NPS-AM-26-278

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Modeling Operational Energy at the Tactical Level

December 2025

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The research presented in this report was supported by the Acquisition Research Program of the Department of Acquisition, Finance and Manpower Naval Postgraduate School.

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ABSTRACT

The thesis focuses on exploring operational energy at the tactical level. To make these ideas concrete, we study a notional ground unit informed by open-source data. Data is gathered from public sources; the primary sources are the NATO ENSECCOE report, the NPS thesis by Thomas Atkinson on USMC energy usage, and Finnish research on truck fuel consumption in the forest industry. In this thesis, we first develop a conceptual model representing the energy forms and conversions that occur within a ground unit. Next, we present these energy flows as a network, and from there, a linear programming (LP) model is developed. The model represents units' energy usage in a 24-hour period, and all energy forms are converted to kilowatt-hours (kWh). The LP model is small and tractable, and therefore is able to be instantiated and evaluated in Microsoft Excel, with an objective function that minimizes fuel consumption for electricity production. A key feature of our work is visualization; here, we use the novel approach of Sankey Charts. The model is then applied to several specific use cases. Finally, we explore how the model can be further developed.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFDC	Alternative Fuel Data Center of the U.S. Department of Energy
AI	Artificial Intelligence
Ampere	Unit of electric current, ampere
Btu	Unit of energy, British Thermal Unit
E	Symbol for Energy
ENSECCOE	NATO Energy Security Centre of Excellence
ExFOB	Experimental Forward Operating Base
FBCF	Fully burdened cost of fuel
FDF	The Finnish Defence Forces
gal	Unit of volume, gallon (in this thesis U.S. gallon)
h	Unit of time, hour
HPGS	Hybrid Power Generation and Management System
I	Symbol for electric current
IEA	International Energy Agency
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
J	Unit of measurement, Joule
k	Symbol for SI unit prefix for 10^3
km	Unit of length, kilometer
kVA	Unit of measurement of nominal power, kilovolt-amperes
kW	Unit of measurement of real power, kilowatt
kWh	Unit of measurement of energy, kilowatt-hour
kW_p	Unit of measurement of peak real power, kilowatt-peak
l	Unit of measurement of volume, liter
LOC	Lines of Communications
LP	Linear Programming
mi	Unit of length, mile
MRP	Marine Rifle Platoon
NATO ACT	NATO Allied Command Transformation
NATO OEC	NATO Operational Energy Concept
NATO	North Atlantic Treaty Organization

NIST	National Institute of Standards and Technology of the U.S. Department of Commerce
NPS	Naval Postgraduate School
PFISTERER	PFISTERER Kontaktsysteme GmbH, German electric product manufacturer
PV	Photovoltaic
t	Symbol for time
U	Symbol for electric voltage
U.S. DoD	The United States Department of Defense
U.S. OES	Department of Defense Operational Energy Strategy of The United States
UK MOD	The United Kingdom Ministry of Defence
UK OES	Defence Operational Energy Strategy of The United Kingdom Ministry of Defence
UK	The United Kingdom
US	The United States
USA	United States Army
USMC	United States Marine Corps
V	Unit of electric voltage, volt
VA	Unit of electric power, volt-ampere
VAC	Volts of alternating current
Wh	Unit of measurement, watt-hour
WWII	The Second World War

EXECUTIVE SUMMARY

Energy is a vital enabler in military operations. The term "operational energy" as used here covers all energy required to execute a military mission. This research examines operational energy applied to a notional tactical-level ground unit and explores modeling it. Visualizing energy flows is a novel aspect of our work that helps increase understanding of operational energy. The thesis emphasizes treating energy not as an engineering subject but as a logistical subject.

The conceptual operational energy model visualizes the energy forms required by a tactical-level ground unit, whether they are supplied to the unit or generated within it, and the types of conversions needed within the unit. The conceptual model includes fuel, electricity, and batteries. The conceptual model focuses on representing what "all energy needed" in a unit really means and how energy is attached to the capabilities.

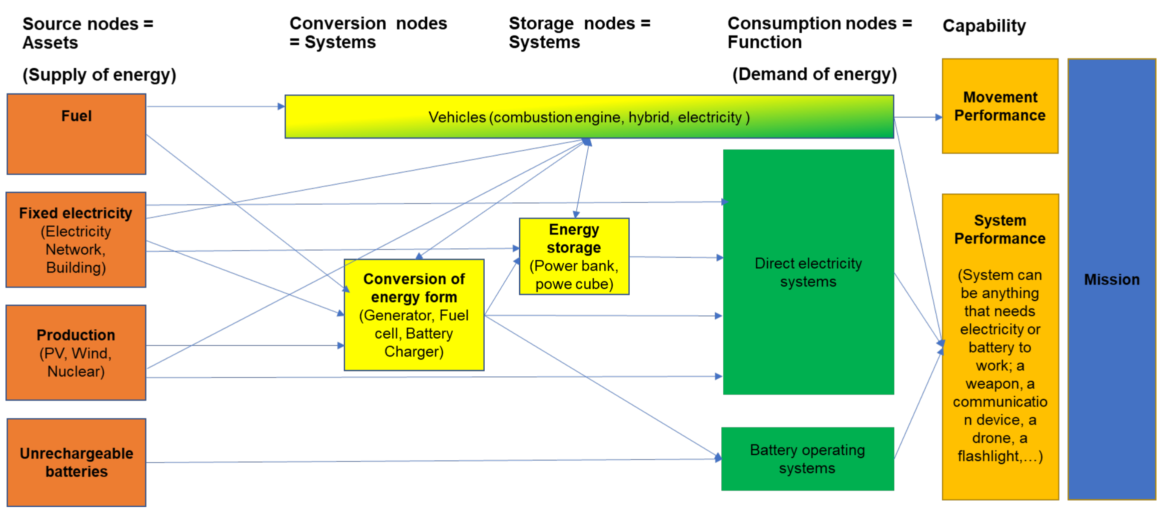

Figure 1. Conceptual model of operational energy in a tactical-level ground unit. This diagram shows the interrelationship and dependencies between energy forms. Note that the end results (Orange) are Movement Performance and System performance.

The thesis models operational energy in a notional tactical-level ground unit, which is created with data available from public sources. The unit combines data from NATO ENSECCOE, USMC, and Finland. The model can later be used with actual data from real units. The unit's energy flows are represented as a network instantiated in the R programming language, taking advantage of the iGraph and VisNetwork packages. The resulting Linear Programming (LP) model is based on the network and our understanding of consumption, production, and conversions. The model represents units' energy usage in a 24-hour period, and all energy forms are converted to kilowatt-hours (kWh). We evaluate this LP model to optimize the energy flows in the unit, with the objective function being to minimize fuel consumption for electricity production. Our specific use case has the LP model implemented in Microsoft Excel and evaluated with the standard Solver. Excel has the advantage of being organically available on both unclassified and restricted computing systems. The unit's basic scenario solution is visualized with Sankey Charts created with Power BI.

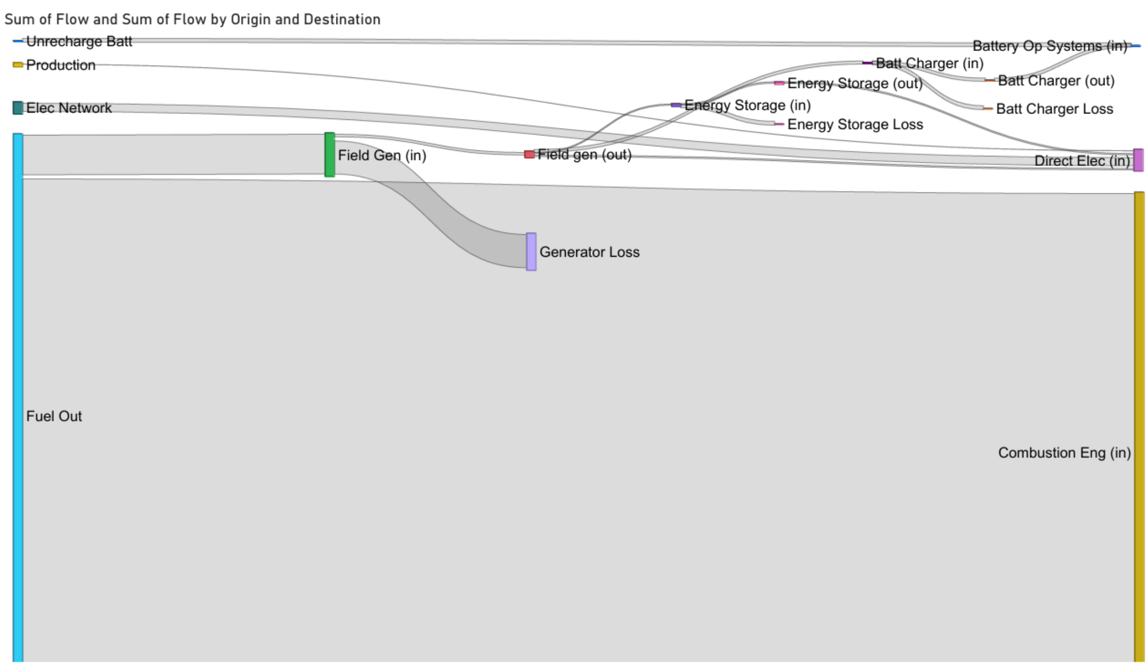

Figure 2. Unit's basic scenario energy flows in a Sankey Chart.The chart shows all energy flows in the unit and their relative share of the total energy flow. The fuel flow to vehicles is dominating this chart.

The LP model illuminates questions that may arise in logistical planning. The effects of different operational areas and weather conditions on energy flows are researched, generator capacities are explored, and limits of electricity consumption and the need for electricity outlets are examined. Our LP model has excellent runtime and convergence capabilities, with most instances solving under one second. Notional solutions may be either adjusted or extrapolated to apply to real-world situations.

To develop the model into a practical tool for logistical planning, it is essential to understand the model's limitations. Specifically, we treat electricity as static and fungible, and do not consider issues such as consumption curves and transmission losses, etc. While this is not strictly true in the physical world, it is a close enough approximation for the scales both in space and time we consider here. Batteries are included in the model in this thesis to visualize and explore the total operational energy. However, it should be considered whether they should have an individual model with an output of the number of batteries. The model can be relatively easily modified with different unit construction and energy mix. Its usability would need to be developed, though, to create a tool for an "everyday user."

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I. INTRODUCTION

"Energy is an essential enabler of military capacity" (US DoD, 2023). Like all of modern society, the armed forces are also highly dependent on energy. Most equipment needs some external energy to function. Logistics is necessary to supply fuel and other energy sources, but the logistical burden to do so has continuously increased, as the energy needs on the battlefield keep growing. New energy technologies offer solutions to decrease the logistical burden of fuel supply, but they come with a tradeoff in the complexity of energy supply systems. This chapter delivers an overview of the importance of energy, especially operational energy, in a military context. It also describes the complexity of these terms and the need for holistic and systemic thinking to understand the overall picture of operational energy at the tactical level, as it is crucial for completing the mission.

A. BACKGROUND

Energy has been a key enabler and constraint of military operations throughout history. In the Second World War (WWII), the resources of fuel and the capability to supply it distinguished the winners from the losers (Goralski & Freeburg, 2021). Even though the energy sources and technologies have evolved, the main principle has not changed; the one who can supply energy longer will win.

The source of energy in the military has evolved from hay for horses to coal and oil, to nuclear power (for some nations), and finally to renewable sources such as wind and solar. As energy sources and technologies provide more options than distributing fuel, the logistical emphasis of the subject gets complicated. Each combat soldier has a varying amount of equipment that requires energy, and the energy is needed in various forms. Figure 1, from 2010, still captures the growing number of electronic devices a Marine in the United States Marine Corps (USMC) has to carry, which require energy to function. Then, add to the unit vehicles and weapon systems, and the energy needs continue to grow. The combustion engines need liquid fuel, but, for example, weapon systems may need either fuel, direct electricity, batteries, or all of them at the same time. Therefore, planning a unit's energy mix and supplying it gets complicated. For example, in the United States

(US), logistics classes of supply include a supply class for field generators and batteries, but no supply class for electricity (*Joint Publication 4-0 Joint Logistics*, 2023, Figure II-2). Although the troop as a user does not need a generator, ultimately, it requires energy to operate its equipment and perform its mission.

Figure 1. Individual marine power requirements. Source: Wilson (2010). This graphic shows the breadth and depth of energy required for a single soldier in the current age.

The consumption of energy on the battlefield keeps increasing. The need for fuel for combustion engines and generators has increased, and the need for electricity for weapon systems and drones also plays a significant role. Every new technology added to the battlefield consumes energy. For example, directed energy weapons will significantly increase the need for power. Usually, multiple sources of energy are needed at the same time. In operational logistics, the way to do logistics has three options: obtain, carry, and ship (Kress, 2016, pp.9-11). While logistics have evolved from obtaining and carrying to mainly shipping nowadays, it is interesting to see how energy logistics utilizes all modes simultaneously. The troop is generating energy by harnessing renewable sources. It carries batteries with it, and fuel is shipped to it. In today's warfare, the energy needs and supply options are more complicated, but technology also offers multiple solutions. One vital motivation to increase the production of energy from renewable sources is to decrease the need for fuel and, in that way, decrease the logistical footprint.

Operational energy is defined as “energy required for training, moving, and sustaining military forces and weapons platforms for military operations” (Howard et al., 2024, p.3). This definition reflects an attempt to define a significant topic succinctly. At the strategic level, the definition is understandable, but at the operational and tactical levels, where actual energy supply, production, and usage decisions are made, the picture becomes blurry. The biggest challenge in transitioning from the strategic level to the tactical level is understanding the comprehensive approach to energy at a tactical level. At that level, all the energy sources, forms, and technologies are present at the same time, so the complexity needs to be handled as a whole. Since energy-related subjects are dealt with in conjunction with several logistical functions, it is not easy to plan, develop, or report operational energy as a whole.

While energy is recognized as an essential subject, compiling the overall picture of energy is complicated. Solutions are developed system by system in acquisition; facilities are dealt with separately, and the logistics system mainly concerns fuel. The planning of a unit’s overall energy solution is complex since the understanding of the overall need is not planned at any stage. For example, adding energy storage or renewable sources is not directly in anyone’s interest, since they would serve a unit, not necessarily an individual system. The use of direct energy from the electricity network or buildings is not planned consistently, as the use of field generators is deeply ingrained in the logistical system that provides fuel. Moreover, in certain areas, infrastructure may not exist, or in wartime, it may be unusable, so field generators are often the only option. This thesis aims to clarify the picture at the tactical level by visualizing and modeling energy supply, production, conversion, and use at the unit level.

The thesis derives its motivation from the writer’s experiences as Chief of Electricity in the Finnish Defence Forces (FDF). The term” operational energy” is not yet widely used in Finland, but since the North Atlantic Treaty Organization (NATO) has developed its Operational Energy Concept, it needs to be incorporated into the Finnish defense system.

B. PURPOSE AND SCOPE

1. Problem Statement

In the military domain, the term "operational energy" has been used for over 20 years. For this project, operational energy encompasses all phases of energy production, conversion, and delivery in the scenario of interest. This conceptualization synthesizes competing ideas as follows: In the military, energy is often viewed as a technical problem that engineers are tasked with resolving. Nonetheless, energy consumption decisions are made during operational planning, and solutions to meet the needs are determined in logistical planning. The technical solutions to produce and consume energy are dealt with in the acquisition process for an individual weapon system. However, the overall energy consumption for a unit is not addressed until logistical planning is complete. Logisticians are accustomed to planning fuel supply, but planning operational energy as a whole requires a broader view. Our research seeks to accelerate the translation from engineering language to logistical language.

Given these challenges, operational energy in a military unit should be modeled with logistical concepts and tools. A military unit uses energy in multiple ways, which requires different supply solutions and energy conversions within the unit. Renewable energy sources also make it possible for the unit to produce part of its energy needs. To make this overall energy flow observable in a unit, it needs to be modeled as a whole. Models are traditionally used in other logistic functions. So, the logistical models are part of the language that logisticians understand. Using similar approaches, operational energy could be more easily combined with logistical planning and also be connected to operational planning. The result would be a new model that enables observing the logistical feasibility of the operational plan through the view of operational energy feasibility. This thesis will describe one such potential model and explain how our understanding of energy in a military context can be enhanced and applied more effectively.

2. Primary Research Question

How should the definition of operational energy, "energy required for training, moving, and sustaining military forces and weapons platforms for military operations" (Howard et al., 2024), be interpreted at a unit level?

3. Secondary Research Questions

1. What alternative models of energy use in the military are available?
2. How can operational energy at the unit level be modeled with the concepts, terms, and visualizations used in operational logistics modeling?
3. How should energy supply (source), energy conversions, and demand be categorized at the unit level?
4. What conversions between energy forms are needed in a model, and what data is needed for conversions (for example, fuel to electricity, electricity to battery capacity)?

C. LIMITATIONS

By 'unit' we mean a notional land unit with vehicles, weapon systems, communications systems, personal equipment, and needed accommodation equipment. The unit is located in a geographically restricted area, so it is sustained as one supported unit.

In the basic scenario, the unit is placed in an area where infrastructure, such as an electricity network and buildings, exists, so the operational environment is not entirely austere. Later analyses include scenarios where the infrastructure may not be usable at all times or the unit can temporarily relocate to an area where infrastructure is inaccessible.

The energy flow is considered from the point where the unit either receives the energy from the supply or produces it itself. The endpoint is the unit's usage of energy. The unit is considered an end user of energy; it does not distribute energy further. Figure 2 represents the unit limits on the view of energy.

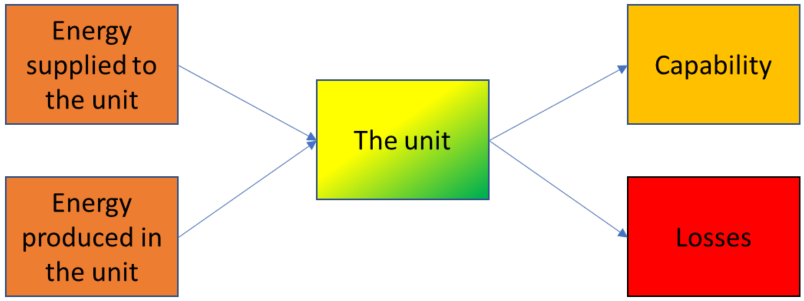

Figure 2. Limits of energy flow in the unit. Energy is either supplied to the unit or it produces it itself. The unit consumes the energy to obtain capabilities, and part of the energy is lost within the unit. The unit does not distribute energy to other units.

D. ORGANIZATION

This research begins with a literature review of operational energy policies at the strategic level, operational energy case studies, particularly those conducted in NPS theses, and a brief examination of modeling energy and logistics. The next step involves the methodology, focusing on the data collected to describe the energy supply, production, conversions, and usage at the notional tactical level unit, and building the model. In the analysis section, there are four parts: a discussion of the basic scenario of the unit solved with the model, the visualization of the solution with Sankey charts, three examples of how the model can be utilized, and a discussion about the limitations of the model. The research will conclude with a summary and deliver an evaluation of the fulfillment of research questions. Finally, recommendations highlight continuing research needs.

II. LITERATURE REVIEW

This literature review is divided into three themes. Initially, existing operational energy policies are reviewed to gain a basic understanding of operational energy at the strategic level. The operational energy strategies of the United States (US) and the United Kingdom (UK) are reviewed as examples. NATO also has an operational energy concept, which is briefly discussed. The second theme is operational energy from a military perspective in real-life applications. This part includes a review of the first operational energy textbook and theses and reports about operational energy case studies. The third part is about operational logistics and energy modeling. Modeling can make a phenomenon understandable and manageable. Understanding how models are used in logistics provides a basis for applying modeling to operational energy at the tactical level.

A. OPERATIONAL ENERGY POLICIES

To gain an understanding of the military view of operational energy, two strategic-level policies are first assessed. The first approach is to identify the differences and similarities in managing operational energy now and in the future. Secondly, strategy papers set the stage for the tactical level approach in the big picture. Although the devil lives in the details at the tactical level, the goal was to examine the question: Does the strategic level recognize the possible tactical-level challenges?

The Department of Defense of the United States (US DoD) published the latest Department of Defense Operational Energy Strategy (US OES) in May 2023 (US DoD, 2023). U.S. DoD published its first U.S. OES in 2011, so this is the third version (Howard et al., 2024, pp. 114–115). The Ministry of Defence of the United Kingdom published its first Defence Operational Energy Strategy (UK OES) in December 2023 (UK MOD, 2023). NATO Allied Command Transformation (NATO ACT) has published the NATO Operational Energy Concept (NATO OEC) in 2024, but the document is not public. NATO OEC aims to be an operational-level concept (NATO ACT, 2023), addressing operational energy at different levels, as in the U.S. and UK strategies. This review only deals with NATO OEC with the level of information published in a fact sheet in 2023.

With both strategies, even though the definition of operational energy has been provided, what energy really means in different parts of the text varies. For example, there is a strong motivation for both strategies to sever ties with fossil fuels and their logistical burden. While UK OES uses the term energy efficiency, as does NATO ACT, U.S. OES uses the term energy demand reduction. Demand reduction is an interesting choice, since if the unit or system can produce its needed energy with renewable sources, is reduction required anymore? The reduction of demand for fossil fuels, or broader energy that is necessary to deliver, would seem to be a more reasonable target. This example illustrates how the term "energy," or in this context, "operational energy," is not an unambiguous term (UK MOD, 2023) (US DoD, 2023).

Other notable differences between U.S. OES and UK OES include the handling of costs and the approach to manpower management. In the UK, OES cost savings are highlighted as one driver of operational energy changes from the perspective of energy efficiency and life cycle costs. U.S. OES does not mention costs as directly under one deadline, though costs are mentioned as a driver in several contexts. The UK OES highlights the resistance to changes in personnel associated with the transition from a simpler "fossil fuel world" to a more complex "energy diversification world." There is also a road map for how to appoint an owner of the operational energy to the UK MOD organization. It appears that in the U.S., ownership is already resolved at the strategic level, and resistance to changes is not as pronounced at this level. Knowing human nature, one might guess that at the tactical level, the resistance against change might still also exist in the U.S. (UK MOD, 2023; US DoD, 2023).

Introduction of new energy technologies to the military is set as an objective in both strategies. The U.S. OES sets the goal of utilizing new technologies "to increase range, endurance, tempo, and operational flexibility while reducing energy demand of platforms and operations" (US DoD, 2023, p.7). This seems a desirable goal, but it will probably need some trade-offs. While UK OES also highlights the possibilities of new energy technologies, it also raises broader concerns, such as the missing skill sets to operate these technologies and the need for renovation of existing logistical processes (UK MOD, 2023, p. 21). U.S. OES seems to assume that it is possible to decrease the energy usage in future battlefields, though in history, the energy needs have consistently grown with new weapon technologies. UK OES realizes that energy needs will probably increase, but assumes that new energy technologies will solve the problem. The future will show which approach, if either, was right. (UK MOD, 2023; US DoD, 2023)

At the tactical level, both strategies emphasize the importance of measurement, data collection, analysis tools, and developing an understanding of the energy consumed. In the U.S. OES, understanding the risks of the last mile is recognized as still partly unknown (US DoD, 2023, p. 8). As strategy policies, they neither offer nor should they deliver exact solutions at the tactical level. NATO OEC will likely delve deeper, but it will not provide straightforward solutions at the tactical level either. Primarily, since the NATO OEC should serve all allies, it cannot be too detailed. The strategies and concepts remain well above the tactical level, but they do provide a solid foundation for developing solutions at the tactical level. (UK MOD, 2023; US DoD, 2023).

B. OPERATIONAL ENERGY AND CASE STUDIES

In the second part of the literature review, operational energy is dealt with through examples from the real world. Operational energy has always existed, but it has gained more interest since the beginning of the 2000s. The concept of operational energy continues to spark discussions about its true meaning. The operational energy textbook is first discussed, followed by a review of case studies from the NATO Energy Security Center of Excellence (ENSECCOE) and the Naval Postgraduate School (NPS) theses.

1. Operational Energy Textbook

The first operational energy textbook to teach the subject in the military community was published in 2023 by members of the NPS Energy Academic Group. *Operational Energy* (Howard et al., 2024) underscores the comprehensive effect of energy on military operations from history to the present. With several examples of crises, the authors demonstrate how energy geopolitics influences the root causes of crises and how both energy security and operational energy impact the execution of a military operation. The importance of fixed homeland and host nation infrastructure is highlighted in the book;

operational energy cannot be handled solely by military assets, but is considered broadly to encompass the entire supply chain of both energy and materials (pp. 41–42).

Although Chapter 6, "Operational Energy Vulnerabilities and Resilience," primarily focuses on larger energy systems, the approach can also be applied to tactical-level systems. For example, the conceptual view presented also describes the relationships at the tactical level (Howard et al., 2024, Figure 6.1, p. 130). The idea of Figure 6.1 from the book is presented in Figure 3. Additionally, the resilience and efficiency of energy systems are discussed, with the tradeoffs highlighted (Howard et al., 2024, pp. 143–146). Choosing a strategy to improve the resilience of an energy system often causes conflicts between different sub-areas of resilience (Howard et al., 2024, p.145). The complexity is one feature of a system that is often part of the tradeoffs. Although renewable energy sources offer variability, instead of relying solely on fossil fuels, the complexity of the system and the introduction of new technologies also require new skill sets from users.

Figure 3. "A conceptual view of the relationship between assets, function, and mission success." Source: Howard et al. (2024, Figure 6.1. p.130).

Our work fits this profile because it explains operational energy relationships also at the tactical level in a single unit. The book presents a framework for building an operational energy education system in the U.S. military in Chapter 7.

The education and awareness of operational energy, ranging from tactical-level user education to strategic-level understanding of the operational energy's role in a mission, require different educational approaches for different levels (Howard et al., 2024, pp. 155–157). Operational energy can be an enabler, but it may also limit the use of capabilities if a constant supply is not available. Since WWII, the U.S. has enjoyed the luxury of uncontested energy supply chains, but in today's possible near-peer conflict, the situation has changed (Howard et al., 2024, p. 153). From the point of view of Finland, the energy supply has always been contested. Still, military exercises and war games often lack this view; they strive to avoid the disturbance to maneuvering caused by an energy shortfall.

The book summarizes the challenges concerning operational energy in the U.S. Armed Forces branches. While the branches have different functions and challenges, there are common themes. The dependency on energy and the increasing need for it on the battlefield are the first, and the lack of understanding of the connection between operational decisions and energy needs is the second highlighted common theme (Howard et al., 2024, p. 16). Other common themes are aviation as the highest energy consumer (Howard et al., 2024, p.172, p.175, p.179), long intended shelf-life of weapon systems (Howard et al., 2024, p. 189), and assets and increasing electrification of the battlefield (Howard et al., 2024, pp.165-167). Since this thesis's focus is on ground units, the USMC and the U.S. Army (USA) are the most important subjects. Both branches face similar challenges. The need for digital devices has driven a surge in electricity demand among individual soldiers, primarily met through the use of batteries (Howard et al., 2024, p. 167). It has also significantly affected the electricity needs of command posts and bases (Howard et al., 2024, p. 169). At the strategic level, it is easy to promulgate operational energy targets, but the real-world challenges are met at the tactical level. One significant challenge is that targets are often interpreted in isolation for an individual asset in an acquisition without a thorough understanding of the broader energy picture of the unit that will utilize it. These frequently result in partial optimization, incompatible batteries, adapters, and wiring, leading to increased weight and complexity in the electricity system per unit. When adding the level of multinational operations, the complexity increases with the different national technical specifications.

To better understand the complexity of operational energy at the tactical level, case studies offer valuable insights into real-world problems encountered in the field. Adding new technology adds complexity and often raises new issues to solve. Frequently, these problems cannot be solved at the unit level, but they require broader changes to the logistics system, supply chain, acquisition, and even to the unit's tasks and composition. A holistic and systemic approach is necessary to develop feasible operational energy solutions that align with the goals set in strategic-level policies.

2. NATO ENSECCOE Field Study

NATO ENSECCOE contributed to a pilot project with a prototype Hybrid Power Generation and Management System (HPGS) produced by PFISTERER Kontaktsysteme GmbH (PFISTERER) starting in 2016 (Manfredini et al., 2018). Figure 4 shows a demonstration figure of the HPGS, and Figure 5 shows a schematic drawing of the HPGS Structure. The project's mission was to find real-time experiences of using the HPGS system (Manfredini et al., 2018). Initially, the project also included testing a smaller miniHPGS system; however, the configuration proved to have significant issues, and the project subsequently focused solely on HPGS (Manfredini et al., 2018, p. 29).

Figure 4. Hybrid Power Generation System (HPGS) demonstration figure. Source: Gogoreliani et al. (2021, p.29). HPGS includes PV and wind production, along with two containers. One container includes two generators, an energy storage system, and an automation system; the other container stores PV-cells.

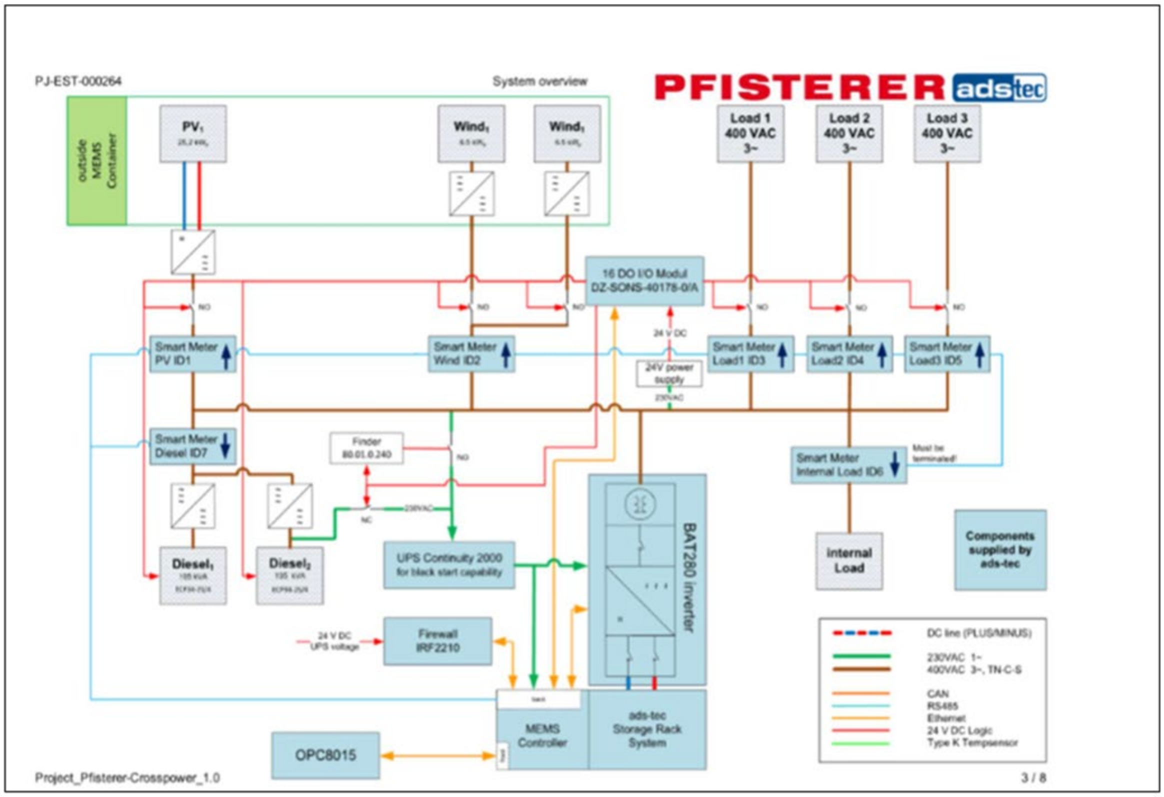

Figure 5. Schematic drawing of HPGS. Source: Manfredini et al. (2018, p.21). HPGS is important to this work because its field test gives data about using a hybrid energy system in a military camp.

During the project's first phase, ten tests were executed with various settings either during military training or separately by manufacturer or field tests (Manfredini et al., 2018 pp. 30–39). Findings concerning operational energy production were that a hybrid system will decrease the fuel consumption compared to the use of a conventional generator if the load stays under 40 % of the hybrid system's peak load, primarily because of the energy storage, allowing generators to run only part-time (Manfredini et al., 2018, pp. 54–56). In HPGS, solar panels' contribution to total energy production was between 3 % and 24 %, the wind turbine was not functional, and its share of energy production was minimal (Manfredini et al., 2018, p. 49). HPGS tested only in central/northern Europe latitudes, so the renewable energy production would probably perform better in southern and less forested areas (Manfredini et al., 2018, p. 49). The report also indicates several necessary improvements for the system and various tests that will be required later on; however, the result remains unknown, as ENSECCOE has not published any subsequent reports on HPGS.

The report is important for the thesis, in addition to its hands-on experience, as it presents technical data on a hybrid system, including generators, PV systems, wind turbines, energy storage, and support systems. Especially, measurements of the electrical power produced per liter of fuel in a military exercise environment are unique for public sources.

3. NPS Theses on Modeling the USMC Expeditionary Forces Energy Usage

The USMC has been seeking to decrease the energy burden in its expeditionary forces. In this subsection, two theses on this subject are reviewed. One addresses modeling energy at the brigade level and the other at the platoon level. Both are using a war game to observe energy consumption in a unit and were completed about 10 years ago. Both theses are based on goals outlined in the *United States Marine Corps Expeditionary Energy Strategy and Implementation plan* (Marine Corps Expeditionary Energy Office, 2011).

The NPS thesis *Marine Corps Expeditionary Rifle Platoon Energy Burden* (Atkinson, 2014) provides a tactical-level view for a model of actual energy use in a unit. The energy burden is estimated through a war game (Atkinson, 2014, p. 13). Expeditionary Rifle Platoons had at that time 12 mission essential tasks, nine of which involved tactical logistics and were dependent on some form of energy (Atkinson, 2014, p. 11). Functional analysis is used to explore the platoon's energy consumption and identify areas where improvements are possible (Atkinson, 2014, p. 14). The thesis highlights the dependency of energy in two forms of energy: the fuel needed for transportation supplies to platoon, and the need for batteries, especially for command and control, but also other equipment (Atkinson, 2014, Exsum pp. xv). The platoon does not have vehicles, so the energy used in the platoon was only batteries (Atkinson, 2014, p. 21). Since the limitations of this thesis are different than Atkinson's, only the battery model is strictly relevant since it describes energy use in the unit. The fuel model, though, also gives an example of how fuel consumption can be estimated for different vehicles with different missions.

To build a battery model for a platoon, Atkinson first allocates the company's equipment to a platoon, then calculates the energy consumption of each equipment, and then turns the consumption into the number of batteries (Atkinson, 2014, p. 26). The estimated amount of batteries needed in a platoon's 14-day mission is astonishing: 5,550 to 13,500 single-use batteries, the platoon has to charge 775 times rechargeable batteries, and carry 10 different battery types (Atkinson, 2014, pp. 31–33). The estimated daily usage times significantly impact the number of batteries required. It seems that there are assumptions that might overestimate the use of equipment. For example, both flashlights and night vision have a use time of 14 hours/day. It is reasonable to assume that they are actually not used at the same time. It is safe to believe that the battery model overestimates the need for batteries.

The thesis suggests that to reduce the number of batteries required, battery types should be standardized and, where possible, replaced with rechargeable ones (Atkinson, 2014, pp. 39–40). In the Recommendations chapter, there is a suggestion to explore a robotic solution with rechargeable batteries for carrying the supplies of the platoon to reduce the need for a supply flight (Atkinson, 2014, p. 42). The thesis does not take a stand on how the platoon is going to charge the rechargeable batteries. In the easiest solution, the platoon would need access to a building or infrastructure that can provide electricity, and this solution would require a charger and possibly adapters to carry in the unit. For a self-sustained solution in an austere environment, either an energy storage system, a PV system, or a field generator, and with any of them, a charger would also be needed. All of them would add weight that would need to be carried, and a field generator would also need a fuel supply to the unit and to carry the fuel. This highlights the complexity of measures to reduce energy burden at a unit level.

The NPS thesis *Operational energy/operational effectiveness investigation for scalable Marine expeditionary brigade forces in contingency response scenarios* (Bennett et al., 2014), addresses energy issues at the brigade level from a systems engineering view. The thesis adopts a system engineering perspective to examine the balance between efficiency and energy, aiming to find a way to maintain combat effectiveness while reducing equipment and logistical burdens associated with supplying energy (Bennett et al., 2014, p. 1). The need for tradeoffs is a crucial observation; having all possible equipment and simultaneously reducing energy consumption significantly is not a feasible option. The force structure is presented as a key subject that affects energy efficiency, and the thesis explores how to understand this relationship (Bennett et al., 2014, p. 12).

The stakeholder analysis, as part of the systems engineering process, recognizes primary and secondary stakeholders within the U.S. Navy and Marine Corps organizations (Bennett et al., 2014, pp. 20–25). The analysis highlights the critical feature of operational energy; developing and changing energy solutions have a broad impact, extending from development and planning through acquisition to end-users and operators. Interestingly, logistics is not mentioned as a stakeholder. "End Users, Operators, Maintainers" (Bennett et al., 2014, Table 1 p. 24) includes also logisticians, when reading between the lines and later in Operational Effectiveness Requirements include supportability of logistics (Bennett et al., 2014 p. 29) but the choice of stakeholders may also be an example how energy in system engineering view is not seen as a part of logistics but more as an engineering subject.

The thesis team selects one part of a wargame scenario and creates a detailed description of the operational area, units, and potential operational methods (Bennett et al., 2014, pp. 42–63). They also made a functional hierarchy from the chosen segment of operation. (Bennett et al., 2014, pp. 65–82). While creating the description, it is highlighted that the team had to make decisions and restrictions to make the operation possible to model in a capstone (Bennett et al., 2014, p. 42). Also, in Chapter IV, where the creation of the model with the chosen tool is explained, it is clearly stated that the thesis team still had to decide which core elements to model and what limitations to accept to reach a feasible solution (Bennett et al., 2014, pp. 99–102). These observations make it clear that modeling energy consumption in detail based on an operational scenario or plan is possible; however, it is time- and resource-intensive and will require making assumptions. Since plans in a contested environment change frequently, creating a detailed model of each operation is not feasible. Though using artificial intelligence (AI) to generate energy consumption from operational planning or logistic planning systems, such solutions may become available in the future.

In the thesis, operational energy means fuel only for ground and air vehicles. (Bennett et al., 2014, p. 114). Fuel consumption varies significantly depending on the use profile of the equipment. For example, a vehicle's fuel consumption varies depending on the speed and road conditions. The thesis team decided to use the unit of fuel use rate in terms of time rather than a distance to show fuel consumption (Bennett et al., 2014, p. 114). As the thesis team states, the assumption will not yield entirely correct results; however, they need to use the operation time for measurement to run the model (Bennett et al., 2014, p. 114). In their scenario, operation time was short enough, about 75 minutes (Bennett et al., 2014, p. 184). Only the fill rate in the beginning and in the end was measured to find out the fuel consumption, because the vehicles did not need to be refueled during the modeled operation (Bennett et al., 2014, p. 114).

This limitation highlights an assumption that is often made in both military exercises and war games: the operation is so short that refueling is not needed. If the military exercises and war games are used to give a basis to planning for real operations, this assumption is likely false, and probably dangerous. For example, suppose the batteries will last a couple of days of exercise, and they are charged only in barracks before and after exercise to spare the valuable exercise time. In that case, the charging time is easily neglected when planning the use of the troop in a real mission. Also, the mindset of personnel towards operational energy is affected. As is evident in the latest Russian-Ukrainian War, short military conflicts have tended to become protracted.

The energy link analysis states that the total fuel consumption increases while the platoon size increases (Bennett et al., 2014, p. 199). The use of air assets is the primary driver of the fuel consumption, adding ground vehicles have only a minor impact (Bennett et al., 2014, Table 42, p. 200). The trade space analysis between the operational energy consumption and operational effectiveness shows that the force size and construction affect both of them, but there is a turning point where the ratio between them improves no longer (Bennett et al., 2014, Figure 24, p. 222). Key energy drivers were the length of the operation and the casualty rate, causing evacuation flights (Bennett et al., 2014, pp. 231–232). The results seem obvious, but the method to find them through a war game and modeling suggests how complicated it is to model a military operation, even though the thesis team made assumptions, limitations, and decisions on which variables are considered core elements for modeling.

Key takeaways from the two theses are the complexity of energy consumption in the real world and the ambiguity of the term ‘operational energy.’ In both theses, limitations and assumptions were inevitable to create a model. However, especially when comparing cases with the same assumptions, the analysis will deliver comparable results. Atkinson’s thesis (Atkinson, 2014) does not mention operational energy, just energy, meaning fuels and batteries. On the other hand, Bennett et al.’s thesis (Bennett et al., 2014) uses the term and means only fuels. Probably all writers of these theses have had a clear vision of what energy or operational energy means in their context, but for the reader, clarification of the term is the first task. This highlights the ambiguity of the term’ operational energy’ despite the definitions used in policies.

4. NPS Thesis of the U.S. Corps of Engineers Case in Afghanistan

The NPS thesis, *Development and Application of an Approach to Optimize Renewable Energy Systems in Afghanistan* (Law & Tyley, 2012), approaches energy issues from the perspective of substituting fossil fuels with renewable energy in Afghanistan National Security Force installations. In the context of this thesis, energy means the energy needed to produce electricity in a fixed installation. These installations are larger than the tactical level approach presented in this thesis, and the approach involves a fixed distribution network and facility without considering a unit as an end user. The decision-making between fossil fuels and renewables is similar, however. Also, the generation of inputs, especially energy load profile and renewable energy parameters, is the same as that are needed in a tactical-level unit.

In a fixed installation, load data is an important input to plan electricity production solutions. In the thesis, the hourly data from the USMC Experimental Forward Operating Base (ExFOB) is used to substitute the missing actual load data from Afghanistan Police Stations (Law & Tyley, 2012, p. 40). At the unit level, load data is measurable from the electricity consumption, but it can be applied to a semi-fixed installation only. This means that the load of equipment attached to the same field electricity network can be measured, but the batteries are only calculated with charger loads. When approaching a unit's total energy consumption, load data is only a part, though an important part, of the picture.

Renewables discussed in the thesis are solar and wind, with their potential in Afghanistan and the technical specifications of the solar panels and wind turbines (Law & Tyley, 2012, pp. 43–53). Since the renewable energy production is not constant, energy storage is also needed for the solution (Law & Tyley, 2012, pp. 53–54). For simulation purposes only, solar panels, wind turbines, and energy storage are defined; wiring, inverters, and other necessary technical assets are not considered, although they are also required in real installations. The existing power source solution, generators, is also considered in the decision-making process since they are the current solution and will be the backup to produce electricity if renewables and energy storage cannot keep up with the load (Law & Tyley, 2012, p. 61, p. 63). The product of the thesis is an optimal energy rubric for the combination of energy sources in different areas of Afghanistan (Law & Tyley, 2012, Table 23 p. 67). For decision-making regarding a tactical unit's operational energy solution, this approach would be feasible for the electricity component of the operational energy, provided that solar irradiation and wind potential can be determined for the area where the unit will operate. When comparing energy optimization to the HPGS case study of ENSECCOE, the more open and southern environment seems more suitable for solar and wind energy production.

In all case studies reviewed in this chapter, energy or operational energy is considered differently, and the whole energy consumption is considered only partly. This approach is particularly evident when conducting a study on a technical solution, as seen in the ENSECCOE (Manfredini et al., 2018) and Afghanistan (Law & Tyley, 2012) cases. When attributing to a unit's energy usage, like in both USMC studies (Atkinson, 2014), (Bennett et al., 2014), simulation also requires simplifications. However, when considering the definition of operational energy: "energy required for training, moving, and sustaining military forces and weapons platforms for military operations" (Howard et al., 2024 p. 3), the whole picture of operational energy at the unit level will not be captured in case studies reviewed.

C. MODELING LOGISTICS AND ENERGY

A model is a representation, usually mathematical, of a real-world problem (Balakrishnan et al., 2013, p. 2). Models can be formulated for any situation, but in this subsection, logistic and energy models are the focus. In this subsection, first, models and, particularly, linear programming (LP) models are briefly discussed. Next, logistic and energy models are discussed, and finally, this thesis's approach to model tactical-level operational energy is reflected in the previous paragraphs.

Models can be either deterministic or probabilistic (Balakrishnan et al., 2013). Deterministic models have the assumption that the input data is known with certainty, while in probabilistic models, at least part of the input data includes uncertainty (Balakrishnan et al., 2013, pp. 2–3). One of the most used deterministic models is linear programming, which has four common properties: the problem seeks to minimize or maximize some quantity resulting in an objective function, it includes constraints that limit the solution of the objective function, the problem must have alternative courses of action to choose between, and both the objective and constraints have to be linear equations (Balakrishnan et al., 2013, pp. 21–22). The transshipment model is a type of network flow model comprising three types of nodes: supply nodes, transshipment nodes, and demand nodes (Balakrishnan et al., 2013, p. 174). The transshipment model appears to be a promising approach for operational energy at the tactical level.

Military logistics can be divided into three levels: strategic logistics, operational logistics, and tactical logistics (Kress, 2016, p.15). Our focus is on the tactical level in this thesis. Logistic functions at the tactical level can be represented as a network comprising logistic nodes, logistic edges, and lines of communication (LOC) (Kress, 2016, p.25). Logistic Nodes are places where some logistical activity happens, for example, a refuel point (Kress, 2016, p.25). Logistic Edge connects two logistic nodes, and it can be, for example, a road (Kress, 2016, p.25). The nodes can be divided into source nodes, intermediate nodes, and destination nodes (Kress, 2016, Fig. 2.2 p.25). LOCs are a series of connected logistic edges that will allow the logistic flow from the rear area to the front of the theater, and in some cases, like medical evacuation, also back (Kress, 2016, p.25). This network can be modeled in different ways to facilitate logistical planning. Some examples are routing, scheduling, distribution, and network models (Kress, 2016, p.29). To optimize the performance of a logistic network, network flow models are a helpful tool (Kress, 2016, p.29). They can be either visual descriptive models or mathematical optimization models. (Kress, 2016, pp.29-30)

Energy models are widely used to understand energy networks; they include energy planning models, energy supply-demand models, forecasting models, renewable energy models, emission reduction models, and optimization models (Jebaraj & Iniyan, 2006). In their article, Jebaraj & Iniyan walk through a review of 252 different energy models that could be useful in India as renewable energy is increasing heavily (Jebaraj & Iniyan, 2006). Even though the article is almost 20 years old, the principles of energy modeling have not changed. Linear programming and flow models are mentioned frequently.

Tactical-level logistics includes traditional refueling (Kress, 2016, p. 23), which is a significant part of operational energy. To capture the entire operational energy scheme, other forms of energy must be included. While in the logistic network, the edges, or arcs for now on, are one kind of real physical feature, such as roads (Kress, 2016, p. 25). In tactical-level operational energy modeling, these features can be mixed, including tanks, hoses, or jerry cans for fuel, wires and electricity boxes for electricity, and boxes for batteries. The source nodes in the operational energy network are the sources of energy, intermediate nodes are conversion points of energy, and the destination points are the nodes where the energy is consumed. While there are differences between the tactical level operational energy network and the logistic network Kress defines, as well as physical electricity networks, the primary function of the flow is similar. Because of that, the network flow model is chosen for the approach in this thesis.

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III. METHODOLOGY

The notional unit's operational energy model is a conceptual presentation of total energy usage in a tactical-level unit for managerial purposes. The model does not seek to create an accurate and detailed technical layout of a unit's energy distribution network. For that reason, the energy sources, conversions, and consumption are presented bundled by the energy source, conversion, or consumption form of energy. The conceptual model is bound to the conceptual view of operational energy presented in Chapter 2.B (Howard et al., 2024) with colors. The conceptual model is presented in Figure 6.

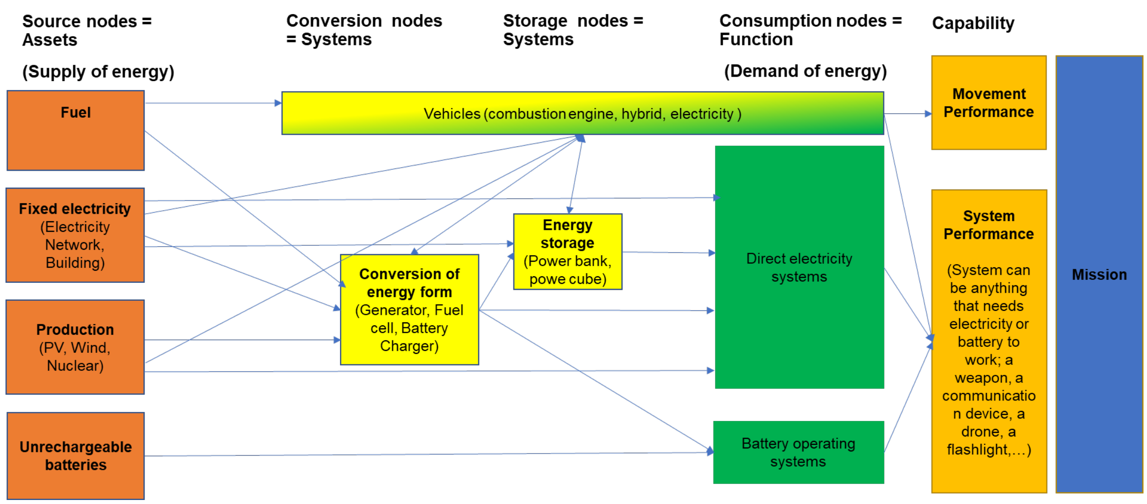

Figure 6. Conceptual model of operational energy in a tactical-level ground unit. This diagram shows the interrelationship and dependencies between energy forms. Note that the end results (Orange) are Movement Performance and System performance.

Our work does not include a uniquely Finnish energy source: firewood. They are an essential form of operational energy in Finland and part of the logistic supply system. They are used to provide heat to tents with stoves, which both create warmth for soldiers during cold seasons and help dry clothing. They are used in a large number of field kitchens for both cooking and providing warm water to troops. Even a simple campfire creates warmth. However, logs are not included in the model because they do not interact with the other energy forms.

Actual military unit's personnel list, material list, and technical data of material, are partly or entirely classified both in Finland and the U.S. Because of that, the personnel and material data in the model is based on a notional unit derived from the NPS thesis *Marine Corps Expeditionary Rifle Platoon Energy Burden* (Atkinson, 2014) and *ENSECCOEs Phase 1 Report Performance Analysis of Hybrid Generation and Management System (HPGS)* (Manfredini et al., 2018). Data not gathered from these sources has been collected from other public sources, which represent similar technical equipment to that used in military applications. Some assumptions are based on the writer's experience. These sources and assumptions are explained in detail in the following subsections. Overall, this means that, for example, a field generator used in the model is just one possible option picked from the ENSECCOE report. Different manufacturers will have different technical specifications, various environments will affect energy consumption, and different missions will result in varying consumption rates. The model is a way to visualize and compare different scenarios of operational energy usage, so the exact technical figures are not necessary in the approach take in this thesis. Later, the model can be applied to actual data.

In subsection III.A, first, the basic energy units and their conversions are presented. In subsection III.B, the unit's structure and environment are discussed. Also, the technical data and calculations are presented. In subsection III.C, the network structure created with the R language is introduced. Finally, in subsection III.D, the Linear Programming (LP) model for a unit's operational energy is unveiled.

A. ENERGY UNITS, CONVERSIONS, AND FORMULAS

Energy can be presented in different units that can be converted with conversion factors. For example, electricity energy is typically measured in kilowatt-hours (kWh), and liquid fuel energy density in British Thermal Units (Btu) per liter (l) or gallon (gal) (AFDC, 2024). Energy, volume, and length units and their symbols are presented in Table 1. The conversions between energy, volume, and length units are presented in Table 2.

Table 1. Units and their symbols. Adapted from IEA (2023), NIST (2025a), IEEE (2021, Table 9, pp. 28–29).

Unit	**Symbol**
Gallon	gal (US)
Liter	l
Joule	J
British Thermal Unit	Btu
Watt hours	Wh
Kilometer	km
Mile	mi
Volt	V
Ampere	A
Volt-Amperes	VA

Table 2. Conversions between units. Adapted from IEA (2023), NIST (2025a), NIST (2025b).

	Unit	Conversion
Volume	1 gal	3.785 l
	1 l	0.2642 gal
Energy	1 J	0.0009478 Btu
	1 J	0.0002778 Wh
	1 Wh	3600 J
	1 Wh	3.412 Btu
	1 Btu	0.2931 Wh
	1 Btu	1055 J
Length	1 km	0.62 ml
	1 mi	1.61 km

Formulas used in calculating the data are presented in detail in the next subsection. For the energy forms that include electricity, the basic formula to calculate energy is

$$Energy\ (E) = Voltage\ (U) \times Current(I) \times Time(t)$$

Though the formula does not capture the alternating current perfectly, for the conceptual model and for the purposes of this thesis, the formula is accurate enough.

B. THE UNIT'S ENERGY DATA FOR THE MODEL

The unit is approximately company-sized, with 200 soldiers, as presented in Test 4 of ENSECCOE's *Phase 1 Report Performance Analysis of Hybrid Generation and Management System (HPGS)*. The camp is electrified half by HPGS and half by a conventional 200 kVA field generator. The HPGS structure is explained in Chapter 2.B.1. The average electrical power is 13 kW during the 48-hour test. Solar power was produced during the test, and it was 17 % of the total electricity consumption. Wind power was not produced during the test. Efficiencies of field generators and energy storage are also calculated based on the Test 4. (Manfredini et al., 2018)

Since the ENSECCOE's field test did not include vehicles, fixed electricity, or batteries, they have been added to the unit. Vehicles and fixed electricity are derived from assumptions made by the writer and data from civilian equipment. The unit energy data, calculations, and assumptions are presented in Table 3. Energy data is observed for a 24-hour period. All energy is converted to kWh with conversions presented in Chapter III.A. The battery model is derived from the MRP battery model presented in Atkinson's thesis and presented in Table 4, with the assumptions explained below it (Atkinson, 2014).

Table 3. The unit's energy data for the model. Adapted from AFDC (2024), Manfredini et al. (2018), Duracell (2025), Bren Tronics (2024a), Bren-Tronics (2024b) L3Harris (2019), Wikipedia (2025), Väkevä et al. (2004), Atkinson (2014)

Source nodes	Focus	Unit	Data	Formula
Fuel	Low Sulfur Diesel	kWh/l	10.724	=138 490 Btu/gal * 0.642 gal/l * 0.2931 Wh/Btu * 0.001 kWh/Wh
Fixed Electricity	3-phase outlet 16 A – 400 VAC	kWh	153.6	=400V*16 A*24h*0.001 kWh/Wh
Production (solar)	HPGS	kWh	53.0	= 17% of camps electricity consumption = 0.17*13 kW*24 h
Unrechargeable Batteries	AA battery (Duracell)[a]	kWh/unit	0.00045	=1,5 V*0.3A[b]*1h*0.001 kWh/Wh
Conversion nodes				
Field generators out	3 generators	kWh	8640	=(4800 kWh+3840 kWh)
	-Conventional (200kW)	kWh	4800	=200 kW * 24 h
	-Part of HPGS (2*80 kW)	kWh	3840	=160 kW * 24 h
	-efficiency		0.15	=(1.63 kWh/l) /10.724 kWh/l)
Energy storage	Part of HPGS	kWh	2400	=100 kW * 24 h
	-efficiency		0.91	=1-[(2.59 kWh/l) / (10.724 kWh/l)-0.15]
Battery charger[c d]	For chargeable batteries (25 units[e])	kWh	39	= 25 units * 65 W/unit * 24 h * 0.001 kWh/Wh
- chargeable batteries	BA 590/U[f]	kWh/unit	0.0528	= 2.2 Ah * 24 V * 0.001 kWh/Wh
	-efficiency		0.8	
Consumption nodes				
Combustion engine vehicles	Trucks (20 units[g])	kWh	6574	=20 units *50 km/24 h*61.3 l/100 km[h] *10.724 kWh/l
Direct electricity systems	200 soldiers camp	kWh	273	= 312 kWh – 39 kWh[i]
Battery operated systems	MRP company's material list[j]	kWh	14.1	=3.6 kWh + 10.5 kWh
	- unrechargeable batteries (7924 units)	kWh	3.6	=7924 units * 0.00045 kWh/unit
	- chargeable batteries (198 units)	kWh	10.5	=198 units * 0.0528 kWh/unit

[a] Assumed that all unrechargeable batteries are Duracell AA-batteries.
[b] 0.3 A was chosen for current, because it was the current that in datasheet was used to represent optimal temperature.
[c] A battery charger means only chargers needed for chargeable batteries. HPGS also includes a battery charger, which is used between generators and energy storage, but it is not included in the model. Its capacity is bigger than the energy storage, so it will not constrain the energy flow.

[d] The battery charger chosen based on the battery type BA590/U from the same producer.
[e] 198 rechargeable batteries, one is charged in 3 hours, so one charger can charge 8 batteries/day. 198/8 = 24.75 → 25 charges needed.
[f] Assumed that all rechargeable batteries are 590/U, since it was compatible with the most used radio set.
[g] Trucks are added to the unit in a ratio of 1 truck per 20 soldiers. 200 soldiers*1/10 truck/soldier = 20 trucks.
[h] The trucks' consumption km/l is based on timber truck research in Finland. The daily driving distance per truck is assumed to be 50 km.
[i] The total electricity consumption from the ENSECCOE report is 24 h*13 kW average = 312 kWh. Assumed that the battery charger consumption is included in the total electricity consumption. To get the direct electricity system consumption, the battery chargers' consumption is reduced from the total electricity consumption.
[j] Calculations for batteries from Atkinson's battery model are in Table 4.

Table 4. The battery model. Adapted from Atkinson (2014)

Nomenclature[a]	Number/ Company	Battery Nomenclature	Battery Qty/ System	Battery Qty/ Company	Batts/ Day/ System[b]	Batts/ day/ Company	Unrechargeable batteries/day/ Company	Chargeable batteries/ day/ Company
RADIO SET -AN/PRC-153(V)1	176	BATTERY, RECHARGEABLE, LITHIUM IO	1	176	0.740741	130		130
RECEIVER-TRANSMITTE – AN/PRC-152(V)1©	34	BATTERY, RECHARGEABLE, LITHIUM	1	34	0.612245	21		21
RECEIVER,RADIO NAVI – AN/PSN-13(B)	6	BATTERY, NONRECHARGEABLE, ALKAL	4	24	2.086957	50	50	
DEMOLITION SET,EXPL	3	BATTERY, NONRECHARGEABLE, ALKAL	1	3	1.4	4	4	
VIEWING SET, INFRARE – NH11	5	BATTERY, RECHARGEABLE, NICKEL MET	1	5	9.333333	47		47
FLASHLIGHT – 14032	182	BATTERY, NON-RECHARGEABLE, ALKAL	2	364	14	5096	5096	
NIGHT VISION DEVICE – AN/PVS-24A	36	BATTERY, NONRECHARGEABLE, LITHIU	1	36		16	16	
ILLUMINATOR, INFRARE – AN/PEQ-16B	155	LITHIUM/MANGANESE DIOXIDE PRIMA	2	310	7	2170	2170	
BORELIGHT SYSTEM,LA – LBS-300-A2	15	BATTERY, NONRECHARGEABLE, ALKAL	1	15	1.75	26	26	
NIGHT VISION DEVICE - AN/PVS14	182	BATTERY, NONRECHARGEABLE, ALKAL	1	182	0.466667	85	85	
NIGHT VISION SIGHT – AN/PVS17C	36	BATTERY, NONRECHARGEABLE, ALKAL	1	36	1.75	63	63	
SIGHT,GRENADE LAUNC – AN/PSQ18A	35	BATTERY, NONRECHARGEABLE, ALKAL	1	35	1.75	61	61	
ILLUMINATOR, INFRARE – AN/PEQ-15	36	BATTERY, NONRECHARGEABLE, ALKAL	2	72	4.307692	310	310	
NAVIGATION SET,SATE – AN/PSN-13(A)	5	BATTERY, NONRECHARGEABLE, ALKAL	4	20	2.086957	42	42	
							7924	**198**

[a] Included only equipment from the company that was included at the company level in Atkinson's platoon model.
[b] Atkinson has calculated daily consumption based on manufacturers' computed or advertised run time.

In the model, energy is not stored, but it flows through the network, representing one day's energy need. Since the energy is not stored, the smaller capacity of the origin and destination node for an arc gives the capacity for the arc. "You cannot push more than you can receive, you cannot receive more than you can push." The efficiency is calculated for three nodes: "in-out" nodes for field generators, energy storage, and battery chargers. To keep the two different battery flows separate, the flow from the battery chargers to the battery operating systems is set to the needs of rechargeable batteries, and the flow from the supply of unrechargeable batteries to the battery operating systems is set to the needs of unrechargeable batteries. The battery operating system output combines these into the total energy flow of batteries. Capacities of arcs in the basic scenario are presented in Table 5.

Table 5. The capacities of the network arcs. The node names are shortened from the ones used in Figure 6.

Start node	End node	Capacity (kWh)
Source	Fuel Out	800000
Source	Elec Network	800000
Source	Production	800000
Source	Unrecharge Batt	800000
Fuel Out	Combustion Eng (in)	6574
Fuel Out	Field Gen (in)	8640
Elec Network	Direct Elec (in)	153.6
Elec Network	Energy Storage (in)	153.6
Elec Network	Batt Charger (in)	39
Production	Energy Storage (in)	53
Production	Direct Elec (in)	53
Production	Batt Charger (in)	39
Unrecharge Batt	Battery Op Systems (in)	3.6
Combustion Eng (in)	Combustion Eng (out)	6574
Combustion Eng (out)	Batt Charger (in)	39
Field Gen (in)	Field gen (out)	1296
Field gen (out)	Direct Elec (in)	273
Field gen (out)	Batt Charger (in)	39
Field gen (out)	Energy Storage (in)	576
Energy Storage (in)	Energy Storage (out)	524.2
Energy Storage (out)	Direct Elec (in)	273
Energy Storage (out)	Batt Charger (in)	39
Batt Charger (in)	Batt Charger (out)	31.2
Batt Charger (out)	Battery Op Systems (in)	10.5
Direct Elec (in)	Direct Elec (out)	273
Battery Op Systems (in)	Batt Op Systems (out)	14.1
Field Gen (in)	Generator Loss	8640
Energy Storage (in)	Energy Storage Loss	2400
Batt Charger (in)	Batt Charger Loss	39
Batt Op Systems (out)	Terminus	800000
Direct Elec (out)	Terminus	800000
Combustion Eng (out)	Terminus	800000

In this table, 800000 represents unconstrained capability. There are losses in field generators, energy storage, and battery chargers. Their capacity is set to the maximum capacity of the device; losses cannot be larger. All capacities are expressed in kWh. Table 5 represents the capacities of the basic scenario. In the spreadsheet, some capacities are defined as formulas to facilitate easier modifications.

C. VISUALIZING THE OPERATIONAL ENERGY NETWORK

The network visual was built with the R programming language, implemented in the RStudio Integrated Development Environment (IDE). The network was created by a .csv file presenting arcs of the network, as presented in subsection III.B, Table 5. Because visualizing only the network structure, all arcs have a capacity of 1. Losses were not included in the network visualization. Conversion nodes were presented as dual nodes, where the arch between nodes represents the capacity of the original node. The losses are not included in the visualization even though they appear from the conversion nodes. The code is presented in Appendix A. The network is presented in Figure 7.

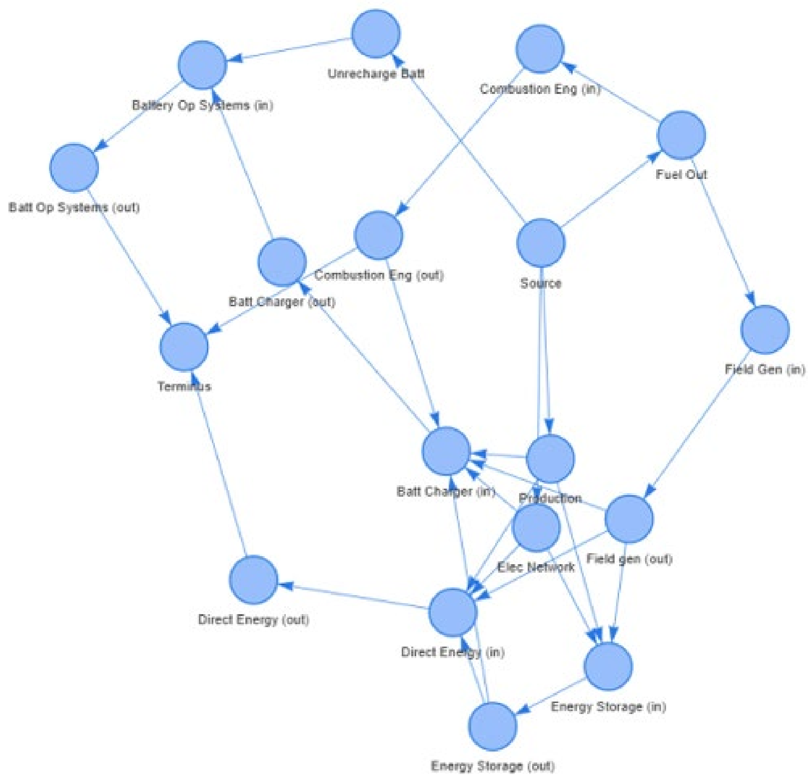

Figure 7. Unit's operational energy network. The nodes represent the source of energy, the conversion of energy, and the consumption of energy. The arcs represent the flow of energy. The Source and Terminus nodes are needed to create a feedback loop.

D. LP MODEL FOR OPERATIONAL ENERGY

Operational energy in a tactical unit consists of several energy forms that interact with each other. For the optimization model, the minimization of fuel to produce electricity was chosen as the objective function. Fuel for vehicles is directly tied to the number of vehicles and their driving distances, so in the model, it is a straight path from the start to the end. Also, with unrechargeable batteries, the path from battery supply to the systems they are needed for is straight. These features can be seen in Figure 7 in subsection III.C. The transshipment model is used as a base for the network flow model.

1. Formulation of the LP Model

The LP model formulation in NPS style is presented below. It primarily follows a basic transshipment model, with a few additional constraints. The production of solar power is forced to use with a constraint, and the energy content of unrechargeable batteries is forced to flow to the destination node because they cannot be replaced with rechargeable batteries. Also, the production of generators attached to HPGS is forced to flow to the energy storage.

Indices and sets

$i,j \in N = \{1,..,19\}$ *all nodes*

$p \in P \subseteq N = \{1,\ldots,4\}$ *supply nodes*

$k \in K \subseteq N\{5,\ldots,13\}$ *conversion (transshipment) nodes*

$m \in M \subseteq N = \{14,15,16\}$ *demand nodes*

$l \in L \subseteq N = \{17,18,19\}$ *loss nodes*

$$(ij) \in A = \begin{Bmatrix} (1,11),(1,5),(2,12),(2,7),(2,9),(3,7),(3,12),(3,13),(4,13),(11,14), \\ (14,9),(5,6),(6,12),(6,9),(6,7),(7,8),(8,12),(8,9),(9,10),(10,13), \\ (13,16),(12,15),(5,17),(7,18),(9,19) \end{Bmatrix}$$

$(ij) \in B \subseteq A = \{(5,6),(7,8),(9,10)\}$ *generator, energy storage and battery charger capacity (in − out) arcs*

Parameters

C_{ij} = *capacity of energy flow [kWh] over arc ij* $\in A$

S_i = *supply of energy [kWh] a node i* $\in P$

C_{HPGS} = *capacity of generators in HPGS [kWh]*

C_{conv} = *capacity of conventional generator [kWh]*

$r = \dfrac{C_{HPGS}}{C_{conv} + C_{HPGS}}$ *ratio to energy flow from HPGS generators to the energy storage*

E_l = *efficiency at node l* $\in L$

Variables

$x_{ij} = flow\ of\ energy\ [kWh]\ from\ node\ i\ to\ node\ j$

Objective Function

$\min_{z} z$

Constraints

$S_p \geq \sum_{j:(pj)\in A} \left(x_{pj}\right) \quad \forall\ p \in P \quad Flow\ conversation\ supply\ nodes$

$\sum_{j:(jk)\in A} \left(x_{jk}\right) = \sum_{j:(kj)\in A} \left(x_{kj}\right) \quad \forall\ k \in K\ Flow\ conversation\ transshipment\ nodes$

$\sum_{j:(jm)\in A} \left(x_{jm}\right) = D_m \quad \forall\ m \in M \quad Flow\ conversation\ demand\ nodes$

$\sum_{j:(jl)\in B} \left(x_{jl}\right) = \frac{1 - E_i}{E_i} \cdot x_{ij} \quad \forall\ ij \in B\ \ Flow\ conversation\ loss\ nodes, \text{"}demand\ of\ loss\text{"}$

$x_{ij} \leq C_{ij} \quad \forall\ ij \in A \quad Capacity\ constraint\ for\ arcs$

$x_{67} = r \cdot x_{5\,6} \quad Energy\ from\ HPGS\ generators\ must\ go\ the\ energy\ storage$

$S_3 = C_3 = x_{3\,7} + x_{3\,9} + x_{3\,12} \quad All\ production\ must\ be\ used$

$S_4 = C_4 = x_{4\,13} \quad Supply\ of\ unrechargeable\ batteries\ must\ meet\ the\ demand\ of\ them$

$z \geq x_{15}$

$x_{ij} \geq 0 \quad non\ negativity$

2. Creating and Solving the LP-model and Creating Visuals

Microsoft Excel was chosen as the tool to solve the LP model because it can be operated in a classified environment. This is important if the actual military unit data is used later. The network structure is presented in Figure 7. Microsoft Excel standard Solver was used to solve the model. The spreadsheet and solution for the basic scenario are given as a picture in Appendix B, and the functional spreadsheet is provided as a supplemental.

The spreadsheet cells are color-coded. Blue cells are parameters, grey cells are formulas, green cells are variables, the yellow cell is the optimal objective function, and orange cells are conversion cells from kWh to liters. The spreadsheet is organized into three sections. First, there is a table for arcs, including the capacity parameters and formulas, flow variables, and excess. This table includes “Switch” to ease taking arcs out in different scenarios. The second table is for nodes and flow conservation in supply, transshipment, demand, and loss nodes. The third part includes the objective function, parameters, and formulas that are needed in the first two tables and constraints for Solver written out.

Notably, the model does not capture the energy storage as an inventory node, only as a transshipment node. The model captures one day’s total energy consumption and does not include periodicity. For the model’s simplicity, this restriction was approved.

Microsoft Power BI Desktop was used to create the Sankey charts to visualize energy flows. The Sankey 3.4.5.0 visual from Microsoft was imported to Power BI Desktop. The data for Power BI was imported from Microsoft Excel.

IV. ANALYSIS

The analysis includes observations of the LP model and its application in optimizing the operational energy usage of the notional unit. First, the optimal solution of the notional unit is observed based on the spreadsheet solution. Next, three analyses are presented to demonstrate how the model can be applied: the effects of the environment and weather, the optimization of the field generators' capacity, and the electricity consumption analysis. The operational energy is also visualized with Sankey charts created in Power BI. Finally, there is a discussion of the model's limitations and how the assumptions made will impact the results. These analyses are examples of how to utilize the model, but do not represent all options.

A. UNIT'S OPERATIONAL ENERGY IN THE BASIC SCENARIO

With the notional unit's basic scenario, the optimal solution is in Appendix B. The energy forms for a 24-hour period are available as follows. The source of fuel and unrechargeable batteries is unlimited, as it is assumed that the logistic supply system can transfer the required amount of fuel and number of batteries. Energy from the electricity network is 153.6 kWh, which is the capacity of the most common Finnish 3-phase outlet, which is available in almost every building's electrical box. The unit has a PV system that produces 53.0 kWh. The energy content of fuel and batteries is converted to kWh.

The unit needs 613.0 liters of fuel to execute the daily mission of 50 km of driving per truck, which converts to 6574 kWh. It requires 7924 unrechargeable AA batteries, which have an energy content of 3.6 kWh total, and 198 rechargeable batteries, which have an energy content of 10.5 kWh total. Totally battery-operated systems need 14.1 kWh of energy. Direct electricity systems will need a total of 273 kWh of energy. In a 24-hour period, the unit's total energy need is 6862.7 kWh.

The LP model requires the unit to utilize all the energy produced by the PV system before drawing electricity from the network. All PV production of 53.0 kWh flows straight to direct electricity systems. Also, all electrical energy from the electricity network of 153.6 kWh flows straight to the direct electricity systems. In the basic scenario, the PV system and the electricity network do not satisfy the need for electricity in direct electricity systems and battery chargers, so the generators also produce 552.3 kWh, which means they use 51.5 liters of fuel. The energy the generators produce is divided into three arcs: 32.9 kWh straight to the direct electricity system, 13.1 kWh to battery chargers, and 36.8 kWh to energy storage. The model requires the energy produced in field generators attached to HPGS to flow to the energy storage. The direct electricity systems will receive the remaining 32.9 kWh of the energy demand from the energy storage. The battery-operated systems will obtain the required 10.5 kWh from the battery chargers and 3.6 kWh from the supply of unrechargeable batteries, totaling 14.1 kWh.

The losses for the field generators are high, 469.4 kWh, due to the low efficiency of 0.15. The efficiency is derived from the ENSECCOE report as an actual measurement in a test conducted in a military exercise. The generators also have an excess of 8087.7 kWh. Energy storage has a loss of 3.3 kWh, and battery chargers have a loss of 2.6 kWh.

B. VISUALIZATION OF THE SOLUTION

A Sankey chart is a way to visualize energy flows. It presents the nodes and shows the flows between nodes in a relative manner. It is easy to see which flow is bigger than the other and where they originate and end. The unit's basic scenario in the Sankey Chart is presented in Figure 8.

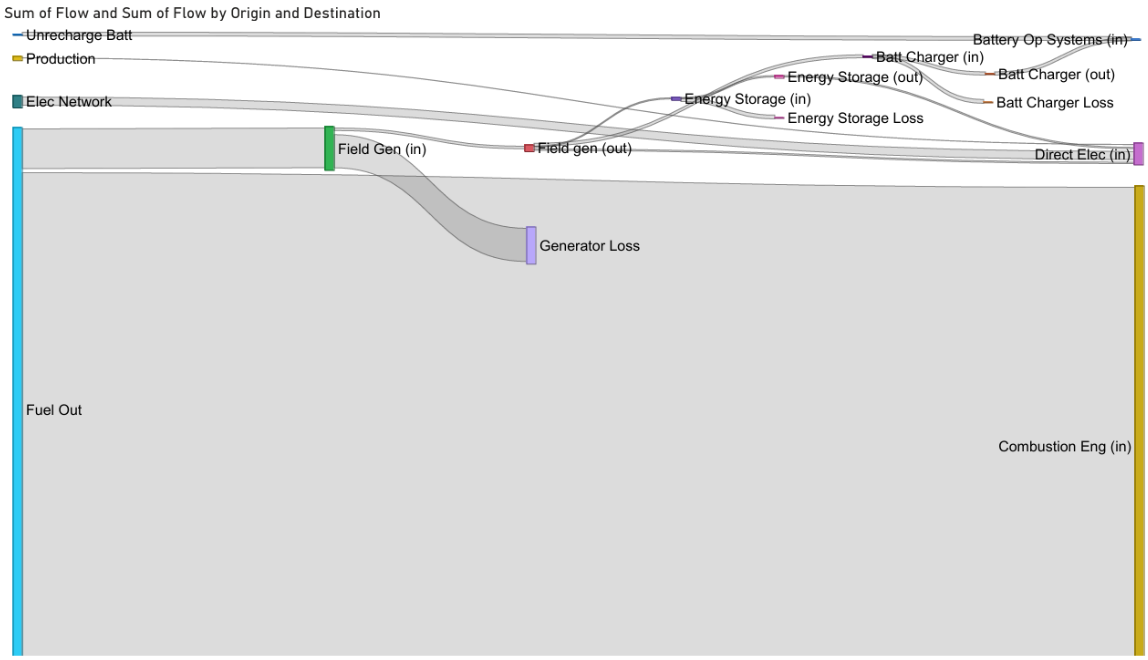

Figure 8. Unit's basic scenario energy flows in a Sankey Chart. The chart shows all energy flows in the unit and their relative share of the total energy flow. The fuel flow to vehicles is dominating this chart. The Sankey chart has filters that sort out arcs that do not have flow. Also, nodes that are not essential, such as the "consumption out" nodes, are sorted out to make the visualization simpler. Fuel for vehicles dominates the basic scenario, and it is the most powerful message of this figure: even though electricity and batteries are essential for the unit, the mass of operational energy is fuel. To give better visibility to other flows, in Figure 9, the vehicles' fuel is sorted out.

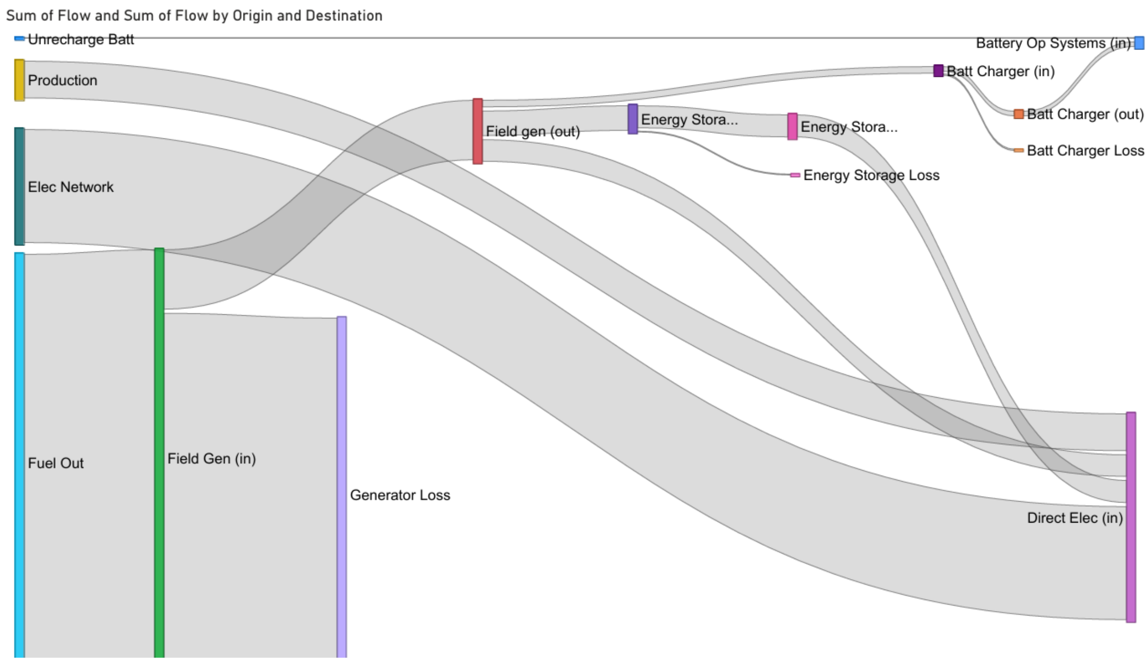

Figure 9. Unit's basic scenario energy flows in a Sankey Chart without fuel for vehicles. Now, the electricity flow and battery flow can be seen more clearly.The Sankey chart in Figure 9 clearly illustrates the energy flows to the direct electricity systems and the battery-operating systems. To fulfill the electrical energy needs, all electricity sources are involved. Even though the number of batteries is high, their energy content is one order of magnitude lower than the electricity needs.

The visualization of the unit's total energy flows makes it visible what the definition of operational energy means at the tactical level. Although the visualization highlights the significant differences in the magnitudes of the flows on different energy forms, it is essential to remember that they are all necessary and cannot be substituted for one another.

C. USING THE LP MODEL FOR ANALYSIS

Next, the LP model is utilized to produce answers that might have been asked to plan the unit's energy solutions in logistical planning. These analyses are examples of how the LP model can be utilized.

1. Analysis for Operational Area and Weather Effects

The basic scenario had both PV production and the electricity network available. However, the sun does not always shine, and the unit can be placed in an austere area. This subsection examines the impact of weather conditions and the operational area. The LP-models switch is used to solve the model in four different cases: “Sunny day in an urban area,” “Cloudy day in an urban area,” “Sunny day in an austere area,” and “Cloudy day in an austere area.” “Sunny” refers to a scenario where PV is available, “cloudy” when it is not. “Urban” refers to an area where the electricity network is available, and “austere” refers to an area where the unit has to produce its own electricity either by PV or field generators. “Sunny day in an urban area” is the same baseline case as in subsection IV.A.

The weather and operational area affect only the energy sources of production and the electricity network. One might speculate whether, for example, flashlights and night vision devices are needed more in austere areas, and in that way, the need for batteries might also increase. However, battery consumption changes are not included in this analysis because they are speculative. The analysis is executed by using the switches of the model to “turn off” the capacity of the energy sources. If the capacity is zero, the capacity constraint will keep the flow also zero. The results are presented in Table 6.

Table 6. Results of the analysis of changes in the operational area and weather. The fuel required to produce electricity increases when the option to use a PV system or a fixed connection to the electricity network is eliminated. The share of fuel to produce electricity increases compared to the vehicles’ fuel requirements.

	Fuel to electricity (l)	Share of the total fuel consumption
Sunny day in an urban area	51.5	8%
Cloudy day in an urban area	85.8	12%
Sunny day in an austere area	151.0	20%
Cloudy day in an austere area	185.3	23%

Fuel needed to produce electricity obviously grows when the PV production and/ or the electricity network is not available as an energy source. The fuel consumption to produce electricity increases 260 % from the lower bound of the first scenario to the upper bound of the last one. Also, the proportion of the fuel used to produce electricity from the total fuel consumption grows from 8 % to 23 %.

When comparing the fuel consumption between urban and austere areas, the increase in “sunny day” is 193 % and in “cloudy day” 116 %. The difference is smaller when the fuel consumption is already higher due to a lack of PV production. The need for fuel in urban areas grows 67 % if PV is not available. In an austere area, losing PV increases the fuel consumption by 23 %, so the difference is not as significant when the fuel consumption is already higher. In both cases, if the consumption is higher in the beginning, the proportional growth is smaller. PV production has a lower impact than the electricity network, which is assumed because the amount from PV production is smaller than the input from the electricity network.

Even though the results are assumable, they highlight the growing need for fuel supply when a unit loses access to infrastructure or loses its capability to produce from sustainable sources. The fuel supply is needed for the vehicles in any case, but the proportion of fuel necessary to produce electricity grows in austere areas. Harvesting electrical energy from renewable sources in austere areas can reduce the need of fuel supply.

2. Analysis of Field Generator Capacities

The LP model is next used to analyze the capacity of the field generators. As mentioned in subsection IV.A. there is existing overcapacity. The analysis focuses on three use cases:

1. The unit uses only HPGS, including two field generators
2. The unit uses only one conventional field generator
3. The unit uses both, and they have to be able to replace each other

The target is to achieve a usage percentage between 60% and 80% with typical field generator sizes. The analysis is done with two scenarios from subsection 4.C.1: “Sunny day in an urban area” and “Cloudy day in an austere area,” since they set the lower and upper bounds for the field generator capacities. The results are presented in Table 7 and visualized in Figures 10 and 11.

Table 7. Results for the analysis of field generator capacities

	Generator choice	Generators	Total capacity (kWh)	Excess (kWh)	Use percentage
Sunny day in an urban area	Conv +HPGS (basic scenario)	200 + 2*80	8640	8087.7	6%
	HPGS	2*80	3840	3257.4	15%
	HPGS	2*32	1536	953.4	38%
	HPGS	2*25	1200	617.4	49%
	HPGS	**2*16.5**	**792**	**209.4**	**74%**
	HPGS	2*12.5	600	17.4	97%
	Conv	50	1200	669.8	44%
	Conv	**32**	**768**	**237.8**	**69%**
	Conv	25	600	69.8	88%
	Conv + HPGS	**32 + 2*16.5**	**1560**	**1004.4**	**36%**
	Conv + HPGS (upper bound)	***100+2*60***	***5280***	***4722.5***	**11%**
Cloudy day in an austere area	Conv +HPGS (basic scenario)	200 + 2*80	8640	6653	23%
	HPGS	2*80	3840	1743.8	55%
	HPGS	**2*60**	**2880**	**738.8**	**74%**
	HPGS	2*50	2400	303.8	87%
	Conv	150	3600	1692.5	53%
	Conv	**100**	**2400**	**492.5**	**79%**
	Conv	80	1920	**12.5**	99%
	Conv + HPGS	**100 + 2*60**	**5280**	**3274**	**38%**

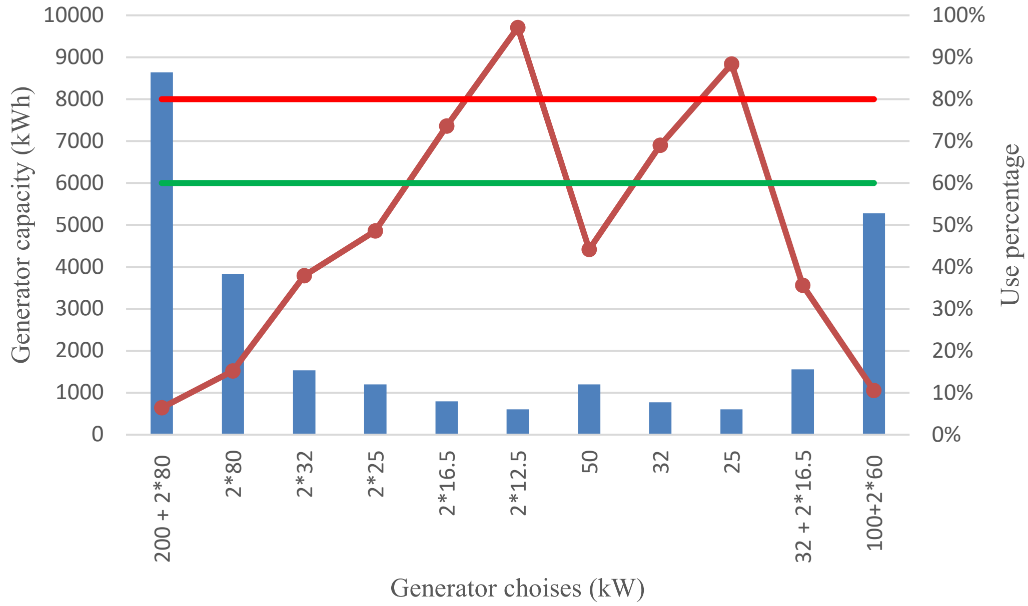

Figure 10. The generator choices in the "Sunny day in an urban area" scenario. The lower threshold (green) is 60 % and the upper (red) is 80 %.

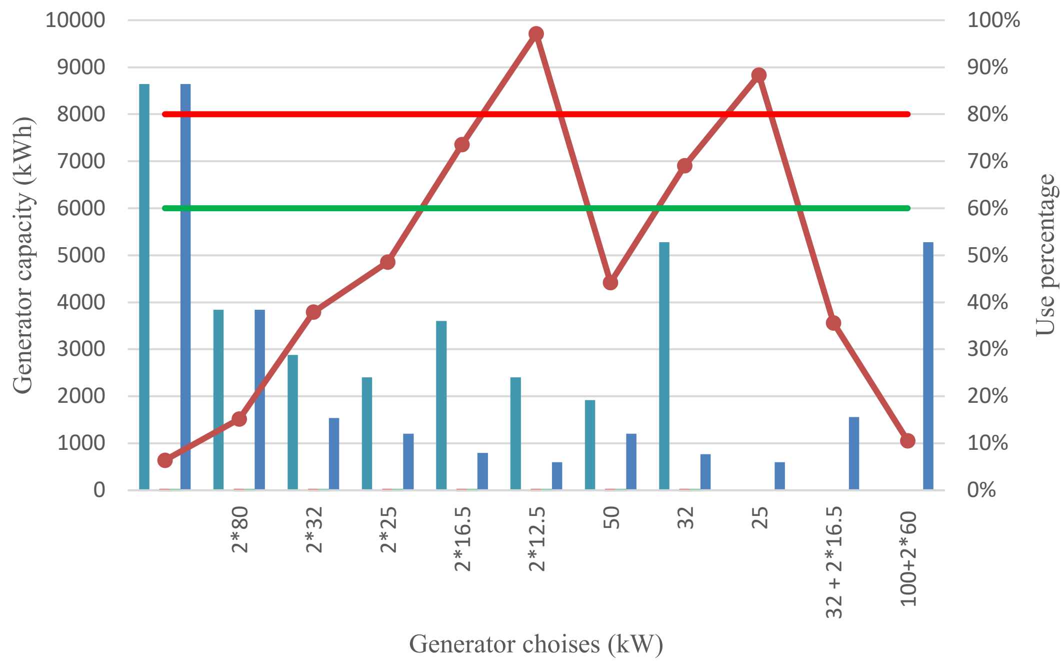

Figure 11. The generator choices in the "Cloudy day in an austere area" scenario. The lower threshold (green) is 60 % and the upper (red) is 80 %.

The best solutions for the use cases are bolded in the Table 7 and are placed between the green and red threshold lines in Figures 10 and 11. For the lower-bound use case, generator choice for HPGS would be 2x16.5 kW, which is significantly smaller than the original 2x80 kW. If using only one conventional field generator, the choice would be 32 kW instead of 200 kW. For a resilient solution where HPGS and a conventional field generator can replace each other, the choice would be a 32 kW conventional field generator and 2 x 16.5 kW generators for HPGS. From the original subset, the generator capacity decreases significantly. With the resilient choice, the use percentage is only 36 %. In the real world, the solution would be to use HPGS and a conventional field generator by turns to increase the use percentage. However, in this case, the unit has to have a connection to the electricity network and the capability to produce electricity using a PV system.

When the unit is placed in an austere environment and clouds fill the sky, the upper bound solution is needed. Now, the generator choice for HPGS would be 2x60 kW, which is smaller than the original 2x80 kW, but not significantly. If using only one conventional field generator, the choice would be 100 kW instead of 200 kW. For a resilient solution where HPGS and a conventional field generator can replace each other, the choice would be a 100 kW conventional field generator and 2 x 60 kW generators for HPGS. From the original subset, the conventional field generator capacity halves while the change for the HPGS generators is more minor. The self-sufficiency requires more capacity in the unit than it needs in an area where it can rely on existing infrastructure.

When the resilient solution for the upper bound use case is placed in the lower bound use case, the use percentage drops to 11 %. This highlights the difficulty of measuring field generators and also other energy production and distribution equipment to a unit whose position can vary in different environments and changing weather conditions. From a Finnish perspective, it is easier to measure energy equipment in a unit that will deploy to a permanent position, for example, to Iraq, than to measure a national unit that will be moving between urban and austere areas in Finland, with the weather varying seasonally.

3. Analysis of Changes in Supply from the Electricity Network and Electricity Demand

In previous case analyses, there has been an assumption that the electricity demand will remain constant. Also, in urban areas, larger capacity electricity outlets are often available, or there is more than one outlet available. The analysis focuses on two questions:

1. How much can the electricity demand increase before the original model becomes infeasible?
2. How many electricity outlets in what capacities are needed to fulfill the electricity demand? With or without the PV production.

For the first question, the demand for energy for the direct electricity systems is increased until Solver cannot find a feasible solution. It is clear from the previous analyses that since all capacities of PV production and the electricity network are already used in the basic scenario, the capacity of the generators will be the threshold. The excess of field generators and the fuel used to produce electricity are chosen to be the parameters to track during the analysis. The electricity demand is first multiplied until no feasible solution is found, and then the sampling rate is adjusted as the threshold is closing. The results are presented in Table 8.

Table 8. Results for the analysis of the increase in electricity demand. The unit's electricity demand cannot exceed 1437 kWh.

Electricity demand (kWh)	Generators Excess (kWh)	Fuel to electricity (l)
273 (basic)	8087.7	51.5
546	6191.9	228.3
1092	2400.2	581.8
1365	504.4	758.6
1638	no feasible solution	
1400	261.4	781.3
1430	53	800.7
1435	18.3	804
1437	4.4	805.3
1438	no feasible solution	

The electricity consumption for the unit can increase to 1437 kWh in a 24-hour period before the current subset of electricity supply reaches its limit. In percentage terms, the growth is 429 %. This result is a different view of the analysis in subsection 4.C.2, where generator capacities were analyzed. If there is overcapacity in generators, it is obvious that the electricity consumption may increase. This analysis highlights the potential for a significant increase in electricity consumption.

The second question seeks to find an answer to how the fuel consumption to produce electricity can be eliminated when the unit is placed in an urban area. In the basic scenario, the unit is connected to the electricity network with one 3-phase 16 A – 400 VAC outlet. In an urban area, it is reasonable to expect that several outlets are available, or larger capacities, such as 3-phase 32 A – 400 VAC outlets, are also available. The choice of outlet in relation to fuel consumption and outlet capacity excess is presented in Table 9.

Table 9. Results for the analysis of choices of outlets

Outlet	# of outlets	Capacity (kWh)	Fuel to electricity (l)	Outlet Excess (kWh)
3-phase 16 A – 400 VAC	1	153.6	51.5	0
3-phase 16 A – 400 VAC	2	307.2	0	74.1
3-phase 32 A – 400 VAC	1	307.2	0	74.1
3-phase 16 A – 400 VAC and 3-phase 32 A – 400 VAC	2	460.8	0	227.7

In the basic scenario, the outlet's capacity restricts the utilization of the electricity network, and generators are also needed to fulfill the electricity needs. By adding access to another 3-phase 16 A -400 VAC outlet, the fuel consumption is eliminated. The electricity consumption may still increase by 74.1 kWh before the generators need to be started. If there were both 16 A and 32 A outlets available, the electricity consumption of the unit could almost double before the need to start generators. From a logistics view, not only does the fuel consumption matter, but if the generators are not used, the maintenance can also be postponed, and the need for spare parts will decrease.

With these analyses, the model can easily highlight different views for the electricity supply and consumption for a unit. Even though the results are apparent, figuring them out without the LP model is not as straightforward.

D. LIMITATIONS OF THE LP MODEL

The leading idea for the LP model was to keep it simple. This approach, though, forced us to accept limitations for the model. In this subsection, limitations of the model are discussed in detail. Additionally, the usability of the Excel spreadsheet is not at a level that would make it a suitable tool for an inexperienced user.

The model does not capture the energy storage as an inventory node since there are no periods in the model. In the real world, since both the electricity consumption and production vary, the energy storage can be used to store energy in times of overproduction and release it when the consumption is higher. Often, in these kinds of situations, the generators run only the time required to fill the energy storage, and then they are shut down until the storage's lower threshold is reached. The model cannot capture this kind of usage because it is designed to capture only the total energy over 24 hours.

Peaks in consumption or production are not captured for the same reason when using a 24-hour period total energy. The model can be used to measure production, electricity network, and generator capacities; however, if the consumption includes demand or start-up peaks, these need to be addressed separately.

The generator efficiency is represented by one number from the ENSECCOE report. The generator efficiency, though, changes with different loads. To find an accurate efficiency for different scenarios, measurements are needed. The efficiencies of the battery charger and energy storage would also need to be measured using the equipment in a real unit.

The batteries were included in the LP model to find out if it is possible to include them also in the operational energy model, since they have a connection to fuel and electricity flows through battery chargers. From a logistical point of view, the number of batteries would be the important output needed for logistical planning, not the energy content. In this thesis, all batteries are assumed to be similar. It would be possible to count the energy content also from different batteries, but the input and output would not differ, so the LP model would not add any knowledge. An approach similar to the battery model in Atkinson's thesis would be more suitable to calculate battery needs separately, and the LP model could be simplified by adding battery chargers' electricity requirements to the direct electricity systems.

An LP model does not include uncertainty by default. The model requires fixed capacities that will deliver a single solution. While this is a tempting way to look at operational energy, one must keep in mind that the real world does not work with exact numbers and a single solution. The model is though applicable with different data. One can relatively easily fill in data from various scenarios to find lower and upper bounds.

Using the model in analysis requires changing parameters. While doing analyses in the previous subsections, the input cells and formulas were added on the run to ease the changing of parameters. If this model were further developed into a tool, a separate input spreadsheet would be essential. In that way, the user could change parameters in one place, and they would be delivered to the model without changing the parameter cells in the model. Additionally, a results spreadsheet could be created, but this would require envisioning what results are needed in the planning process.

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V. CONCLUSION

A. SUMMARY

This research underscores the necessity for a comprehensive approach to operational energy. At the tactical level, the unit uses several energy forms simultaneously. They can be supplied or produced. They can interact with each other or even replace each other partly. However, the energy demand will ultimately require different energy forms to enable the unit to accomplish its mission. Operational energy must encompass all the energy that flows through the unit.

The model developed in this thesis was created and utilized with data from a notional unit comprising various sources of information. The model is functional, and in this thesis, it uses notional data; however, the model can later be applied with actual data. To develop it into a useful, tactical tool would require more work on usability, based on the form from which the data will be gathered, specifically from actual material lists and needs derived from operational plans. However, the model is not a planning tool for electrical measurement and optimization, since it does not capture the ongoing changes in production and consumption. The model can provide a reasonably accurate representation of a unit's energy needs for logistical purposes and a relatively easy way to answer questions concerning logistical planning.

B. ADDRESSING THE RESEARCH QUESTIONS

This thesis was based on the following primary and secondary research questions:

1. Primary Research Question

> How should the definition of operational energy, "energy required for training, moving, and sustaining military forces and weapons platforms for military operations" (Howard et al., 2024), be interpreted at a unit level?

At the unit level, all energy forms have to be taken into account. In this thesis, fuel, electricity, and batteries were combined into a single model. There might also be other energy forms, like firewood, as in the Finnish system. The definition includes all energy forms, and policies concerning operational energy should also include them. The answer to the question of how much operational energy consumption is in a unit should include everything. However, it is reasonable to classify energy forms based on whether they are connected when building a model. If an energy form is not linked to any other energy form, it cannot be replaced with another or converted to another; it should be planned and modeled separately.

2. Secondary Research Questions

1. What alternative models of energy use in the military are available?

In the literature review, models of energy use in the military were identified, including the fuel and battery models in Atkinson's thesis and the electricity model in Law & Tyley's thesis. Nevertheless, none was found that would comprise fuel, electricity, and batteries. Additionally, numerous energy models were identified that laid the foundation and provided inspiration for the LP model developed in this thesis.

2. How can operational energy at the unit level be modeled with the concepts, terms, and visualizations used in operational logistics modeling?

The transshipment model is a network flow model that can be used in various types of flows. In logistics, it has been used for fuel flow or the shipment of goods. The difference is that, in this thesis, the arcs do not represent actual physical assets, such as roads or pipes, but only the capacity between the nodes. Overall, energy flow can be treated similarly to other logistic flows.

3. How should energy supply (source), energy conversions, and demand be categorized at the unit level?

The LP model is a transshipment model. The unit's energy network consists of supply nodes (fuel supply, the electricity network, production, and an unrechargeable battery supply), conversion nodes as transshipment nodes (field generators, energy storage, battery chargers, and combustion engine vehicles), and demand nodes (combustion engine vehicles, direct electricity systems, and battery operating systems). The idea of categorization in the unit is delivered with different kinds of nodes.

4. What conversions between energy forms are needed in a model, and what data is needed for conversions (for example, fuel to electricity, electricity to battery capacity)?

The transshipment nodes are the conversion nodes. All units' energy figures were converted to kWh using the conversion tools provided by AFDC, IEA, IEEE, and NIST. The information on efficiency was gathered from the ENSECCOE's HPGS report and other public sources. To verify the efficiency, more measurements would be required using the equipment currently in use.

C. RECOMMENDATIONS

While developing and creating this thesis, several viewpoints were found essential to modeling operational energy. They were solved on the way by relying on public sources; however, there is a need to acquire more accurate data from actual units and to measure energy consumption from both equipment and functions. Additionally, to create the model into an easy-access tool for logistical planners, the usability of the spreadsheet will need improvement.

Estimating demand is critical. It includes evaluating material lists, unit missions, and tasks. Using war games and military exercises to measure actual energy consumption is also essential. The data sheets of equipment do not provide all the information needed to analyze and optimize the energy network, even at the conceptual level.

Measuring the energy conversions in real-world situations, either in military exercises, if possible, without interfering too much with the exercise, or providing field experiences just for measuring purposes, with similar load and load variation as in an exercise, can provide real-world data. With these kinds of measurements, though, one should not fall into the fallacy of a single number representing the truth in all scenarios. The LP model can be used to find lower and upper bound solutions. The technical specifications and manuals will provide basic information, but with only them, the conversions cannot be delivered at all, or they will remain at only a theoretical level.

For logistical planning purposes, batteries would require a different model that calculates the number of batteries or reloads needed. An approach similar to the battery model in Atkinson's thesis is one example, but it also needs development. By removing batteries, the LP model can be simplified by incorporating the electricity requirements of battery chargers into the direct electricity systems. This would decrease the size of the network and reduce one constraint.

Using the model as a tool for logistical planning is not feasible at this stage. The tool would need a separate spreadsheet to allow the easy input of the data, and also another result spreadsheet to easily read the results. At the moment, the model is relatively easy to use for the writer, but it would need some explanations for someone else to use it.

D. CONCLUSION

Energy is an essential resource for a unit to complete its mission. Operational energy at the unit level includes several energy forms, all of which are essential. The energy forms that interact can be modeled with a transshipment model, keeping in mind that averaging energy consumption over 24 hours will lose the changes of the consumption or production curve and possible start spikes in equipment. Even the simplified model can still provide a perspective and visualization of the total energy flows and needs in a unit for logistics planning. This way, it can help to include operational energy as a whole in logistical planning.

APPENDIX A. R CODE

```
library(igraph)
```

```
##
## Attaching package: 'igraph'
```

```
## The following objects are masked from 'package:stats':
##
##     decompose, spectrum
```

```
## The following object is masked from 'package:base':
##
##     union
```

```
library(visNetwork)
library(magrittr)
library(dplyr)
```

```
##
## Attaching package: 'dplyr'
```

```
## The following objects are masked from 'package:igraph':
##
##     as_data_frame, groups, union
```

```
## The following objects are masked from 'package:stats':
##
##     filter, lag
```

```
## The following objects are masked from 'package:base':
##
##     intersect, setdiff, setequal, union
```

```
library(ggplot2)
theme_set(theme_minimal())
set.seed(2255)
library(htmlwidgets)
```

Get data for this graph:

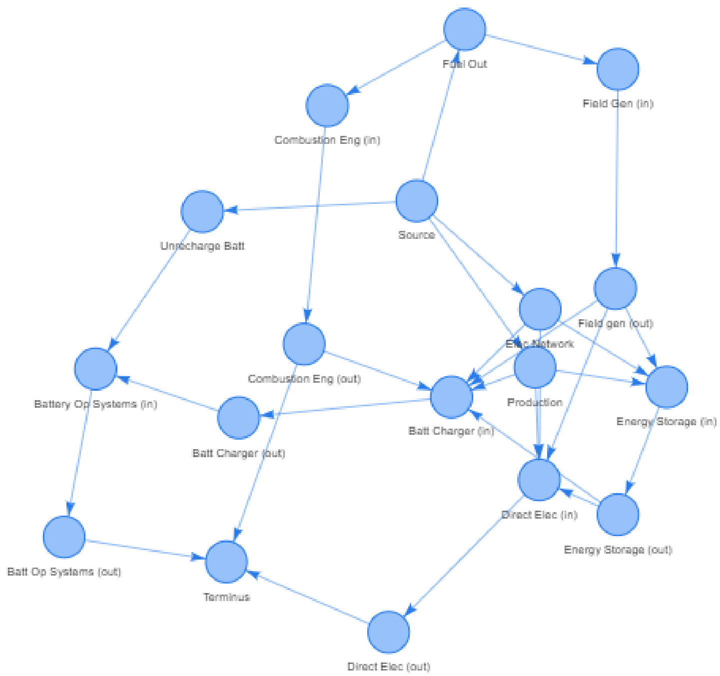
```
Edges = read.csv("EdgeWeights_1.csv", header = FALSE)
```

Prepare the data:

```
Edges = Edges[,1:3] #drop extreneous columns
names(Edges) = c("from", "to", "capacity") #igraph is VERY picky about this!
g = graph_from_data_frame(Edges, directed = TRUE)
#V(g)$name = Nodes$Name #Put the names in the graph
```

Plot the data:

```
visIgraph(g)
```



Draw the network to .html:

```
vis <- visIgraph(g)
saveWidget(vis, "graph.html")
```

APPENDIX B. DISPLAY OF THE LP MODEL SPREADSHEET

Operational energy flow model

Network formulation

Arc	Origin	Destination	"Switch"	Capacity (kWh)	Capacity RHS	Flow (kWh)	Excess
1,11	Fuel Out	Combustion Eng (in)	1	6574	6574	6574.0	0.0
1,5	Fuel Out	Field Gen (in)	1	8640	8640	552.3	8087.7
2,12	Elec Network	Direct Elec (in)	1	153.6	153.6	153.6	0.0
2,7	Elec Network	Energy Storage (in)	1	153.6	153.6	0.0	153.6
2,9	Elec Network	Batt Charger (in)	1	39	39	0.0	39.0
3,7	Production	Energy Storage (in)	1	53	53	0.0	53.0
3,12	Production	Direct Elec (in)	1	53	53	53.0	0.0
3.9	Production	Batt Charger (in)	1	39	39	0.0	39.0
4,13	Unrecharge Batt	Battery Op Systems (in)	1	3.6	3.6	3.6	0.0
11,14	Combustion Eng (in)	Combustion Eng (out)	1	6574	6574	6574.0	0.0
14,9	Combustion Eng (out)	Batt Charger (in)	1	39	39	0.0	39.0
5,6	Field Gen (in)	Field gen (out)	1	1296	1296	82.8	1213.2
6,12	Field gen (out)	Direct Elec (in)	1	273	273	32.9	240.1
6,9	Field gen (out)	Batt Charger (in)	1	39	39	13.1	25.9
6,7	Field gen (out)	Energy Storage (in)	1	576	576	36.8	539.2
7,8	Energy Storage (in)	Energy Storage (out)	1	524.2	524.2	33.5	490.7
8,12	Energy Storage (out)	Direct Elec (in)	1	273	273	33.5	239.5
8,9	Energy Storage (out)	Batt Charger (in)	1	39	39	0.0	39.0
9,10	Batt Charger (in)	Batt Charger (out)	1	31.2	31.2	10.5	20.7
10,13	Batt Charger (out)	Battery Op Systems (in)	1	10.5	10.5	10.5	0.0
13,16	Battery Op Systems (in)	Batt Op Systems (out)	1	14.1	14.1	14.1	0.0
12,15	Direct Elec (in)	Direct Elec (out)	1	273	273	273.0	0.0
5,17	Field Gen (in)	Generator Loss	1	8640	8640	469.4	8170.6
7,18	Energy Storage (in)	Energy Storage Loss	1	2400	2400	3.3	2396.7
9,19	Batt Charger (in)	Batt Charger Loss	1	39	39	2.6	36.4

Flow balance constraints

Node	Location	Node capacity	Flow in	Supply	Total LHS	Flow out	Demand	Total RHS		
1	Fuel Out	800000	0.0	800000	800000.0	7126.3		7126.3		
2	Elec Network	153.6	0.0	153.6	153.6	153.6		153.6		
3	Production	53	0.0	53	53.0	53.0		53.0		
4	Unrecharge Batt	800000	0.0	800000	800000.0	3.6		3.6		
5	Field Gen (in)	8640	552.3		552.3	552.3		552.3		
6	Field gen (out)	1296	82.8		82.8	82.8		82.8		
7	Energy Storage (in)	2400	36.8		36.8	36.8		36.8		
8	Energy Storage (out)	524.16	33.5		33.5	33.5		33.5		
9	Batt Charger (in)	39	13.1		13.1	13.1		13.1		
10	Batt Charger (out)	31.2	10.5		10.5	10.5		10.5		
11	Combustion Eng (in)	6574	6574.0		6574.0	6574.0		6574.0		
12	Direct Elec (in)	273	273.0		273.0	273.0		273.0		
13	Battery Op Systems (in)	14.1	14.1		14.1	14.1		14.1		
14	Combustion Eng (out)	6574	6574.0		6574.0	0.0	6574.0	6574.0	613.0	liters
15	Batt Op Systems (out)	14.1	14.1		14.1	0.0	14.1	14.1		
16	Direct Elec (out)	273	273.0		273.0	0.0	273.0	273.0		
17	Generator Loss	8640	469.4		469.4	0.0	469.4	469.4		
18	Energy Storage Loss	2400	3.3		3.3	0.0	3.3	3.3		
19	Batt Charger Loss	39	2.6		2.6	0.0	2.6	2.6		

Objective				**Efficiencies**			
"min fuel to electricity"	552.3	51.5	liters	Field gen	0.15		
				Energy storage	0.91		
Constraints for Solver				Battery charger	0.8		
Production (Solar)	E35=I35			**Loss constraints**			
Unrecarge Batt	I36=F13			Generator Loss	469.4	Demand for loss (1-H55/H55)*G16	
Energy Storage	G19=G65*G16			Energy Storage Loss	3.3	Demand for loss (1-H56/H56)*G20	
Capacity	G5:G29 <= F5:F29			Batt Charger Loss	2.6	Demand for loss ((1-H57)/H57)*G23	
flow conservation supply	E33:36 >= I33:I36	unbalanced network					
flow conservation	E37:E45 = I37:I45			**Generator combinations**	Cap total	Cap one gen	
flow conversation demand	I46:I51 = E46:E51			HPGS	3840	80	
				Conventional	4800	200	
				Ratio	0.444444444		
				To energy storage	576		
					LHS	RHS	
				Energy Storage constraint	36.8	36.8	

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SUPPLEMENTAL: SPREADSHEET OF THE OPERATIONAL ENERGY LP MODEL

The spreadsheet includes the LP model created in this thesis. The input data is the notional unit's data, and the solution is for the basic scenario. The Microsoft Excel standard Solver has the model objective function, variables, and constraints. The constraints are also explained on the spreadsheet. The LP model is color-coded as explained in Chapter III.D.2.

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