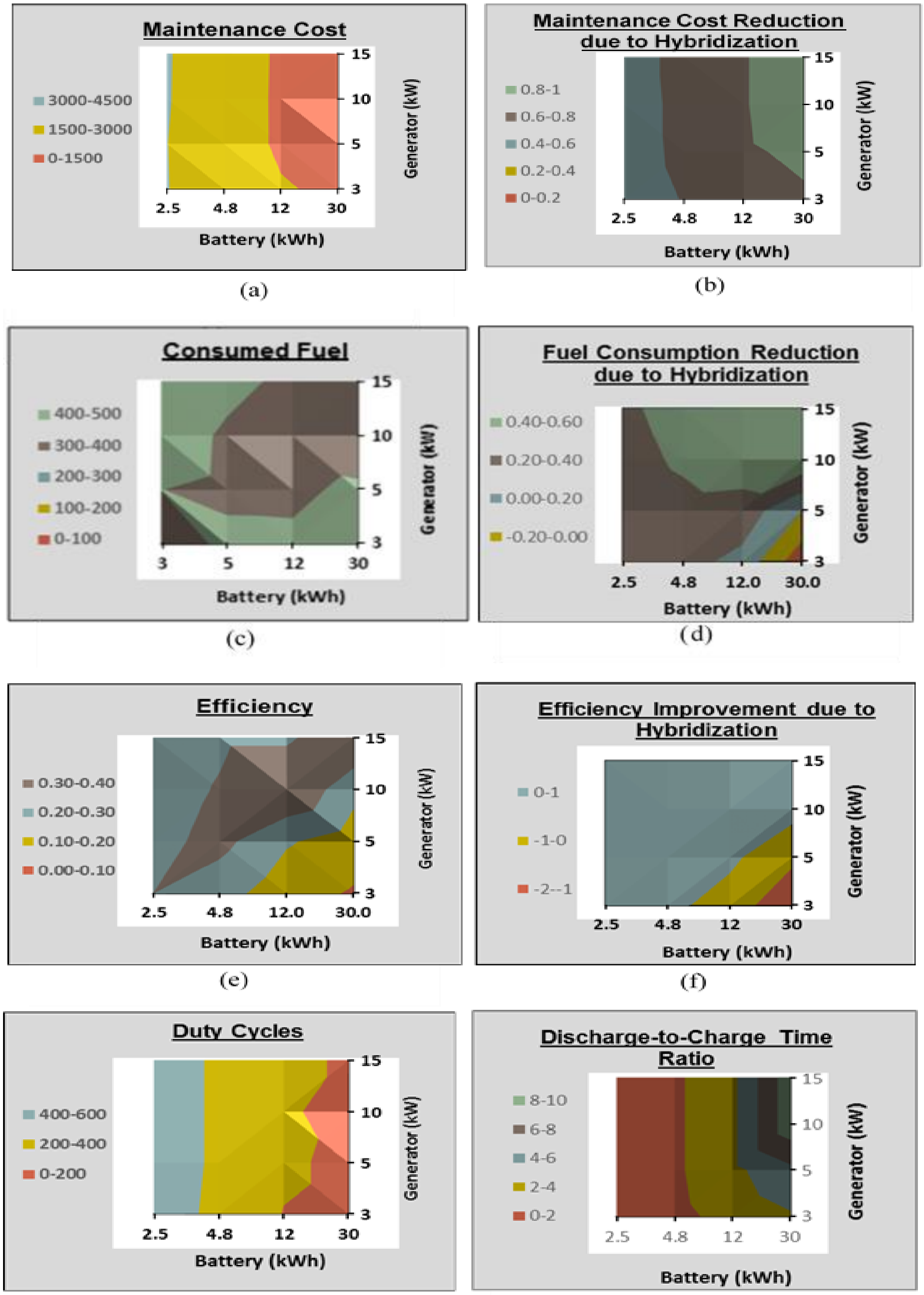
Figure 4.5a. Standalone DG performance metrics on fall/spring load. (a) Load profile; (b) comparison of runtime, fuel consumption, and maintenance cost; (c) efficiency comparison

4.6.2 Hybrid System

The preceding results should be different for a hybrid system. As the research proposed, a battery should enable significant reduction generator runtime, and consequently maintenance cost. However, the extent to which a certain battery and DG capacity would reduce cost is not intuitive. To that end, this research presents result of B-G HPS capacity optimization in the context of design-space analysis. As presented, the analysis visualizes degree flexibility for optimizing a specific B-G HPS performance metric. The space boundaries incorporate constraints established by MEHPS requirements. A raw measurement of each metric is presented, as well as the percentage difference from the measurement taken for a standalone generator. Figure 4.6a-h show design space in which various performance metrics are optimized for the fall/spring load profile, at C-rate of 0.5. It is clear that an optimum occurs at different capacity combinations for each metric.

For maintenance cost, Figure 4.6a and 4.6b show that it is possible to achieve significant improvement from generator-only performance throughout a range of battery and generator capacities. High percentage cost reduction is achieved in the upper bound of the design space; however, improvement at those capacities will come with a penalty on other performance metrics. Given the weight and volume concerns outlined in chapter 2, it would be unwise to pursue such maintenance cost reduction of over 80%, since that would translate to significant increase in battery size. Furthermore, Figures 4.6c and 4.6d show that the region of design space which yields high percentage reduction in maintenance cost also yield the least reduction in fuel consumption. Figure 4.6c also show that for the fuel system capacity limits simulated, there is at least 300 gallons of fuel consumed, which still represents at least 20% reduction from standalone generator fuel consumption.

Figure 4.6e show that maximum efficiency of 40% can be achieved over a wide range of both generator and battery capacities. However, flexibility for optimizing efficiency decreases near the lower bound of the space. Minimum duty cycle is desired because it represents the lowest reduction to battery lifecycle. Figure 4.6g shows that only the upper bound of battery capacity can minimize duty cycle for all generator capacities. That region also achieves the maximum discharge time-to-charge time ratio (D-C time ratio), which must be greater than 2 (Figure 4.6h). The D-C ratio requirement eliminates one-third of the design space (battery capacity less than 4.8kWh) from consideration. However, if all other considerations compel selection of battery capacity in this range, D-C ratio can be improved by increasing C-rate to decrease charge time.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 4.6: B-G HPS Design Space For Fall/Spring Load

Based on the preceding results, an optimal B-G HPS capacity combination can be 5kW-5.9kWh. This combination reduces maintenance cost by 68%, fuel consumption by 35%, improve efficiency by 44%, and yield allow 100% more discharge time than charge (D-C ratio of 2). For MEHPS-specific requirements, a 3kW generator must be used for the load. An optimal battery capacity within the permissible range is can be 7.9kWh. A 3kW-7.9kWh hybrid system cuts maintenance cost by 68%, fuel consumption by 29%, and also achieves a D-C ratio of 2:1. However, the system increases DG inefficiency by 6%. Avoiding efficiency loss would require decreasing battery size, which increase reduces cycle life, and pushes D-C ratio below acceptable threshold.

4.7 Analysis for Summer and Winter Loads

4.7.1 Diesel Generator-only

Table 4.3 and Figure 4.7 summarize characteristics of the summer and winter loads. The summer and winter loads (Figure 4.7) are similar in that they their peak is within range that can be serviced by the 10kW DG. Also, their average is over 40% of the 10kW DG rated capacity, and therefore do not fall under the definition of “low load”. However, the number of transitions, as well as range and standard deviation of the loads present highly transient condition that is potentially harmful to DGs, including those equipped with load-following capability. The following charts compare performance of a standalone DG and the B-G hybrid system on both loads.

Table 4.3 Summer and winter load characteristics (USMC, 2015)

	Summer	Winter
Peak	9.7	7.8
Average	6.3	4.9
Range	6.0	5.3
Standard Deviation	1.9	1.3
Number of transitions	14	12

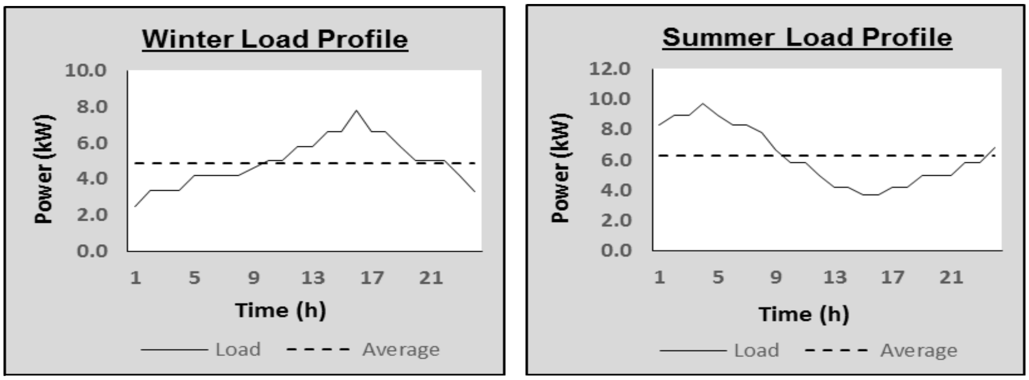
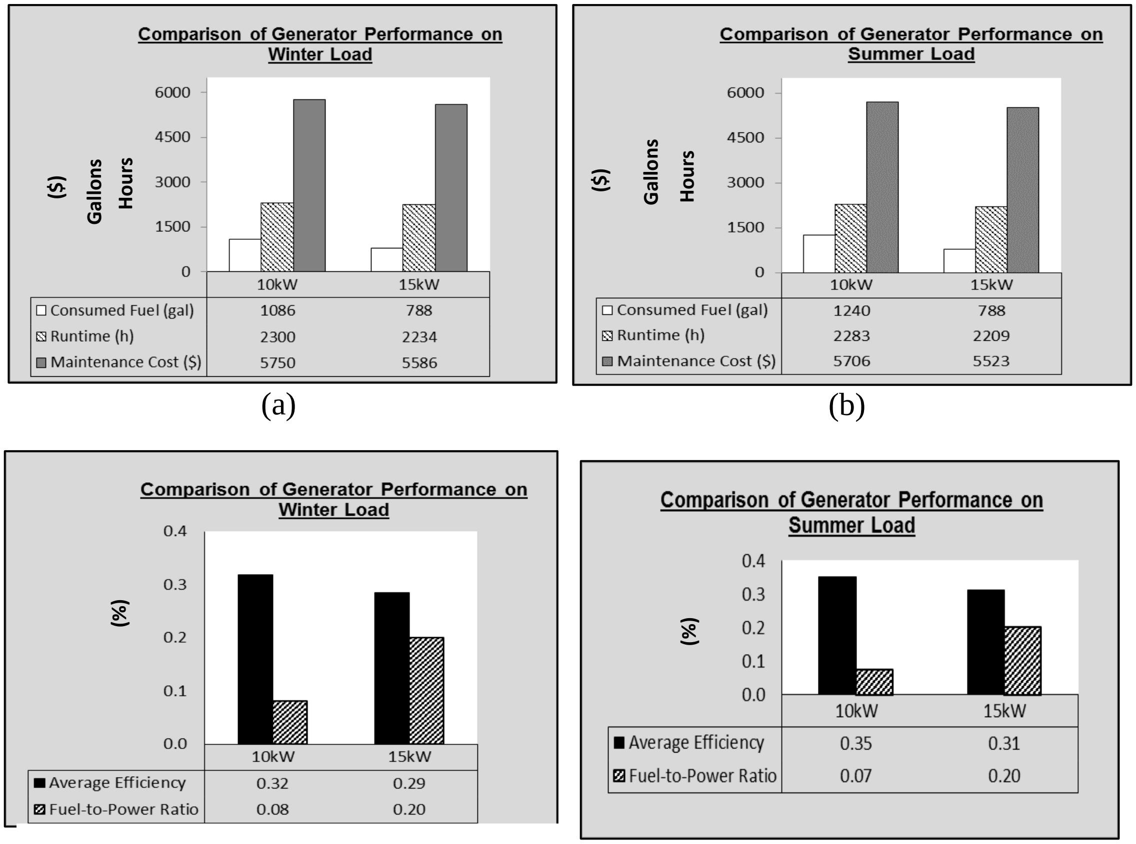


Figure 4.7 Summer and winter load profile

Figure 4.8a-d show performance of 10kW and 15kW standalone DGs on the summer and winter loads. For the winter load, the 15kW DG performs better—it consumes less fuel, has less total runtime (which implies less inefficiency losses), and lower maintenance cost; yet the 10kW DG has a higher energy-conversion efficiency. The same trend is observed for the summer load, and implies that optimization between the two generators will require nuanced analysis.



(a) (b)

(c) (d)

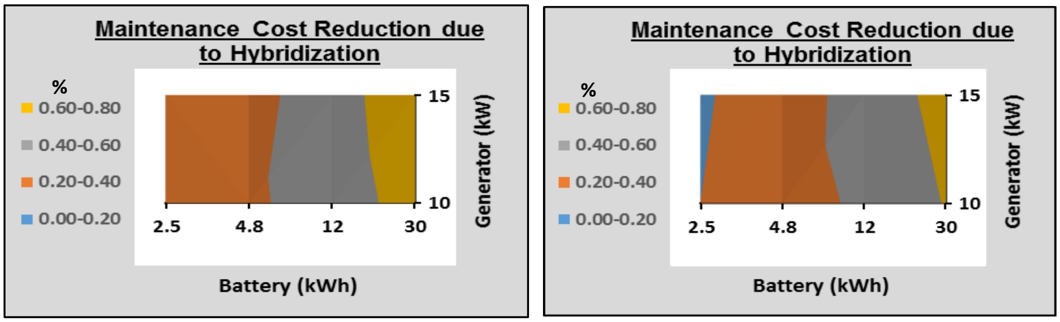
Figure 4.8: Standalone DG performance on summer and winter load.

4.7.2 Hybrid System

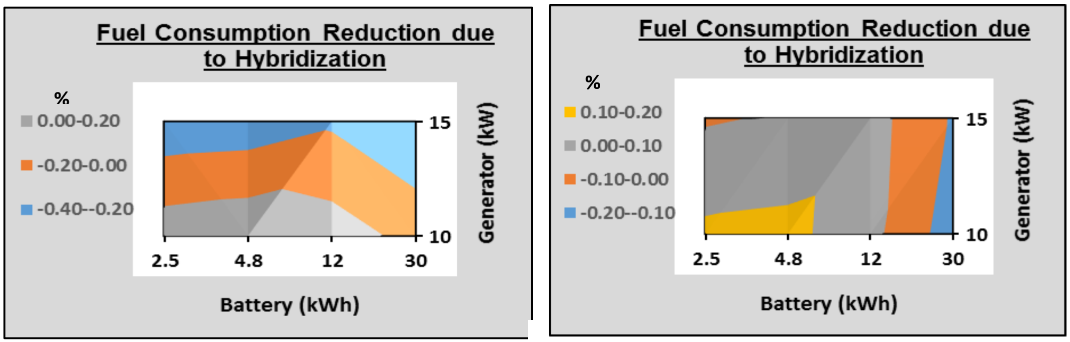
Figure 4.9a to 4.9h below depicts design space of various metrics derived from comparing B-G HPS performance to that of a standalone DG, under summer and winter loads. It should be observed that generator capacity is not continuous. DGs considered in this research are of known capacity; thus analysis of the design space will be limited to the generator capacity boundaries. Nevertheless, the design-space analysis technique employed herein paint a picture of optimization possibilities, and could be helpful for integrating extra generating capacity with renewable energy sources.

In Figure 4.9a and 4.9b, an inverse linear relationship between maintenance-cost reduction and battery capacity are observed in both load scenarios. Increasing battery capacity reduces maintenance cost by up to 80% at both generator boundaries. Also reduction in fuel consumption (Figure 4.9c and 4.9d) can reach up to 20% in the low end of battery for the 10kW generator under both load scenarios. There is negative fuel consumption reduction throughout the 15kW generator boundary under winter load. This means that more fuel is consumed by a B-G system comprised of 15kW and any battery size between 2.5kWh and 30kWh. For analysis in which fuel consumption is an optimization or decision criteria, the 15kW generator would be disqualified. There is, however, slightly more flexibility for using fuel consumption as capacity optimization criteria under the summer load. Both generators can achieve at least 10% fuel reduction when combined with battery capacity between 4.8kWh and 12kWh.

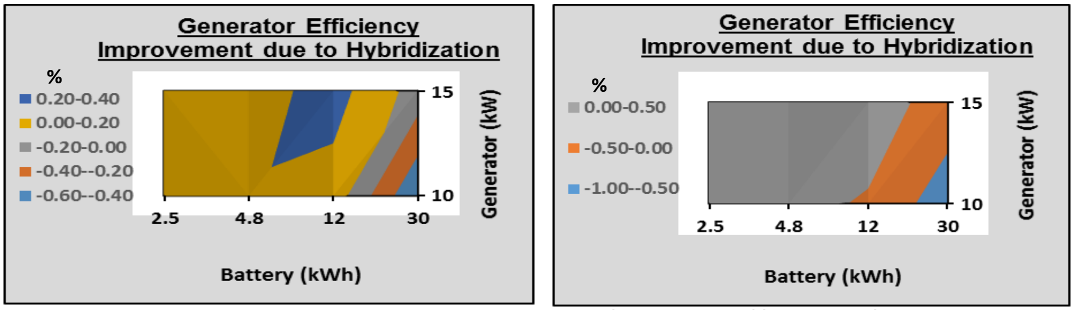
Furthermore, up to 40% improvement in DG power conversion efficiency is possible in the winter, but this can only be achieved with the 15kW generator and a limited battery capacity range. There is more flexibility in the summer load, where both generators can achieve and up to 50% efficiency improvement within a wider battery capacity range. Nevertheless, the upper bound of battery capacity for both loads appears to result in efficiency loss when combined with the 10kW generator. This is because at a fixed C-rate, a larger battery takes more time to charge; so the generator would run longer and consume more aggregate fuel than a standalone generator. Unfortunately, neither load allows for acceptable discharge-charge ratio within battery capacity range of 2.5kWh to 12kWh. For the 10kW and 15kW DGs, battery size must be greater than 12kWh for the hybrid system to spend more time doing useful work.



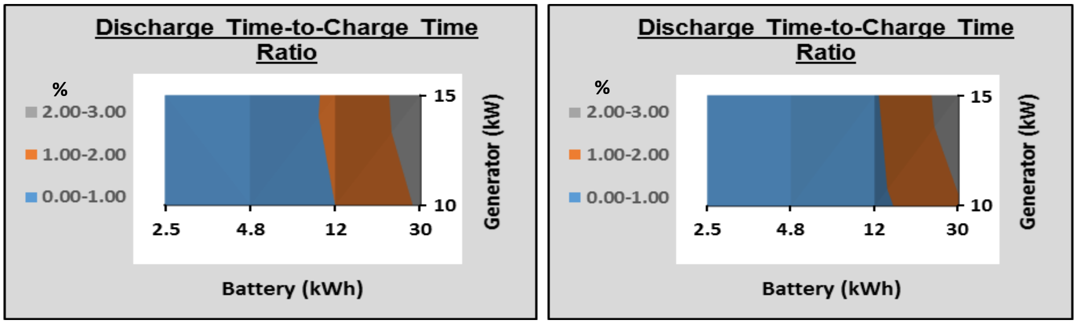
(a) Maintenance cost for winter load (b) Maintenance cost for summer load



(c) Fuel consumption for winter (d) Fuel consumption for summer



(e) Genset efficiency for winter (f) Genset efficiency for summer



(g) D-C time ratio for winter (h) D-C time ratio for summer

Figure 4.9 Design space for various performance metrics for summer and winter load profiles

4.8 Analysis for MEHPS Capacity Requirements

The design spaces analyzed above include a range of system capacities defined by the MEPHS program (Table 4.2). While it is apparent that significant performance enhancements (relative to a standalone DG) are achievable within capacity the capacity range, this research sought to refine the capacity estimate by finding an optimum within that range . Thus B-G HPS with "MEHPS-Low" and "MEPS-Medium" capacity boundaries were simulated respectively with the fall/spring and summer loads. Fixed parameters from preceding simulations were used: 0.5 C-rate, 10% min SOC, and 90% max SOC. Simulation results (Figures 4.10a to 4.10d) show normal cycle behavior. SOC remains within limits throughout duty cycle, and generator and battery power output satisfy demand.

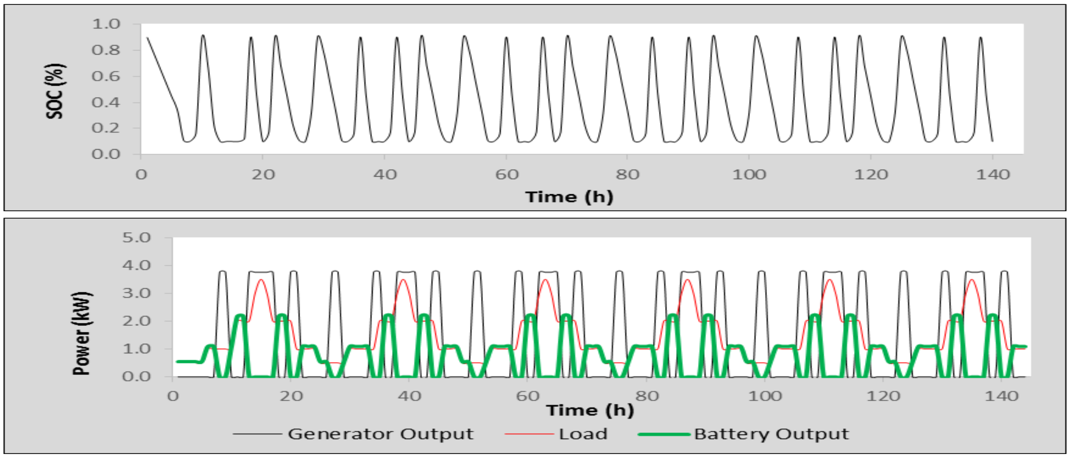


Figure 4.10a Simulation of "MEHPS-Low" lower boundary (3kW-4.8kWh) with fall/spring load.

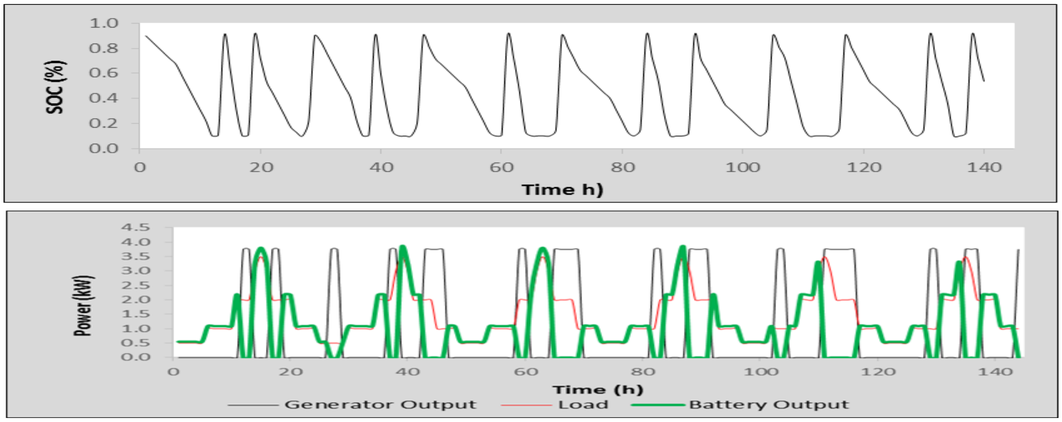


Figure 4.10b Simulation of "MEHPS-Low" upper boundary (3kW-12kWh) with fall/spring load.

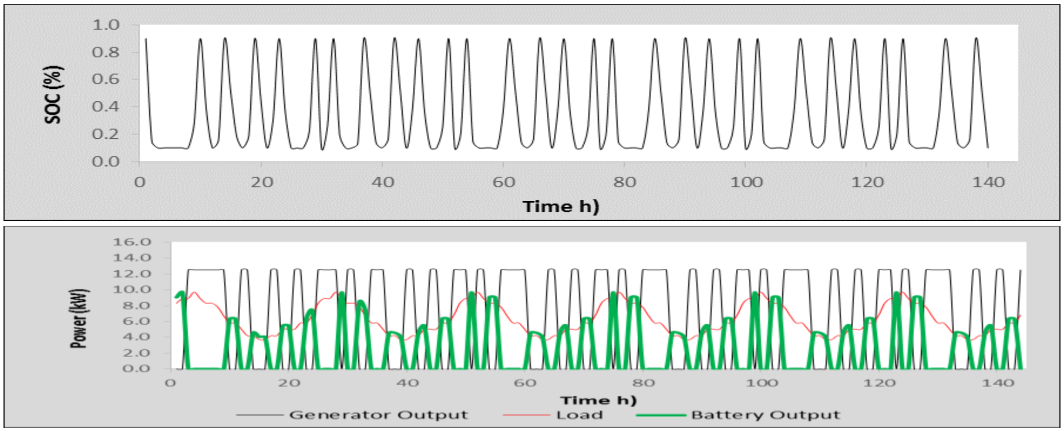


Figure 4.10c Simulation of "MEHPS-Medium lower boundary (10kW-12kWh) with summer load

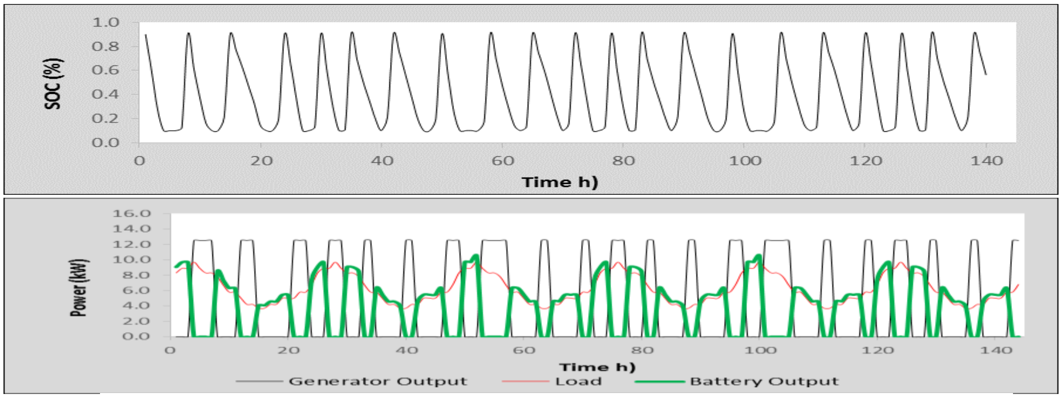
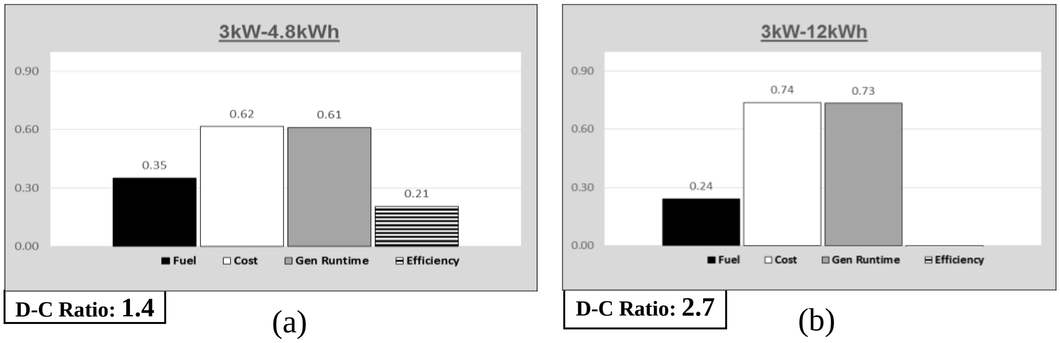


Figure 4.10d Simulation of "MEHPS-Medium" upper boundary (10kW-30kWh) with summer load

Performance metrics for MEHPS-Low (Figures 4.11) show that there is a +12% maintenance cost gap between the lower and upper bound of battery capacity. This signifies improvement relative to maintenance cost of a 3kW standalone DG. However, given that the battery capacity range (7.2kWh) is 50% of the minimum, the 12% maintenance cost margin may not satisfy decision or optimization criteria. Furthermore, the upper battery bound achieves lower fuel consumption improvement and no improvement in power conversion efficiency. Nonetheless, the bigger battery increases discharge-to-charge time ratio by almost 50%. Optimization within the MEHPS-Low capacity range requires tradeoff between minimal change in fuel consumption and maintenance cost, moderate generator efficiency change, and significant change to battery cycle life

.As noted in Chapter 3, the optimization criterion for this research is that D-C time ratio must be greater than two—a B-G HPS capacity must enable twice as much discharge time as charging. The criterion is satisfied for in the upper bound of MEHPS-Low battery capacity, starting precisely from 7.9kWh. This optimal battery capacity (3kW-7.9kWh) , relative to a 3kW standalone DG, yields a 68% and 21% reduction in maintenance cost and fuel consumption, respectively. However, the optimized system leads to 6% loss of energy conversion efficiency, which is significant, given that the standalone DG efficiency (19%) is already low. Nevertheless, the efficiency loss is compensated by a lower reduction to battery cycle life. Compared to a 4.8kWh battery, which enables 24% power conversion efficiency, the 7.9kWh battery would cycle 28% less often and would last longer.



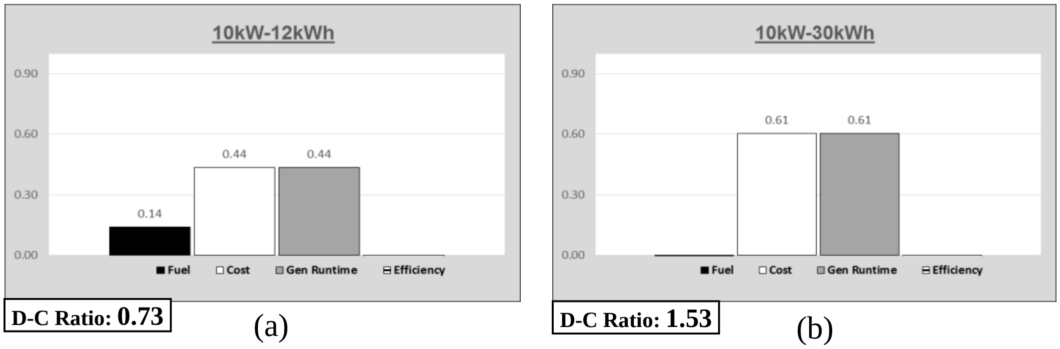
(a) (b)

Figure 4.11 Change in performance of "MEHPS-Low" capacity B-G HPS, relative to standalone DGs, simulated with summer load.

Performance metrics for MEHPS-Medium (Figure 4.12) also show maintenance cost reduction between within the battery capacity range. Fuel consumption reduction is evident only toward the lower boundary. Power conversion efficiency decreases on both boundaries. These results are slightly different from MEHPS-Low results, but similar conclusion is evident: optimization within the battery capacity range will require tradeoff between moderate maintenance cost reduction, fuel consumption increase, and worsening conversion efficiency. Another obvious conclusion is that the D-C time optimization criterion is not satisfied within this battery capacity range. To obtain a D-C ratio of 2, battery size must be at least 39.4kWh, which allows for 15% duty cycle reduction (i.e. battery life extension) from the MEHPS-Medium upper battery capacity limit. However, the 39.4kWh battery would exacerbate DG efficiency loss by efficiency loss by 32% . This is significant and challenges prudence of the D-C ratio criterion.

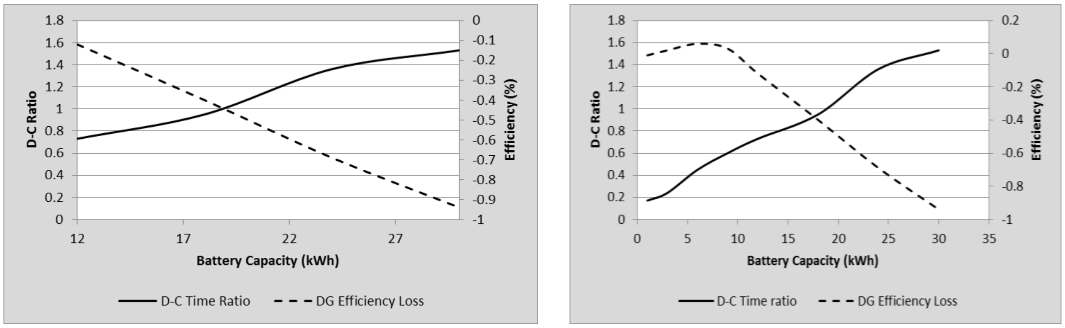
Given the motivations for this research—the need to minimize impact of non-ideal load conditions on DG health, efficiency loss should be minimized or avoided completely. This consideration compels changing the D-C ratio criterion to a point that leads to zero efficiency loss. Such a point would be optimal, but does not exist within the

MEHPS-Medium capacity boundary. The lower limit (12kWh) yields 12% efficiency loss, and increases infinitely with increasing battery capacity. Below the limit, efficiency loss is eliminated between 2.5kWh and 9.4kWh; however, D-C time ratio at this capacity range is less than 1, meaning that charging time exceeds discharging time by no less than 60%. These results suggest that an optimal battery capacity, which satisfies both DG efficiency and D-C ratio criteria, does not exist within the design space defined not only by the MEHPS-Medium capacity range, but also by design variables that were held constant in the simulation. An optimal capacity can be found by varying C-rate and DOD.



(a) (b)

Figure 4.12 Change in performance of "MEHPS-Medium" capacity B-G HPS, relative to standalone DGs, simulated with summer load



(a) (b)

Figure 4.13 Optimization Criteria Analysis for MEHPS-Medium

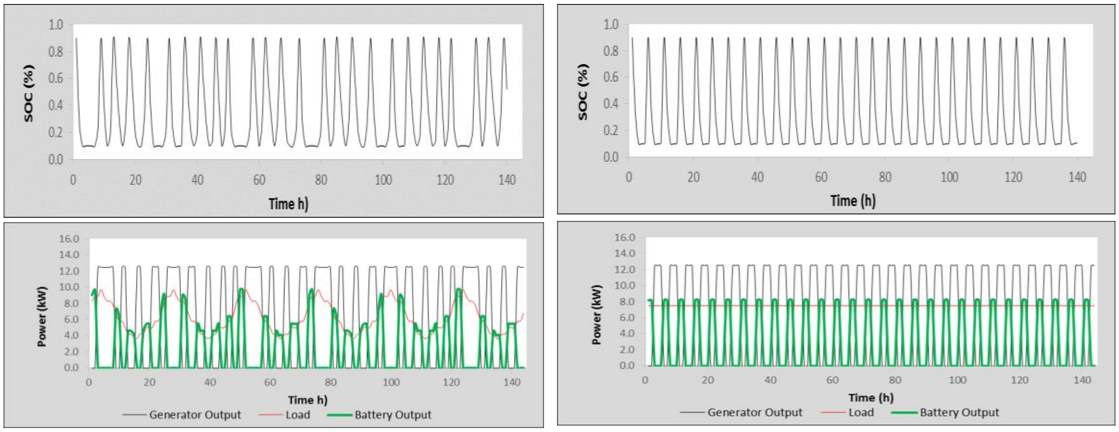
Analysis for CASCOM Systems

As noted in Chapter 2, cost-benefit analysis (C-BA) of the MEHPS program conducted by CASCOM concluded that the life-cycle cost, as well as operation and maintenance (O&M) cost of battery-generator hybrid power systems, relative to other on-going TEP programs, do not justify further R&D investments. The study focused on specific employment scenarios in which hybrid power systems are dedicated to independent static loads such as that of basecamp perimeter-defense systems (CASCOM, 2014, p. 8). These scenarios (Table 4.4) simulate extended system operation under relatively high load factors—67% and 75% respectively—but do not capture nor enable visualization of the attenuating effects of energy storage for operation under less ideal load conditions. While the analysis highlights the cost and technical limitations of hybrid systems, it also reinforced the understanding that solutions to contingency basecamp energy problems inherently require tradeoffs, and should be comprehensive. This research presents results of simulation and optimization for the CASCOM hybrid systems employed against the dynamic fall/spring load profile. The results highlight need for tradeoffs and nuance.

Simulation of CASCOM systems also assumed 100-hour service intervals, and per-service cost of $250. Table 4.5 compares performance of the Storage-Only Low system to performance of a standalone 3kW DG, while Table 4.6 compares results for the Storage-Only Medium system with a 10kW standalone DG. At a maximum discharge rate of 1C, the hybrid systems yield moderate to significant reduction in generator runtime, fuel consumption, and maintenance cost over a 90-day mission cycle. Analysis in this research also shows that capacity of both CASCOM systems could be further optimized. Reduction in the battery's DOD to 50% from 80% allowed for the battery capacity to be reduced while simultaneously increasing fuel consumption savings from 13% to 30%. This adjustment, however, increased maintenance cost by 15%, and decreased cycle life by 25%. The aggregate impact of these adjustments on life-cycle and O&M cost constitute tradeoffs that would inform a more nuanced analysis and conclusion.

Table 4.4 System Parameters used in CASCOM 2014 C-B Analysis of MEHPS

	Storage-Only-Hybrid-Low	Storage-Only-Hybrid-Medium
Generator Capacity	3kW	10kW
Battery Capacity	5kWh	14.4kWh
Load	2.5kW static over 12 hours	7.5kW static over 24 hours



(a) (b)

Figure 4.14 Simulation of CASCOM "Storage-Only-Hybrid-Medium" system on (a) summer dynamic load, and (b) 7.5 static load.

Table 4.5 Comparison of Standalone DG and Hybrid System Performance on Dynamic and Static Load

	10kW-Only on static load	10kW-Only on dynamic load	10kW-14.4kWh-Hybrid on static load	10kW-14.4kWh-Hybrid on dynamic load
Generator Runtime (h)	2272	2283	1321	1111
Fuel (gallons)	1386	1240	1388	1122
#services	23	23	13	11
Maintenance Cost ($)	5679	5706	3303	2777
Efficiency	0.39	0.35	0.31	0.32
Duty Cycles	NA	NA	420	435
Discharge Time (h)	NA	NA	58	72
Charge Time (h)	NA	NA	86	72

Table 4.6 Effect of Load Type and Hybridization on System Performance

	% Change for 10kW-Only due to change in load type	% change between hybrid system and standalone DG on static load	% change between hybrid system and standalone DG on dynamic load	Difference due to dynamic load
Generator Runtime (h)	0	-0.72	-1.05	-0.33
Fuel (gallons)	-0.12	0	-0.11	-0.11
#services	0	-0.43	-0.52	-0.09
Maintenance Cost ($)	0	-0.72	-1.05	-0.33
Efficiency	-0.11	-0.13	-0.09	0.04
Duty Cycles	N/A	N/A	N/A	0.03
D-C Ratio	N/A	N/A	N/A	0.33

Results in Tables 4.5 and 4.6 indicate that the CASCOM analysis is moderately sensitive to load type. Using the 7.5kW static load is used to the”Medium” hybrid system yields a 72% reduction in maintenance cost relative to a 10kW standalone DG. However, using the dynamic summer load is used to simulate the hybrid system yields 33% more maintenance cost reduction relative to standalone DG. Similar result is evident when the dynamic load is used to simulate the 10kW standalone DG. However, in both hybrid system and standalone DG, simulation with the dynamic load yielded loss in DG efficiency. The efficiency loss under dynamic load reflects the fact that the static load presents a high load factor to the 10kW generator, making it run more efficiency. The loss also suggests that there are enough low-load periods to reduce the DG’s average load factor of the dynamic profile below that of the static load. This is evident in the fat that the hybrid system’s battery would cycle 33% more times under the dynamic load. The dynamic load reveals more non-linearities and tradeoffs, considerations of which may influence cost-benefit analysis.

CHAPTER 5. CONCLUSION

Diesel generators are reliable source of power in isolated settings where grid electricity is either practically inaccessible or not available. However, their performance suffers when subjected to low and transient load conditions, which are prevalent in expeditionary basecamps that support military contingency operations and disaster-relief activities. The dynamic tempo and sustainment requirements of contingency operations give rise to sustained periods of low-average power demand and frequent short-duration peaks. Such conditions are less-than-ideal, and subject diesel engines to energy-intensive and mechanically-tasking operations, which lead to inefficient combustion, inefficient fuel consumption, increased wear and tear, and greater chance of essential function failure.

According to 2010 estimates, there are approximately 106,000 generators sets across the Department of Defense (Richard, 2009; RDECOM, 2013). This inventory and recent acquisition and R&D investments represent a long-term commitment to DGs as the military's primary source of TEP (CASCOM, 2014a, 2014b). Underlying this commitment is role of innovative combustion technologies—such as variable-speed engines, electronic fuel injection, and power control electronics— in improving performance modern generators such as AMMPS. Nevertheless, investment in DGs unfortunately keeps the military tethered to fuel and its attendant logistical challenges, which are exacerbated by the effects of non-ideal load condition on DG's power conversion efficiency and reliability.

Notwithstanding the ability to adjust speed, follow load changes, the science of combustion suggests that DGs are inherently vulnerable to non-ideal load conditions. The process of dealing with those conditions are potentially deleterious to healthy DG operation. Even with ideal conditions that are favorable for efficient generator operation, the burdens associated with contingency basecamp energy logistics are significant, and include risks inherent in protecting extensive supply lines that often run through treacherous terrain or hostile territory. The deleterious impact of low and transient load conditions exacerbates that inherent burden, and contributes to increased requirement for fuel and repair parts. The ultimate solution to this problem may be to replace diesel generators with renewable energy or non-combustion technologies that do not rely on externally-provided fuel. However, cost, energy density, and deployability limitations of renewable energy technologies continue to mar their wide application to TEP generation. Until those challenges are overcome, DG's vulnerability to non-ideal load conditions will

This research investigated the potential of an interim solution—hybridizing diesel generators with energy storage batteries. The solution is based on the simple idea that a battery would provide additional load that forces generators to operate at full load, thus eliminating the occurrence of load and transient loads. Batteries provide an energy storage capacity that can be used as prime power source, thus reducing generator runtime and eliminating the need for redundant generators. Results show that hybridizing DGs—combining them with a battery and limiting their usage to the battery's recharging period, enables over 50% in the generator's runtime. This allows for equally significant reduction in the number of times the generator needs to under maintenance services. Consequently, maintenance cost over a given period is reduced. The research also showed that a battery improves other generator performance metrics. Depending on the load, fuel consumption can be reduced by up to 30%, and power-conversion efficiency is improved by up to 20%. These improvements are possible while the battery can provide at least twice as much discharge time (silent watch capability) than charging time.

REFERENCES

LIST OF REFERENCES

Aalborg University (2014). Energy plan: Advanced energy systems analysis computer model. Department of Development and Planning. Aalborg, Demark. Retrieved from http://www.energyplan.eu/

Agarwal, N., Kumar, A., & Varun. (2013). Optimization of grid independent hybrid PV-diesel battery system for power generation in remote villages of Uttar Pradesh, India. *Energy for Sustainable Development*, *17*(3), 210–219. doi:10.1016/j.esd.2013.02.002

Army Capability Integration Center. (2010). *Power and energy strategy white paper*. (Research, Development, and Engineering Command). Ft. Monroe, VA: U.S. Army

Army Equipping Enterprise System (AE2S) data, 25 January 2010.

Baring-Gould, E I, Green, H J, van Dijk, V A.P., & Manwell, J F. (1996). Hybrid2: The hybrid power system simulation model. United States. Retrieved from http://www.osti.gov/scitech/servlets/purl/377591

Bilal, B. O., Sambou, V., Kébé, C. M. F., Ndiaye, P. a., & Ndongo, M. (2012). Methodology to size an optimal stand-alone PV/wind/diesel/battery system minimizing the levelized cost of energy and the CO 2 emissions. *Energy Procedia*, *14*, 1636–1647. doi:10.1016/j.egypro.2011.12.1145

Bolton, C. (2009). *Army R&D Efforts*. Electrical Generating Systems Association (EGSA) Fall 2009 Meeting.

Borhanazad, H., Mekhif, S., Gounder Ganapathy, V., Modiri-Delshad, M., & Mirtaheri, A. (2014). Optimization of micro-grid system using MOPSO. *Renewable Energy*, *71*, 295–306. doi:10.1016/j.renene.2014.05.006

Borshchev, A., & Filippov, A. (2004). From system dynamics to agent based modeling. *22nd International Conference of System Dynamics Society*.

Broussely, M., Biensan, P., Bonhomme, F., Blanchard, P., Herreyre, S., Nechev, K., & Staniewicz, R. J. (2005). Main aging mechanisms in Li ion batteries. *Journal of Power Sources*, *146*(1-2), 90–96. http://doi.org/10.1016/j.jpowsour.2005.03.172

Buhaug, Ø. (2003). *Deposit Formation on Cylinder Liner Surface in medium-speed Engines*.

Burke, S. (2013). The Institutional Advantage: Building an energy-informed military. DoD Power, Energy, & Propulsion

Communications-Electronics Research, Development, and Engineering Center. (2013). *Small Tactical Electric Power Technology Transition Brief.* (Research, Development, and Engineering Command). : U.S. Army

Current Operational Analysis Support Team. (2010, September). *Analysis of logistics related casualties for Marine forces in Afghanistan*. (Operations Analysis Division, Marine Corps Combat Development Command): Quantico, VA: U.S. Marine Corps

Deshmukh, M. K., & Deshmukh, S. S. (2008). Modeling of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*. http://doi.org/10.1016/j.rser.2006.07.011

Diaf, S., Diaf, D., Belhamel, M., Haddadi, M., & Louche, a. (2007). A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy*, *35*(11), 5708–5718. doi:10.1016/j.enpol.2007.06.020

Dufo-López, R., & Bernal-Agustín, J. L. (2005). Design and control strategies of PV-Diesel systems using genetic algorithms. *Solar Energy*, *79*(1), 33–46. http://doi.org/10.1016/j.solener.2004.10.004

Doyle, M., Fuller, T. F., & Newman, J. (1993). Modeling of galvanostatic charge and discharge of the lithium/polymer/insertion Cell. *Journal of The Electrochemical Society*, *140*(6), 1526. http://doi.org/10.1149/1.2221597

Doyle, M., & Newman, J. (1995). Modeling the performance of rechargeable lithium-based cells: Design correlations for limiting cases. *Journal of Power Sources*, *54*, 46–51.

Ellwood, L., Cycowski, A., Panozzo, P., & Raney, T. (2009). *Tactical Electric Power (TEP): Emerging technologies and initiatives that influence organization power needs white paper* (Combined Arms Support Command publication). U.S. Army

Expeditionary Energy Office. (2013). *Mobil Electric Hybrid Power Sources (MEHPS) Brief to Industry*. U.S. Marine Corps.

Fares, R. L., & Webber, M. E. (2014). A flexible model for economic operational management of grid battery energy storage. *Energy*, *78*, 768–776. doi:10.1016/j.energy.2014.10.072

Frederich-Alexander University (2014). Hybrid Simulation of Smart Energy Systems. Department of Computer Science. Erlangen-Nuerenburg, Germany. Retrieved from http://www7.cs.fau.de/en/.

Green, H. J., & Dijk, V. A. P. Van. (1996). Hybrid2 - The Hyb System Simulation Power, (July).

Grigoryev, I. (2015). *Anylogic 7 in three days: A quick course in simulation modeling.* Lexington, KY: The AnyLogic Company

Hammack, K., (2012). The Value of Energy Security from Battlefield to the Base: Statement by Assistant Secretary of the Army for Installations, Energy, and Environment. House Armed Services Committee. U.S. House of Representatives. Second Session, 112th Congress.

Harada, Fukzawa and Takimoto (2007). *Investigation Report.* Mitsubishi Heavy Industries, Ltd.

Hong, Y. Y., & Lian, R. C. (2012). Optimal sizing of hybrid wind/PV/diesel generation in a stand-alone power system using markov-based genetic algorithm. *IEEE Transactions on Power Delivery*, *27*(2), 640–647. doi:10.1109/TPWRD.2011.2177102

Jagels, G. (2013). Solving Austerity: How will the DoD provide power to off-the-grid bases? *DoD Power, Energy & Propulsion*, *1*, 2 – 5.

Kaabeche, A., & Ibtiouen, R. (2014). Techno-economic optimization of hybrid photovoltaic/wind/diesel/battery generation in a stand-alone power system. *Solar Energy*, *103,* 171–182. http://doi.org/10.1016/j.solener.2014.02.017

Khare, V., Nema, S., & Baredar, P. (2015). Optimisation of the hybrid renewable energy system by HOMER, PSO and CPSO for the study area. *International Journal of Sustainable Energy*, (June), 1–18. doi:10.1080/14786451.2015.1017500

Kusakana, K., & Vermaak, H. J. (2013). Hybrid diesel generator - battery systems for offgrid rural applications. *Proceedings of the IEEE International Conference on Industrial Technology*, 839–844. doi:10.1109/ICIT.2013.6505781

Larsen, A. (2014). *A method of visualizing state of charge of batteries in hybrid generators*. Unpublished manuscript. Department of Computer and Information Technology, Purdue University, West Lafayette, Indiana, USA.

Lasswell, J. (2010). *Experimental Forward Operating Base (ExFOB), Power and Energy*.

Lee, J. W., Anguchamy, Y. K., & Popov, B. N. (2006). Simulation of charge-discharge cycling of lithium-ion batteries under low-earth-orbit conditions. *Journal of Power Sources*, *162*(2 SPEC. ISS.), 1395–1400. http://doi.org/10.1016/j.jpowsour.2006.07.045

Manghani, R. (2016, March 16). Behind-the-meter energy storage poised for explosive growth. *Greentechmedia.com*. Retrieved from http://www.greentechmedia.com/articles/read/behind-the-meter-energy-storage-market-poised-for-exponential-growth

Marine Corp Systems Command. (2013). *Mobile Electric Hybrid Power Source Analysis of Alternatives (AoA) Final Report*. Quantico, VA: U.S. Marine Corps

Marine Corps Systems Command (n.d.). *Initial Capability Document (ICD) for Expeditionary Energy, Water, and Waste (E2W2)*. U.S. Marine Corps.

Methekar, R. N., Ramadesigan, V., Braatz, R. D., Subramanian, V. R., & Louis, S. (2010). Optimum Charging Profile for Lithium-ion Batteries to Maximize Energy Storage and Utilization. *ECS Transaction*, *25*(35), 139–146.

Ning, G., White, R. E., & Popov, B. N. (2006). A generalized cycle life model of rechargeable Li-ion batteries. *Electrochimica Acta*, *51*(10), 2012–2022. http://doi.org/10.1016/j.electacta.2005.06.033

Office of Naval Research, U. S. N. (2016). Ground Renewable Expeditionary Energy System (GREENS): Fact Sheet.

Pruckner, M., & German, R. (2014). A Simulation Model to Analyze the Residual Load During the Extension of Highly Fluctuating Renewables in Bavaria , Germany, *5*, 3–8.

Pruckner, M., & German, R. (2013). Hybrid simulation model for large-scaled electricity generation systems. In P. Pasupathy, S. Kim, A. Tolk, R. Hill, & M. E. Kuhl (Eds.), *2013 Winter Simulation Conference* (pp. 1881–1892). Erlangen, Germany

Rahimian, S. K., Rayman, S., & White, R. E. (2011). Optimal charge rates for a lithium ion cell. *Journal of Power Sources*, *196*(23), 10297–10304. http://doi.org/10.1016/j.jpowsour.2011.07.019

Richard, P. (2009). Mobile Electric Power Systems Command brief to EGSA. In *Department of Defense Tactical Electric Power (TEP) Initiatives*. Project Manager Mobile Electric Power.

Rakopoulos, C.D., & Giakoumis, E.G. (2009). *Diesel Engine Transient Operation*. London: Springer.

Santhanagopalan, S., Guo, Q., Ramadass, P., & White, R. E. (2006). Review of models for predicting the cycling performance of lithium ion batteries. *Journal of Power Sources*, *156*(2), 620–628. http://doi.org/10.1016/j.jpowsour.2005.05.070

Turnbull, G. (2014, August 20). Unleash the tether: reducing the U.S. military’s thirst for foreign oil. *Kable*. Retrieved from http://www.army-technology.com/features/featureunleash-the-tether-reducing-the-us-militarys-thirst-for-foreign-oil-4346558/

U.S. Army Combined Arms Support Command. (2014). *Cost-benefit analysis summary: Mobile Electric Hybrid Power Source (MEHPS)*. (Material Systems Directorate, Sustainment Center of Excellence). Fort Lee, Virginia: U.S. Army

U.S. Army Combined Arms Support Command. (2014). *Capabilities production document for tactical electrical power (0.5kW to 200kW).* (Material Systems Directorate, Sustainment Center of Excellence), Fort Lee, Virginia: U.S. Army.

U.S. Department of Defense (2012). Operational energy strategy implementation plan.

U.S. Army, (2013). Army operational energy policy letter.

U.S. Army (2010). Army sustainability campaign plan.

USMC Expeditionary Energy Office. (2016). Expeditionary Energy Concepts (E2C). Retrieved from http://www.hqmc.marines.mil/e2o/E2CExFOB.aspx

Wang, L., & Singh, C. (2007). Compromise between cost and reliability in optimum design of an autonomous hybrid power system using mixed-integer PSO algorithm. In *2007 International Conference on Clean Electrical Power, ICCEP ’07* (pp. 682–689). doi:10.1109/ICCEP.2007.384284

Woodyard, Doug. (2009). Pounder's Marine Diesel Engines and Gas Turbines (9th Edition). Retrieved from http://app.knovel.com/hotlink/toc/id:kpPMDEGTE4/pounders-marine-diesel/pounders-marine-diesel

Yang, H., Zhou, W., Lu, L., & Fang, Z. (2008). Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm. *Solar Energy*, *82*(4), 354–367. http://doi.org/10.1016/j.solener.2007.08.00

Zhou, W., Yang, H., & Fang, Z. (2008). Battery behavior prediction and battery working states analysis of a hybrid solar-wind power generation system. *Renewable Energy*, *33*(6), 1413–1423.

APPENDICES

Appendix A: Impact of Low and Transient Load Conditions on Diesel Generators

- Incomplete fuel combustion
- Excessive buildup of carbon deposit in cylinder (wet-stacking)
- Weakening of piston ring seal
- Leakage of high-pressure and high-temperature combustion gas
- Low fuel injection pressure
- Drastic changes to fuel and lubricating oil viscosity
- Soot formation and contamination of lubricating oil
- Water condensation and contamination of lubricating oil
- Poor fuel injection timing
- Poor ignition timing
- Poor timing of intake and exhaust valve openings
- Suboptimal fuel injection dispersion
- Presence of excessive lubricating oil in cylinder liner
- Corrosion from fuel acidity
- Scoring or polishing of cylinder liner
- Fouling of compressor blades from leaked crankcase gases
- Piston scuffing
- Lacquer formation
- Increased consumption of lubricating oil
- Reduction of fuel ignition capacity
- Impairment of gravity-dependent centrifuging process used to purify fuel.
- Growth of “diesel bugs” (bacteria, yeast, and fungus) that clog filters
- Loss of alkaline additives needed to neutralize acidic products of combustion
- Low air/fuel ratio
- Clogging of fuel and oil filters

Table A.1. Diesel generator faults associated with extended low and transient loads

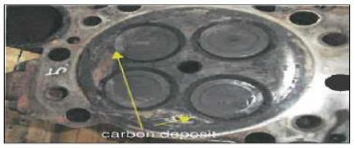
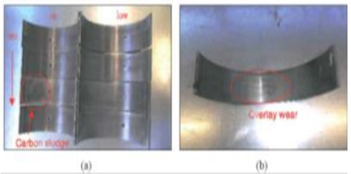
	Carbon deposits and polishing wear in cylinder liner.
	Large amounts of carbon deposits found on cylinder head surface
	Scuffing marks on the entire circumference of a piston.
	a.Carbon sludge on bearing inner surfaces of cylinder b. Large amounts of carbon sludge observed on the plated overlay of connecting rod bearings.
	Broken cylinder line, and polishing wear due to Presence of hard carbon particles.

Table A.2 Faults identified in diesel engine breakdown analysis (Tufts, 2014)

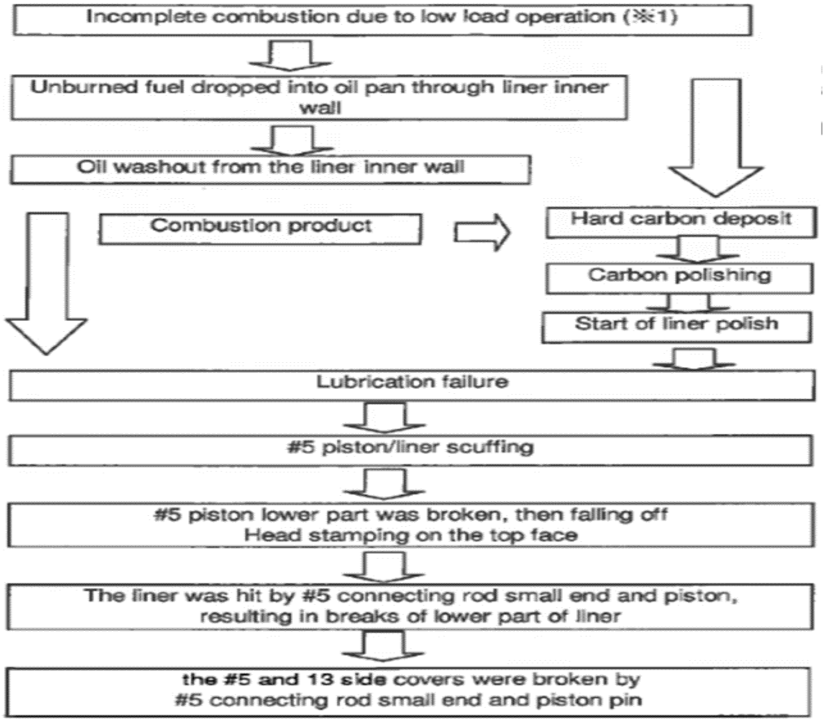


Figure A.1: Mechanism of Diesel Engine Damage
(Harada, Harada, Fukzawa and Takimoto (2007)

Appendix B: Additional Simulation Results

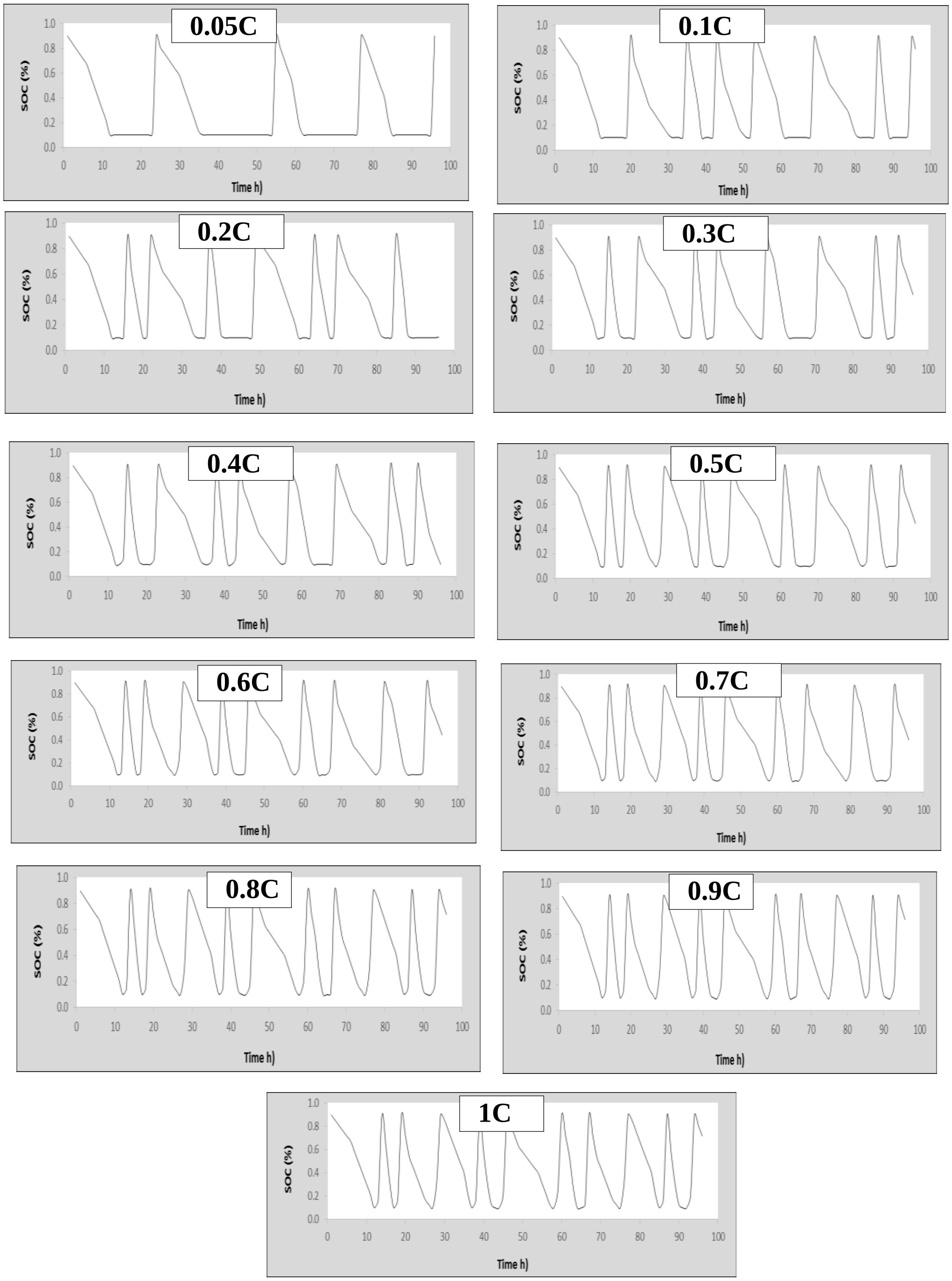


Figure B.1 Battery C-Rate Impact on Charge/Discharge Cycle

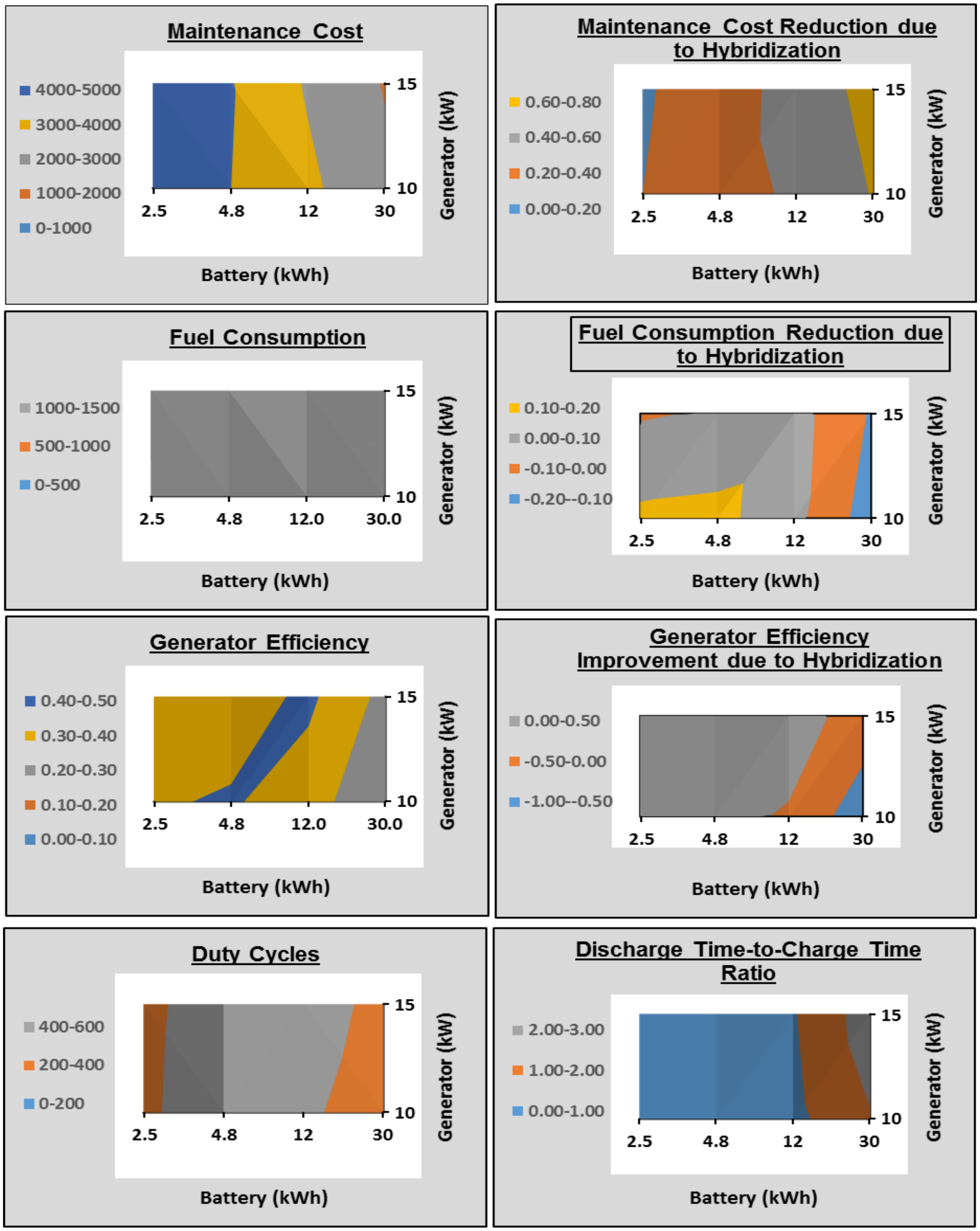


Figure B.2. B-G HPS Capacity Design Space for Summer Load

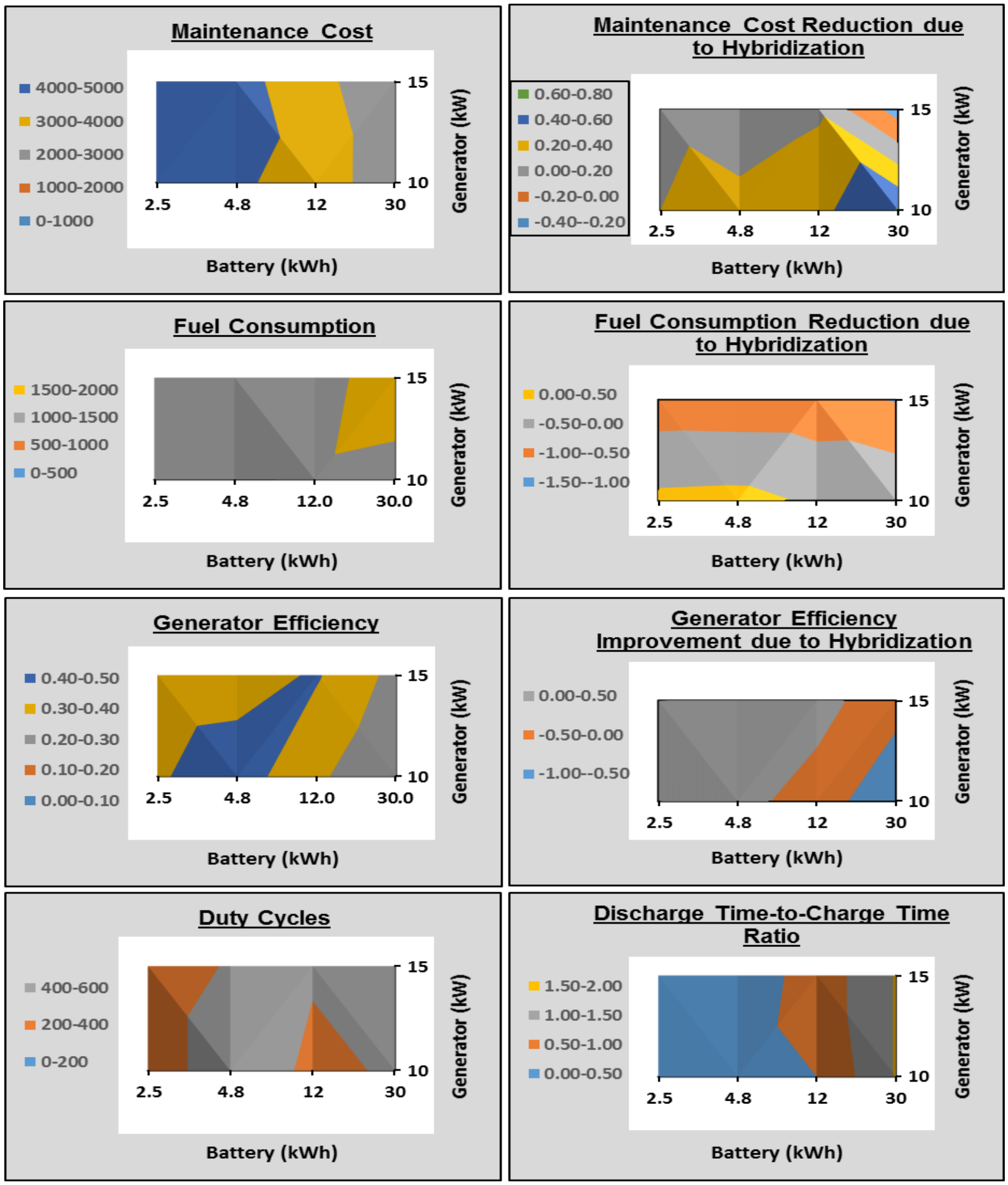
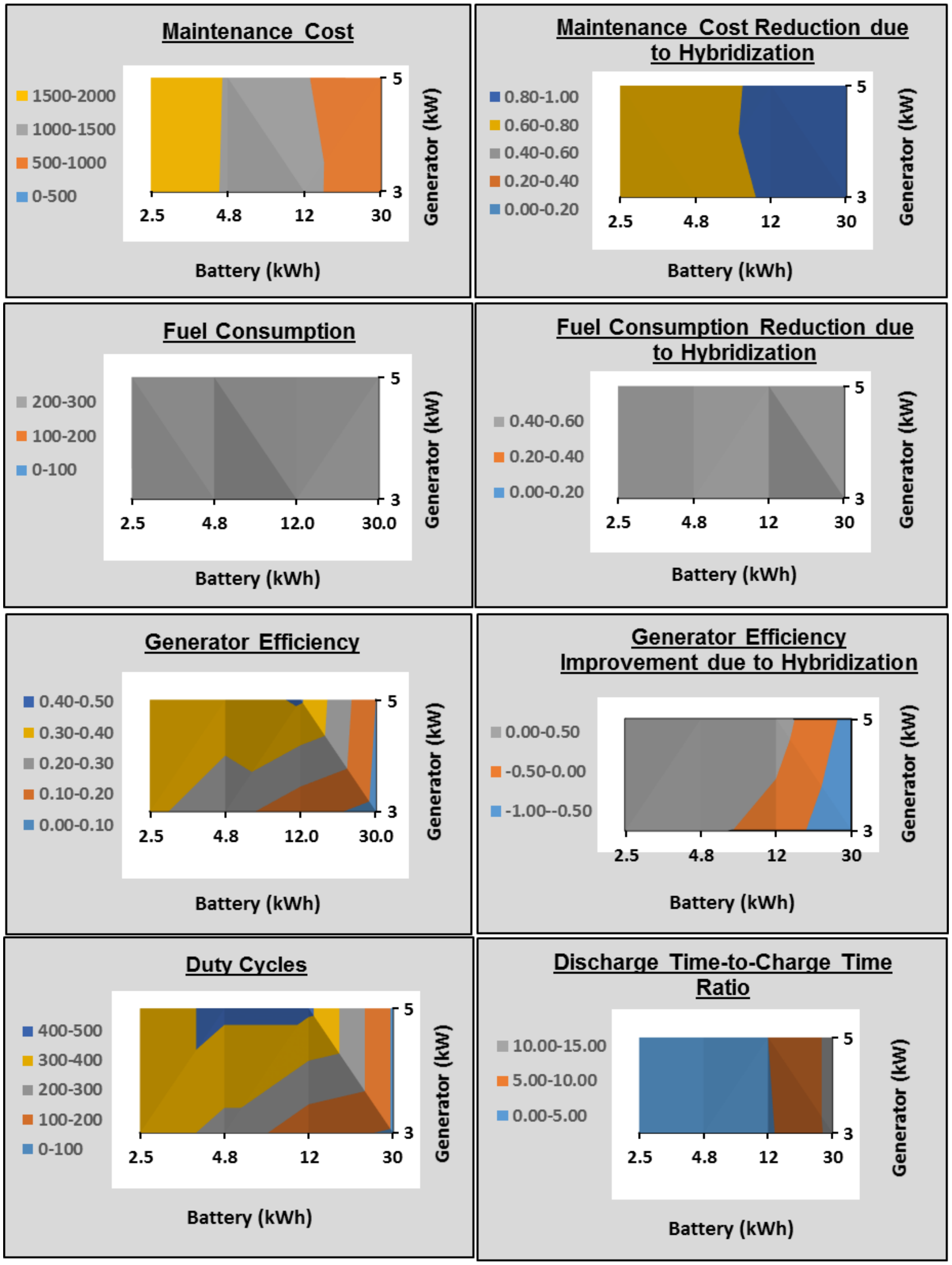


Figure B.3. B-G HPS Design Space Simulation for a 24hr 7.5kW Static Load



Maintenance Cost

Maintenance Cost Reduction due to Hybridization

Fuel Consumption

Fuel Consumption Reduction due to Hybridization

Generator Efficiency

Generator Efficiency Improvement due to Hybridization

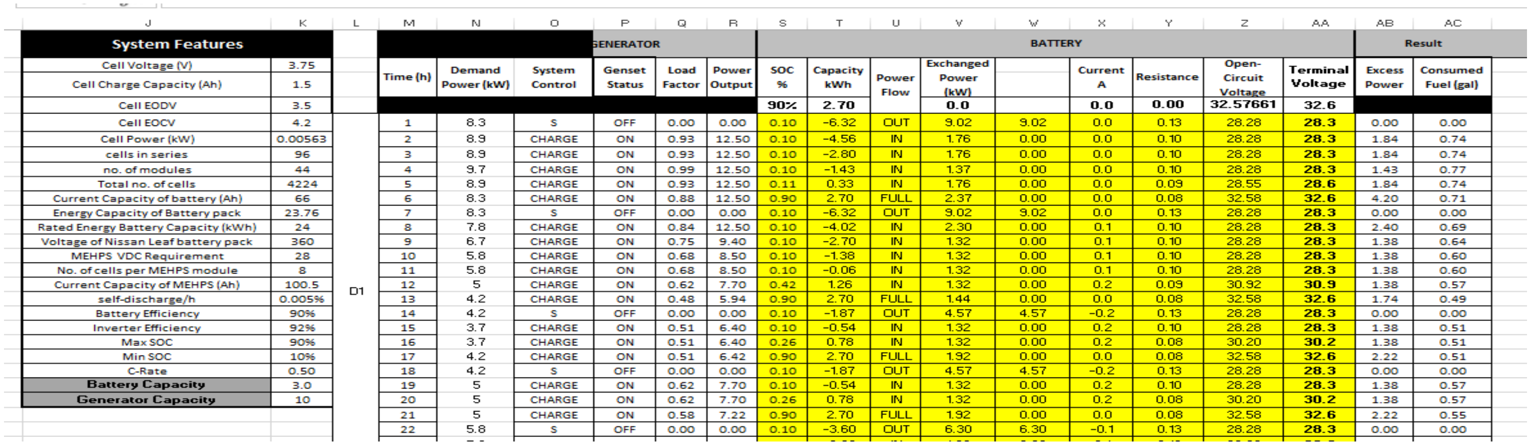
Duty Cycles

Discharge Time-to-Charge Time Ratio

Figure B.4. B-G HPS Design Space Simulation for a 12-hour 2 kW Static Load

Appendix C: Excel Simulation Code and Data

System Control	=IF(AND(R5="OUT",P5>$H$21),"S",IF(AND(R5="IN",P5>=$H$20),"S",IF(R5="FULL","S","CHARGE")))
Generator Status	=IF(L5="S","OFF","ON")
Load Factor	=IF(M5="OFF",0,IF(AND(M5="ON",P5<$H$20),((K5+($H$26-K5))/$H$26)*0.8,IF(AND(M5="ON",P5>$H$21),(K5/$H$26)*0.8,N4)))
Generator Power Output	=IF(M5="ON",($H$26/0.8)*N5,0)
SOC (kWh)	=IF(AND(M5="OFF",Q4>$H$21*$H$25),Q4*(1-$H$17*$H$25)-((K5/$H$19)),IF(AND(M5="ON",Q4<$H$20*$H$25),Q4*(1-$H$17*$H$25)+(($H$26-(K5/$H$19))*$H$23*$H$18),$Q$4))
SOC (%)	=Q5/$H$25
Direction of Power flow in battery	=IF(M5="OFF","OUT",IF(P5>=$H$20,"FULL","IN"))
Quantity of Power flow in Battery	=IF(R5="OUT",Q4-Q5,Q5-Q4)
Current	=(1000*S5/$H$14)
Resistance	=IF(R5="OUT",(0.0694*(P5)^6-0.3484*(P5)^5+0.6135*(P5)^4-0.5054*(P5)^3+0.2078*(P5)^2-0.0407*(P5)+0.0044)*$D$5,(-0.0019*(P5)^6-0.0323*(P5)^5+0.0949*(P5)^4-0.0984*(P5)^3+0.0469*(P5)^2-0.0103*(P5)+0.0021)*$D$5)
Open-Circuit Voltage	=(-43.796*(P5)^6+150.27*(P5)^5-203.96*(P5)^4+139.85*(P5)^3-51.336*(P5)^2+10.17*(P5)+2.9108)*$H$15
Terminal Voltage	=IF(R5="FULL",$W$4,V5-((T5/$H$16)*U5))
Excess Power	=IF(AND(M5="ON",R5="FULL"),O5-K5,IF(AND(M5="ON",R5="IN"),O5-(K5+S5),0))
Consumed Fuel	=IF(M5="OFF",0,IF($H$26=3,0.2*N5+0.132, IF($H$26=5,0.328*N5+0.164, IF($H$26=10,0.538*N5+0.238, IF($H$26=15,0.948*N5+0.25)))))



J	K
System Features	
Cell Voltage (V)	3.75
Cell Charge Capacity (Ah)	1.5
Cell EODV	3.5
Cell EOCV	4.2
Cell Power (kW)	0.00563
cells in series	96
no. of modules	44
Total no. of cells	4224
Current Capacity of battery (Ah)	66
Energy Capacity of Battery pack	23.76
Rated Energy Battery Capacity (kWh)	24
Voltage of Nissan Leaf battery pack	360
MEHPS VDC Requirement	28
No. of cells per MEHPS module	8
Current Capacity of MEHPS (Ah)	100.5
self-discharge/h	0.005%
Battery Efficiency	90%
Inverter Efficiency	92%
Max SOC	90%
Min SOC	10%
C-Rate	0.50
Battery Capacity	3.0
Generator Capacity	10

L: D1

M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
			GENERATOR			BATTERY									Result	
Time (h)	Demand Power (kW)	System Control	Genset Status	Load Factor	Power Output	SOC %	Capacity kWh	Power Flow	Exchanged Power (kW)		Current A	Resistance	Open-Circuit Voltage	Terminal Voltage	Excess Power	Consumed Fuel (gal)
						90%	2.70		0.0		0.0	0.00	32.57661	32.6		
1	8.3	S	OFF	0.00	0.00	0.10	-6.32	OUT	9.02	9.02	0.0	0.13	28.28	**28.3**	0.00	0.00
2	8.9	CHARGE	ON	0.93	12.50	0.10	-4.56	IN	1.76	0.00	0.0	0.10	28.28	**28.3**	1.84	0.74
3	8.9	CHARGE	ON	0.93	12.50	0.10	-2.80	IN	1.76	0.00	0.0	0.10	28.28	**28.3**	1.84	0.74
4	9.7	CHARGE	ON	0.99	12.50	0.10	-1.43	IN	1.37	0.00	0.0	0.10	28.28	**28.3**	1.43	0.77
5	8.9	CHARGE	ON	0.93	12.50	0.11	0.33	IN	1.76	0.00	0.0	0.09	28.55	**28.6**	1.84	0.74
6	8.3	CHARGE	ON	0.88	12.50	0.90	2.70	FULL	2.37	0.00	0.0	0.08	32.58	**32.6**	4.20	0.71
7	8.3	S	OFF	0.00	0.00	0.10	-6.32	OUT	9.02	9.02	0.0	0.13	28.28	**28.3**	0.00	0.00
8	7.8	CHARGE	ON	0.84	12.50	0.10	-4.02	IN	2.30	0.00	0.1	0.10	28.28	**28.3**	2.40	0.69
9	6.7	CHARGE	ON	0.75	9.40	0.10	-2.70	IN	1.32	0.00	0.1	0.10	28.28	**28.3**	1.38	0.64
10	5.8	CHARGE	ON	0.68	8.50	0.10	-1.38	IN	1.32	0.00	0.1	0.10	28.28	**28.3**	1.38	0.60
11	5.8	CHARGE	ON	0.68	8.50	0.10	-0.06	IN	1.32	0.00	0.1	0.10	28.28	**28.3**	1.38	0.60
12	5	CHARGE	ON	0.62	7.70	0.42	1.26	IN	1.32	0.00	0.2	0.09	30.92	**30.9**	1.38	0.57
13	4.2	CHARGE	ON	0.48	5.94	0.90	2.70	FULL	1.44	0.00	0.0	0.08	32.58	**32.6**	1.74	0.49
14	4.2	S	OFF	0.00	0.00	0.10	-1.87	OUT	4.57	4.57	-0.2	0.13	28.28	**28.3**	0.00	0.00
15	3.7	CHARGE	ON	0.51	6.40	0.10	-0.54	IN	1.32	0.00	0.2	0.10	28.28	**28.3**	1.38	0.51
16	3.7	CHARGE	ON	0.51	6.40	0.26	0.78	IN	1.32	0.00	0.2	0.08	30.20	**30.2**	1.38	0.51
17	4.2	CHARGE	ON	0.51	6.42	0.90	2.70	FULL	1.92	0.00	0.0	0.08	32.58	**32.6**	2.22	0.51
18	4.2	S	OFF	0.00	0.00	0.10	-1.87	OUT	4.57	4.57	-0.2	0.13	28.28	**28.3**	0.00	0.00
19	5	CHARGE	ON	0.62	7.70	0.10	-0.54	IN	1.32	0.00	0.2	0.10	28.28	**28.3**	1.38	0.57
20	5	CHARGE	ON	0.62	7.70	0.26	0.78	IN	1.32	0.00	0.2	0.08	30.20	**30.2**	1.38	0.57
21	5	CHARGE	ON	0.58	7.22	0.90	2.70	FULL	1.92	0.00	0.0	0.08	32.58	**32.6**	2.22	0.55
22	5.8	S	OFF	0.00	0.00	0.10	-3.60	OUT	6.30	6.30	-0.1	0.13	28.28	**28.3**	0.00	0.00

Figure C.1: Excel simulation code and sample data