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INVESTIGATING LIFECYCLE COSTS OF OPTIMIZED BATTERY-PHOTOVOLTAIC SYSTEMS ON A FORWARD OPERATING BASE

THESIS

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Abstract

The purpose of this research was to investigate the total life-cycle cost of using utility-scale battery systems to increase the energy efficiency of forward operating bases, thereby reducing the burden of diesel fuel logistics. Specifically, this thesis answered three research questions addressing optimal sizing for various battery types connected with photovoltaic grids, logistical parameters directly impacting total cost, and the cost of increasing the energy resilience of the network. The research questions were answered through a review of literature, modeling, and data analysis. The model determines an optimal size and area for a Vanadium redox flow, Lithium-ion, or Lead-acid battery system, combined with a photovoltaic array, over 5, 10, and 20 years. The optimal Lead-acid battery system was the least expensive, with a 20-year lifecycle system of 142.1 MWh battery and 30.9-acre photovoltaic array costing $13.1M per year. However, after including transportation costs, operations and maintenance, and salvage values, Lithium-ion and Vanadium flow appear to be more cost effective. With a 20-year life-cycle, Lithium-ion and Vanadium redox flow batteries were the most cost-effective option, for the theoretically modeled Alpha forward operating base, with an equivalent annual cost of $24.1M per year and $24.8M per year, respectively. When excluding salvage value from the total cost, both systems cost $25.2M per year and $25.7M per year, respectively. Lead-acid costs for 20 years were $28.4M per year. A breakdown of all costs associated with the final value of each battery system is included in the results. Recommendations on implementation of a battery-photovoltaic system on a forward operating base are discussed. Shortfalls of each technology are also discussed.

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INVESTIGATING LIFECYCLE COSTS OF OPTIMIZED BATTERY-PHOTOVOLTAIC SYSTEMS ON A FORWARD OPERATING BASE

I. Introduction

The United States Department of Defense is investigating alternative power generation as a way to increase energy resilience and reduce defense spending. Several promising technologies are photovoltaics supplemented with utility-scale battery systems. The savings these technologies can realize continues to improve. Flow batteries have been gaining attention recently because of their promising properties: Flow batteries have theoretical life-cycles greater than 20 years, they are not susceptible to thermal runaway thereby reducing the risk of starting a fire, and batteries operating in a reversible aqueous state can repeatedly discharge fully without loss to overall battery life. If flow batteries can be made with off-the-shelf components, they could be extremely cost effective at the utility-scale. Lithium-ion batteries are the most prevalent batteries on the market because of their low cost and dense energy storage. Lead-acid batteries have been utilized in the past for utility-scale application. A renewed interest in increasing its energy density may make this type of battery economical again.

Background

In 2011, the Congress of the United States mandated the downsizing of spending for future budgets [1]. It set a $109 billion reduction in budget per year for nine Fiscal Years (FY) beginning in 2013 [2]. Half of this required reduction was from the Department of Defense (DoD), Department of Energy, and other national security activities [2]. Although the full FY sequestration amount was never fulfilled, the United

States Air Force still implemented the policy to reduce the budget. Due to mission requirements though, certain expenses cannot be reduced; therefore, the United States Air Force requested that its smaller components provide ideas on how to reduce the budget.

The United States Air Force (USAF) is investigating the DoD Operations and Maintenance (O&M) category of the budget for possible reductions. This category accounts for roughly 2-6 percent of the fiscal budget [1]. Within this expense, active duty Air Force operational energy accounts for roughly $4 to 4.5 billion a year, depending on utility prices and fuel consumption [3]–[5]. Table 1 shows the breakdown of fuel and utility consumption in the United States Air Force O&M budget from FY17 to 19. In the Table, the acronyms are defined as: FY, standard form (SF), Defense Working Capital Fund (DWCF), Overseas Contingency Operations (OCO), Defense Logistics Agency (DLA), and fuel cost (FC).

Forward operating bases (FOBs) are typically powered by diesel generators or host nation power. They are usually funded with Overseas Contingency Operations (OCO) money. The OCO breakdown shows that DLA energy—which is mostly jet fuel and some support fuels—is the largest category each year. It also shows that the USAF rarely procures fuels locally. The breakdown does not specify the fuel costs for generators; however, if only 4% of DLA energy goes to fueling the generators, then it could cost between $40M and $100M per year. This cost could double when including the logistics of transporting the fuel, considering $151M was spent on logistics operations in 2018 [5]. This means that over five years, the DoD could be spending nearly $1B on fuel. This fuel would only account for one-tenth of one percent of the total budget [3], but USAF leadership intends to reduce the overall budget by implementing business management tools to reduce many smaller expenses [6].

Table 1. United States Active Duty Air Force Operations and Maintenance Expenses for Fuel and Utilities 2017- 2019 [3]–[5]

In (1000) thousand dollars	FY 2017 Program	FC Rate Dif	Price Growth Percent	Price Growth	Program Growth	FY 2018 Program	FC Rate Dif	Price Growth Percent	Price Growth	Program Growth	FY 2019 Program
DWCF SUPPLIES AND MATERIALS											
DLA ENERGY (FUEL PRODUCTS)	2,634,695	35	11.53%	303,784.00	-866,254	2,072,260	3	-0.40%	-8,289	15,631	2,079,605
OTHER PURCHASES											
LOCALLY PURCHASED FUEL (NON-SF)	3,546	0	11.53%	409.00	8,740	12,695	0	-0.40%	-51	49	12,693
PURCHASED UTILITIES (NON-DWCF)	831,818	5,084	1.70%	14,227.00	-68,163	782,966	5,471	1.80%	14,192	33,299	835,928
DWCF SUPPLIES AND MATERIALS OCO											
DLA ENERGY (FUEL PRODUCTS) OCO	1,007,606	0	11.53%	116,178	106,833	1,230,617	0	-0.40%	-4,922	-19,544	1,206,151
OTHER PURCHASES OCO											
LOCALLY PURCHASED FUEL (NON-SF) OCO	0	0	11.53%	0.00	1	1	0	-0.40%	0	-1	0
PURCHASED UTILITIES (NON-DWCF) OCO	82,895	0	1.70%	1,410	3,749	88,054	0	1.80%	1,585	-2,620	87,019
TOTAL	$4,560,560,000					$4,186,593,000					$4,221,396,000

In response to how the fiscal climate is changing, asset management is now a focus of Air Force Civil Engineers [6]. The civil engineering career field no longer looks at the cheapest short-term cost but at all options and expenses over the 5, 10, or 20-year life of the system [6]. For these reasons, this thesis explores one of the innovative ideas to reduce the life-cycle energy costs of FOBs. One way to potentially reduce energy expenses on FOBs is to replace the diesel generator network with a photovoltaic array and a utility-scale battery system.

The USAF is not the primary maintainer of FOBs: The United States Army and Marine Corps operate many smaller-scale contingency and enduring bases. The rationale for the USAF utilizing solar-battery systems is two-fold. First, contingency bases—bases operationally expected to last 30 days to 24 months—may not have a long enough timeline for large photovoltaic-battery systems to be economically attractive. This makes enduring bases—bases expected to be operational for five or more years—the main focus. Second, if the optimal photovoltaic array is tens of acres in size, then USAF FOBs are better candidates because they typically require a runway, which naturally provides a large perimeter.

In this work, three battery technologies are investigated that are capable of supporting utility-scale storage. They are Vanadium redox flow batteries (VRFB), Lithium-ion (Li-Ion), and Lead-acid batteries. VRFB is a newer technology that utilizes the inherent properties of Vanadium's multiple valence states to store and release charges [7]. Li-Ion batteries are a proven technology that works on a large scale [8]. These are currently assumed to be the most cost-effective battery option on the market. Lead-acid batteries are a reliable technology that is less energy dense than Li-Ion but provide a mostly established solution for end-of-life disposal. By installing batteries into the existing infrastructure, they can charge during non-peak hours, then discharge during the system’s peak demand hours and at night. Installing photovoltaics to charge the batteries during the day may further reduce the overall energy cost and create redundancy to increase the base resilience over complete power loss. New photovoltaics have increased efficiency to convert sunlight to useable power and their price is continuously dropping. Resilience refers to the ability of a base to recover from an attack or catastrophic collapse of critical infrastructure.

Problem Statement

The purpose of this research is to model different utility-scale battery systems and determine the optimal economic viability of each on a theoretical forward operating base. Utility-scale refers to holistic infrastructure systems that range from a large data storing facility to the power grid of a city. Diesel generators will be integrated into the model to supplement the network if the batteries have zero charge and if the photovoltaic network is unable to provide the required load.

VRFB has a theoretical ability to not degrade over its expected 20-year lifecycle, thereby reducing maintenance, repair, and replacement expenses. Li-Ion batteries are currently the best market option for small and large battery energy storage devices. Lead-acid batteries show potential on a utility-scale because of recent advancements in the technology. Lead-acid was also the utility-scale choice before Li-Ion batteries. Diesel fuel was selected as the baseline to determine the cost of current applications. A photovoltaic network may provide additional economic savings when added to supplement the storage system.

Research Questions

This research focuses on three primary questions:

1. What are the optimal size and total cost for the various battery systems given their different parameters? For each option, the intent is to find the size and scale of the optimal battery and photovoltaic system.

2. How does including logistics parameters impact the total cost of the model? These options will investigate how the logistics parameters change the cost of the different battery systems, diesel generators, and diesel fuel. Investigations into whether powdered electrolytes are a more cost-effective solution than typical electrolytes within flow batteries will also be made.

3. What is the cost increase for each battery system when increasing the level of resilience on the system? This will investigate how adding resilience to battery networks impacts the overall cost of the system.

Methodology

The purpose of this research is to model different utility-scale photovoltaic-battery systems and determine the economic viability of each on an FOB over the life-cycle of that asset. Figure 1 shows the underlying architecture of the utility system. Photovoltaic panels will be able to power the grid directly or store the excess energy into a supplemental battery energy storage system.

The two primary components modeled are the total cost for the optimal size, and the logistics. First, the parameters found in the literature review will be integrated into MATLAB simulations to model the optimal size of a battery and photovoltaic network.

This will output the total cost and size for each component. Second, a logistics analysis will be conducted with tangible and intangible parameters to show the full scope of the expenses. A fictitious model is then built to show transportation costs of the assets from the United States to an 1100-person FOB via airlift, sealift, and ground transport. The fictitious FOB will be referred to as Alpha FOB throughout the remainder of the document. This model factors in location-specific details that are discussed further in Chapter III.

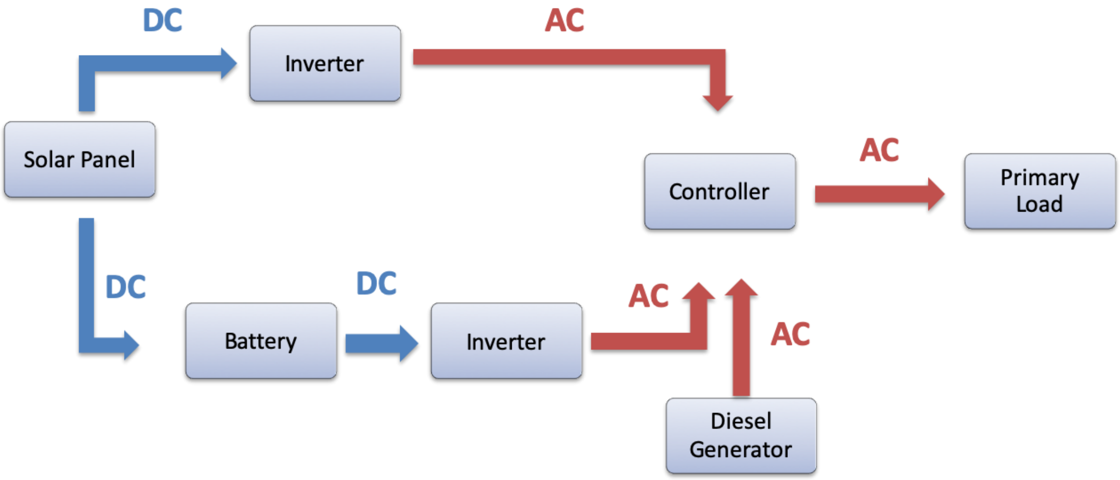

Figure 1. Architecture for Utility-Scale Photovoltaic-Battery Network

Need for Research

As more of our systems become dependent upon electricity, long-term energy storage solutions can prove invaluable to the USAF’s resilience. Investigations into utility-scale batteries may provide a practical solution to reduce the USAF’s reliance on external sources for energy, such as host nation commercial power, expensive refueling convoys, or overburdened commercial grids. This research considers a life-cycle analysis—cost factors, maintenance complexity, location, implementation scale, transportation costs, etc.—and seeks to determine how different energy storage systems, supplemented with photovoltaic technologies, might reduce overall FOB energy expenses.

Assumptions and Limitations

The model assumes that the forward operating base will have a minimum life of five years as part of ongoing operations. The minimum time is required for any battery system to be economically feasible. Anything less than five years was deemed impractical. The assumption here is that the current United States stance for enduring FOBs trends towards 5, 10, or 20-year operation.

The current Fully Burdened Cost of Fuel (FBCF) is fixed throughout the duration of the model. The model also includes diesel generators to be used as a back-up, should the batteries fully discharge and there is insufficient output from the photovoltaic panels. There will always be a minimal cost on the system of $240k per generator, as well as fuel costs to operate them. This cost is derived from a 1250 kW generator.

The theoretical Alpha FOB is capable of accepting airlifted assets as well as ground transported assets.

The energy density is not dependent upon the overall quality and cost of the battery. Therefore, averages of volumetric and gravimetric energy densities will be used for the batteries when calculating the optimal size. The specific power of the photovoltaic array for the logistics model is averaged.

The logistics model assumes that the means of transportation to the Alpha FOB will be by military vehicle except for sealift. Sealift is estimated by commercial costs. The total system cost cannot account for all possible expenditures. Things such as the reduced cost of maintenance, replacement of transformers, replacements of power lines, etc. are not accounted for within the model.

Scope

This project focuses on utility-scale systems utilizing VRFB, Li-Ion, and Lead-acid batteries for a deployed location and include these parameters:

- Logistics and transportation of materials
- Initial purchase price
- Cost of energy storage
- Operations and Maintenance (O&M)
- The Fully Burdened Cost of Fuel (FBCF)
- Expected life of the assets
- Power output
- Number of cycles before replacement/failure
- System Considerations:
    - Hazardous cleanup requirements
    - Other environmental factors

Although the entire USAF energy O&M budget was discussed, this model only accounts for a single FOB. The idea is to see if the model is economically feasible. Future research might be able to upscale this to multiple bases, or the entire USAF, to determine if the higher upfront costs provide significant cost savings at 5, 10, or 20 years for a battery-photovoltaic network.

Materials and Equipment

The model is constructed in the computer program MATLAB 2018b. The datasets provided include one year of estimated time series data for hourly FOB load requirements and hourly solar irradiance. The literature review provides the other input parameters.

Research Schedule and Support

Both AFRL and AFCEC/CN support utility-scale energy storage solutions. They are specifically seeking battery systems that can outperform Li-Ion batteries and do so with a lower life-cycle cost.

Chapter Breakdown

Chapter II discusses the review of literature including additional background information on the dataset, a discussion of the parameters found, and the logistics challenges of transporting a large system. Chapter III then discusses the methodology behind the model creation. Chapter IV analyzes and discusses the results of the model. Finally, Chapter V presents what the results could mean and provides recommendations for future research.

II. Literature Review

Introduction

Fiscal Year (FY) 2017 saw defense spending increase for the first time in a decade. The United States Air Force's (USAF) FY 2018 budget increased by 6.2% to $156.3B [9]. Yet, beyond sequestration, it is still the Department of Defense's policy "to enhance military capability, improve energy security and resilience, and mitigate costs in its use and management of energy" [10]. The USAF is committed to investigating ways to minimize expenditures on infrastructure with sound economic decisions about managing assets, which includes building resilient energy sources [6].

The purpose of this research is to construct a model that compares different utility-scale battery systems and determines the optimal economic life-cycle cost of each on a theoretical FOB. The literature review begins by discussing key terminology used throughout the paper and then investigates the dataset. The dataset for this model consists of an FOB energy requirement and solar irradiance profile.

The first goal of this literature review is to gather and discuss parameters on Vanadium redox flow (VRFB), Lithium-ion (Li-Ion), and Lead-acid batteries. Second, it discusses diesel generator parameters as this asset is the current system used to supplement power grids on installations. Third, it introduces parameters on photovoltaics. Fourth, it reviews logistics parameters and transportation to FOBs. Fifth, it investigates the potential benefits powdered electrolytes may have over standard electrolytes in flow batteries. Finally, it compares the parameters to each other, discusses shortfalls in the research, and briefly talks about how these parameters are used in the methodology.

Key Terminology

The *Fully Burdened Cost of Fuel (FBCF)* refers to the total cost absorbed by transporting an asset from one area to another and supporting that item during its day-to-day operations [11]. As a forward operating base is located in a remote area, using fuel to transport generators, fuel, batteries, and solar panels to the location is unavoidable.

Life-cycle cost analysis is a holistic approach of engineering economics that looks at the total monetary expenditure on an asset over its assumed life. Costs include initial purchase, installation, Operations and Maintenance (O&M), repair, replacement parts, salvage value, and final removal over the assets' assumed life. The Air Force began moving to this way of thinking because of the requirement to reduce overall expenditures per year. Without a proper economic analysis, the lowest purchase price may cost the government more money because O&M is the largest cost over most assets' lifespans [6].

Peak consumption is the maximum loading an asset requires during a 24-hr period. For businesses, this typically occurs at some point during the weekday working hours (9 am to 5 pm). This level often sets the electricity rate for the location and lowering it can result in large cost savings.

A *Supplemental Battery Energy Storage System* is an idea that a battery can charge during non-peak consumption hours and then discharge during peak consumption hours. This reduces the maximum loading required and balances the hour-to-hour power consumption each day. This can significantly shift costs and extend service life for other assets on the system. This potentially reduces the cost rate of the power and creates redundancy for critical assets, which may only be marginally affected by commercial grid loss.

Utility-Scale refers to large infrastructure networks, such as the total power grid of a city—including the power plant, power lines, substations, generators, solar panels, wind turbines, utility poles, transformers, and building connections.

Physical Properties

To understand the model, the characteristics and costs associated with the assets needs to be explored. The following sections discuss physical properties, associated costs, and practical considerations of each battery type, photovoltaic array, and logistics chain. The batteries discussed here have similar characteristics. The difference between them is that some of the parameters stem from data and others assume theoretical numbers from research. Theoretical data will be identified as such. The costs can vary significantly between these systems and the ability to increase the total size of the battery or battery network is completely dependent upon its physical structure. These properties are discussed in depth.

The physical properties describe the capabilities of the battery system. The energy density states how compact energy storage is within the system. A low energy density requires a larger volume for the same amount of power to that of a high energy density system [7]. This density and volume are crucial in determining the weight of a particular battery size. The weight per kilowatt-hour is most important for transportation; ships, airplanes, and ground vehicles burn fuel at a rate that is based on the weight of the cargo [12]. The power output is the size of the battery that can support a load from one kilowatt to several megawatts [13]. Power output does not include how long the battery lasts. For this, the discharge duration describes the amount of time the battery is rated to be used [13]. It is typically measured in hours. A network of batteries theoretically could last longer if they have a phased discharge, where one battery would not run until another was fully discharged. However, not all batteries can fully discharge. The real world has inefficiencies. These inefficiencies are accounted for in the depth of discharge, which considers how much of the real-world battery discharges before it requires recharging [13]. Sometimes this is a manufacturer requirement. Other times, it is a best practice to keep the battery working efficiently for many years. But the working life of a battery is usually defined by cycles. Cycle count considers how many times the asset can technically discharge before requiring significant maintenance, fluid replenishment, or replacement [13], [14].

The operational temperature range investigates what the actual or theoretical usage could be at more remote locations. Currently, desert climates are a primary area for FOBs, with temperatures remaining above 105°F for prolonged periods. Humidity in this climate can range from 2% to over 90% [15]. The charging temperature range is the range of acceptable temperatures that allow the battery to recharge. The range for efficient charging is also smaller than the operational range [14].

Costs Parameters

The USAF quantifies life-cycle costs by O&M, systems considerations, ease of replacement and repair, asset management, and physical costs. The following section describes parameters that can do this, focusing on batteries. For this research, costs are converted to Equivalent Annual Cost (EAC) values to reflect the time value of money [16]. EAC is one method that decision-makers can use because it allows them to compare costs between projects without having to worry about different asset lifespans. EAC encompasses purchase price, annual incurred costs, scheduled major repairs, and salvage value. Salvage value may or may not be a factor as some assets have zero salvage value at the end of their lives [16]. For batteries, this depends if recycling is possible for raw materials or reuse [13]. If it is considered hazardous waste, this could be another cost to add to the EAC.

The Fully Burdened Cost of Fuel (FBCF) depends on the weight of the battery system that needs to be transported to the site [11]. For austere locations, flying or force protected convoys are the only way to move assets. For diesel generators, it is suggested that the FBCF of a \$2.50 gallon of fuel starts at \$15 [12]. The cost for energy storage (\$/kWh) can be extracted from the FBCF and typically ranges from \$1.90 – \$2.70/kWh [12], [17]. Storing and releasing energy costs money. Ideally, this should be cheaper than commercially available power, but it will vary from location to location.

Maintenance is the day-to-day costs associated with keeping the battery or diesel generator efficient and operational. This prolongs the amount of time until repairs are necessary. Repair parts and availability of parts are about cost-effective solutions. Highly technical and complex parts may be more efficient, but off-the-shelf parts can be easily replaced and at a fraction of the cost [13].

Practical Considerations

Other considerations must be accounted for when considering the full impact of a utility-scale battery network. Economy-of-scale refers to how well something can be upsized with a positive effect on cost [18]; a ratio of less than 1:1 is ideal when considering money, materials, and maintenance.

Another consideration to examine is how long each system and its components last. Since we are investigating EAC, Internal Rate of Return (IRR) must be ranked highest to lowest to account for multiples of each asset with shorter lifespans to meet an assumed life-cycle of 20 years [16]. An interest rate of 5% is assigned as the expected inflation rate. Batteries added to the network may extend the lives of the physical wires, transformers, and substations, but the degree to which this life is extended is a contested topic [19].

Vanadium redox flow batteries (VRFB) Parameters

The Vanadium redox flow battery (VRFB) is a newer technology that utilizes the inherent properties of Vanadium's multiple valence states to store and release charges [20]. The battery was first developed in the 1980s for NASA but has since gained some attention for utility-scale application. Figure 2 shows the basic layout of a VRFB system. The system is comprised of an anolyte and catholyte tank that exchange ions through a membrane [21]. By reversing the flow of aqueous vanadium, the system will charge or discharge by changing which side receives the electron [7]. A benefit to the design is that the power output and storage units are separate. Theoretically, this allows VRFB to upscale very well at the utility level while still supporting a 100% depth of discharge (DoD) without degradation in life [22], [23]. Physical properties, cost parameters, and other considerations found in research seem to conclude that these batteries can be as inexpensive as Li-ion batteries but have a lower energy density [22], [24]. Figure 3 shows several low-end and high-end VRFB parameters.

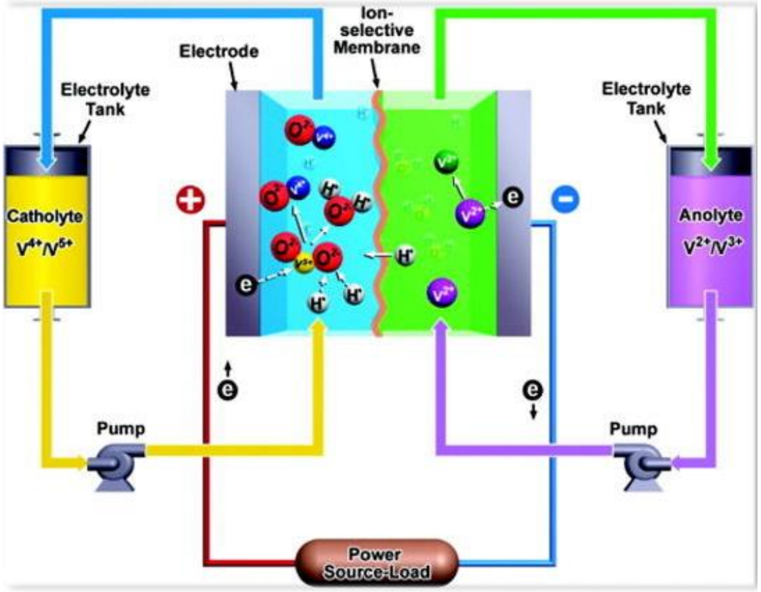

Figure 2. VRFB Diagram [21]

An interesting characteristic in VRFB is that as operating temperature increases, there is a slight increase in the observed power density and voltage efficiency; however, an increase beyond 55°C significantly reduces battery life [25], [26]. This may be why some VRFB systems have expected life-cycles of only 5 years [24]—far from the 20-year theoretical life-cycle [22]. Still, with proper system management, 10 to 15 years appears well within the expected life of VRFB [21].

End-of-life costs are another consideration for the overall economic feasibility. There is not much data on the recyclability of VRFB. Some suggest that 100% of the vanadium is reusable after system decommissioning [22]. If this is the case, the salvage value of VRFB is roughly the market price of vanadium. The market price spiked in 2018 at $60.64/kg but currently sits around $11.57/kg [27], [28]. The yearly output of Vanadium pentoxide (V_2O_5) is expected to decline in the future [27]. With the fact that a one MWh battery requires approximately 10 metric tons of V_2O_5 [27], the ability of the market to inexpensively produce large quantities of VRFB may not occur.

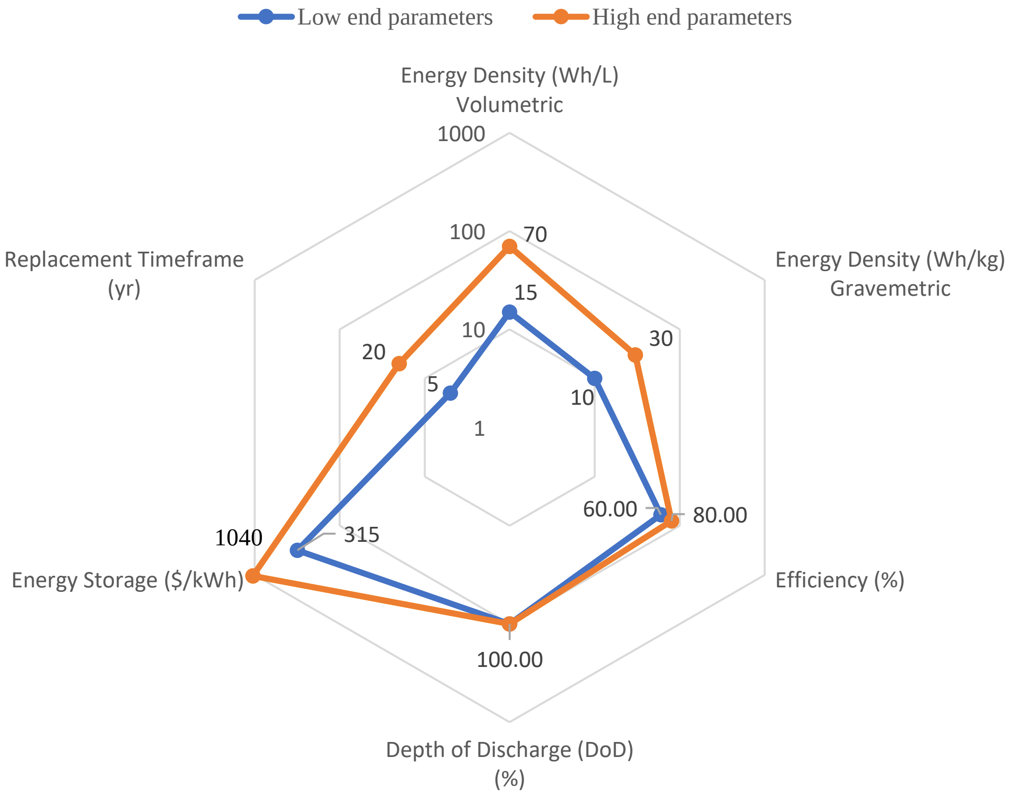

Figure 3: VRFB Parameters Spider Chart (see table 4 and 5)

A compilation of over 150 projects in 2016 concluded that VRFB cost could range from $315/kWh to $1050/kWh [24]. Other models appear to be within this range [19], [22]. The results of the literature search are summarized in Tables 2, 4, and 5 in the Parameter Tables section (pages 26 and 31) of Chapter II.

Lithium-ion Battery (Li-Ion) Parameters

Lithium-ion (Li-Ion) batteries are a known and proven technology that work on a utility-scale [29]. There are many different chemistries for Li-Ion anodes and cathodes. Some work better for small applications, such as a cellphone battery. For utility-scale, a Nickel Manganese Cobalt (NMC) cathode and Graphite anode is the preferred choice because of its low $/kWh, good stability, and higher safety [30]. Physical properties, cost parameters, and other considerations suggest that these are currently the most cost-effective utility-scale battery option on the market.

The energy density of Li-Ion is very high compared to other utility-scale batteries, which makes it much cheaper to transport large quantities [8], [26]. Additionally, Li-Ion NMC provides an 80%-95% DoD with a round-trip efficiency higher than 90%; however, the total expected life is shortened from continuously discharging the battery at the upper DoD limit [8], [23], [24].

End-of-life costs are another consideration for the overall economic feasibility. Li-Ion batteries are one of the most prevalent rechargeable batteries on the market, and there are two ways to dispose of the battery. The first way that is gaining attention is second life use. This is where batteries at end-of-life are broken down into smaller components and assessed for potential usage in another less demanding application [31]. The primary market for this has been electric car batteries that reached end-of-life—the batteries are assessed and reused as backup power or for peak shaving on grids [31].

The second way is recycling the battery. The sophistication of the recycling depends on location and cost with applications ranging from extracting the aluminum and copper to pulling out lithium carbonate, cobalt sulphate, and nickel sulphate [31]. It is mainly the cobalt that currently makes Li-Ion batteries attractive to recycle—with the raw materials salvaged for about $43/kWh [31]. Of course, this is all dependent upon market prices of raw materials at any given time, as well as the complexity of the battery components [32]. Figure 4 shows several low-end and high-end Li-Ion parameters.

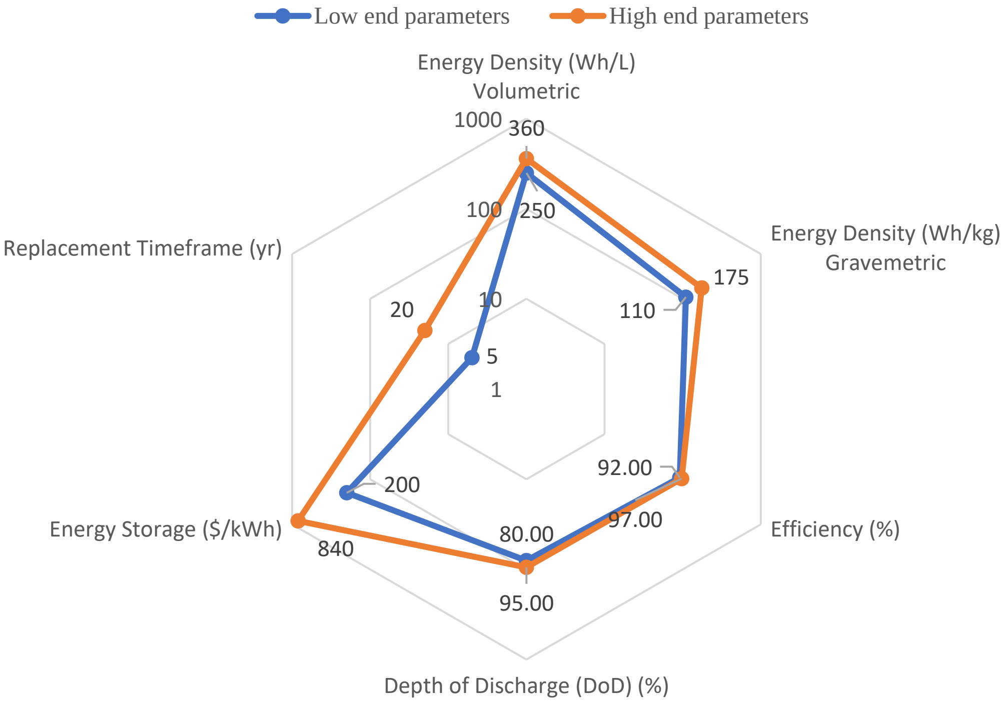

Figure 4: Li-Ion Parameters Spider Chart (see table 4 and 5)

A compilation of over 150 projects in 2016 concluded that Li-Ion batteries could cost anywhere from $200/kWh to $840/kWh [24]. Current research suggests that Li-Ion will continue with a downward trend for cost, with an average of $176/kWh reported in 2018, potentially dropping as low as $62/kWh by 2030 [33]. The results of the literature search are summarized in Tables 2, 4, and 5 in the Parameter Tables section (pages 26 and 31) of Chapter II.

Lead-acid Battery Parameters

Lead-acid batteries were the original utility-scale battery system until Li-ion became affordable. Physical properties, cost parameters, and other considerations found in research seem to conclude that Lead-acid batteries are reliable but need improvements in almost every parameter to make them competitive against other utility-scale batteries.

The upfront cost of Lead-acid is still low compared to Li-Ion and VRFB. However, it is also less energy dense and has poorer DoD compared to other utility-scale batteries. Lead-acid only has a 50%-60% DoD rating to maintain a long life-cycle [8], [14], [24]. This means that this system would need to be at least twice the size of a battery that has 100% DoD. This alone is not entirely problematic; however, the battery's energy density is between 30 to 40 Wh/kg and its life-cycle estimate is as low as three years [8], [24], [26]. The transportation costs here appear to significantly reduce Lead-acid's ability to be economically competitive over a 20-year timeframe. The battery life is also dependent on temperature. For Lead-acid batteries, an 8°C rise in temperature beyond 25°C can cut the effective life of the battery in half [34]. This means that Lead-acid batteries need to be in climate-controlled facilities if used in a desert climate, for instance.

End-of-life costs are another consideration for the overall economic feasibility. There is a significant amount of data on the recyclability of Lead-acid batteries because of the auto industry. Some suggest that up to 96% of the material is recyclable [26]. The United States and Europe can reasonably receive between $0.82/kg and $0.88/kg for the recycled material [35]. These batteries are considered hazardous material, so they normally cannot be shipped overseas for recycling. If this is the case, then the most reasonable salvage value would be the expense to ship the decommissioned batteries to the nearest Defense Logistics Agency site for disposition services.

A compilation of over 150 projects in 2016 concluded that Lead-acid batteries could be purchased from $105/kWh to $473/kWh [24]. Figure 5 shows several low-end and high-end Lead-acid parameters. The results of the literature search are summarized in Tables 2, 4, and 5 in the Parameter Tables section (pages 26 and 31) of Chapter II.

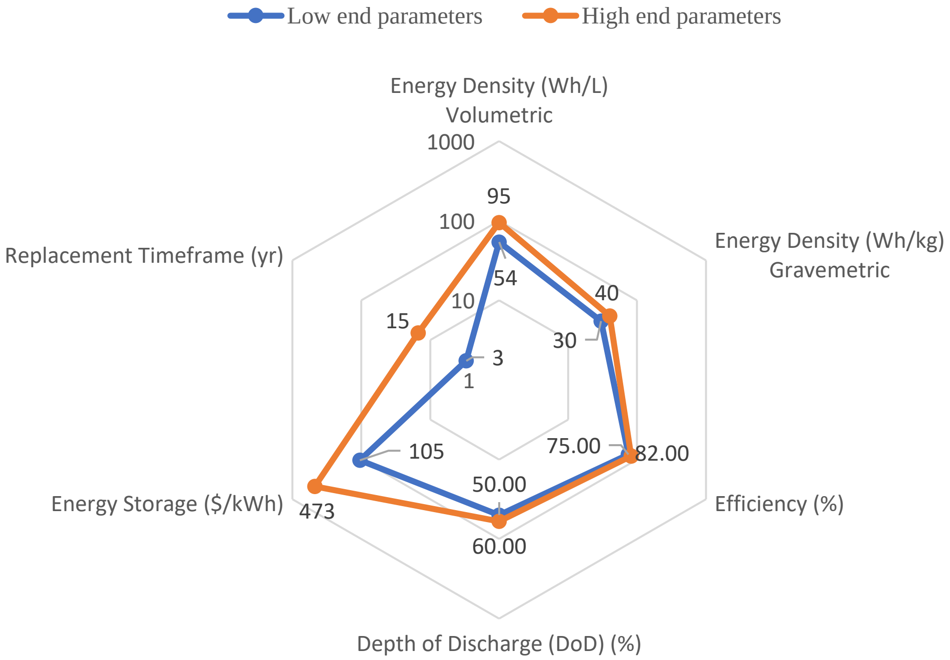

Figure 5: Lead-acid Parameters Spider Chart (see table 4 and 5)

Photovoltaics (PV)

Photovoltaics (PV) are rapidly becoming inexpensive and more efficient. The downside is that localized grids of PV panels must immediately distribute their power directly into the grid. If this system works in tandem with a battery network, PV panels could continue to charge batteries throughout the day and discharge that power at times of peak demand or at night.

The main parameter used to model PV systems is solar irradiance. This value is location specific and fluctuates throughout the day and the year. Its basic value averages the maximum and minimum load days, a clear PV day, an intermittent PV day, a cloudy PV day, and a minimum voltage day determined over the course of one year of data collection [36]. These data points are then compiled into publicly available charts that show the potential solar photovoltaic resource [37]. For instance, North Dakota has a

Direct Normal Irradiance between 4.0 - 5.2 kWh/m^2/day and a Global Horizontal Irradiance between 3.6 – 4.1 kWh/m^2/day [37]. Arizona has a Direct Normal Irradiance between 6.3 – 8.3 kWh/m^2/day and a Global Horizontal Irradiance between 5.1 – 6.1 kWh/m^2/day [37]. Direct Normal Irradiance is the “amount of solar radiation from the direction of the sun” [38]. Global Horizontal Irradiance is the “summation of the Direct Normal Irradiance, the Diffuse Horizontal Irradiance, and the ground-reflected radiation” and is generally more accurate [38]. To size a PV array, the solar irradiance for the location must be known. Figures 6 and 7 show how the Global Horizontal Irradiance can differ between states and climates. Note that North Dakota and Arizona have the same color scheme; However, these colors are specific to the resource range stated on the right side of the figure. Yellow in North Dakota means 3.6 - 3.7 kWh/m^2/day, whereas yellow in Arizona means 5.1 - 5.2 kWh/m^2/day.

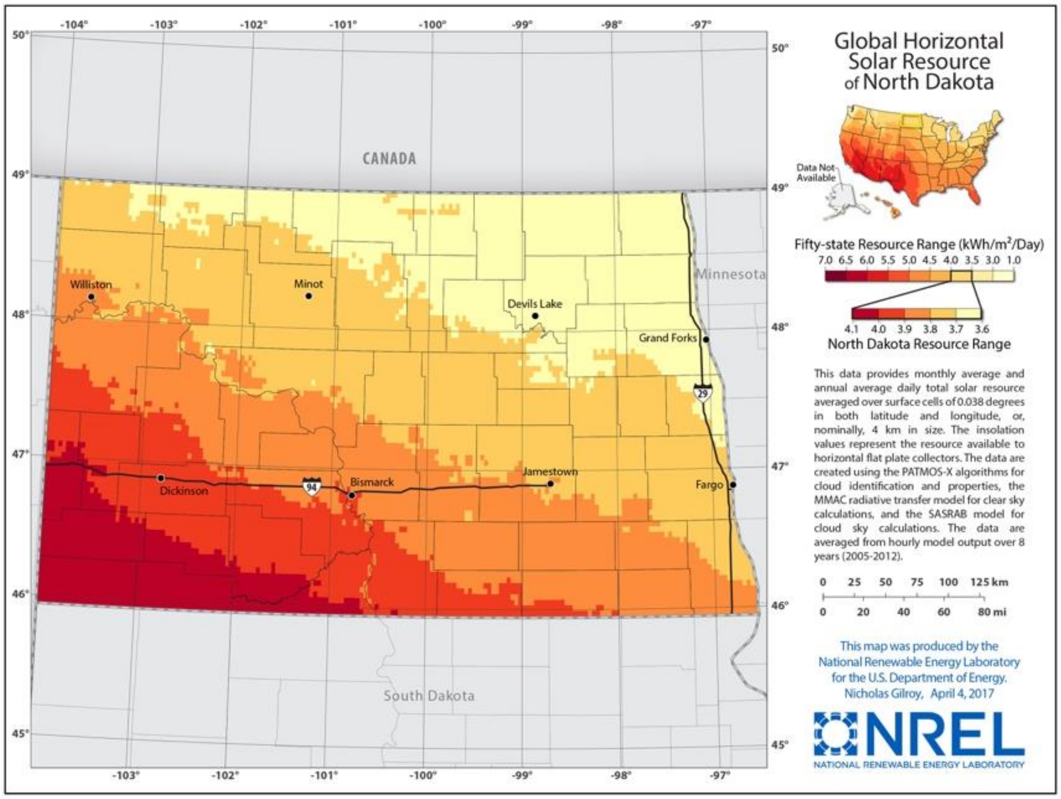

Figure 6. Global Horizontal Irradiance for North Dakota, 2017 [37]

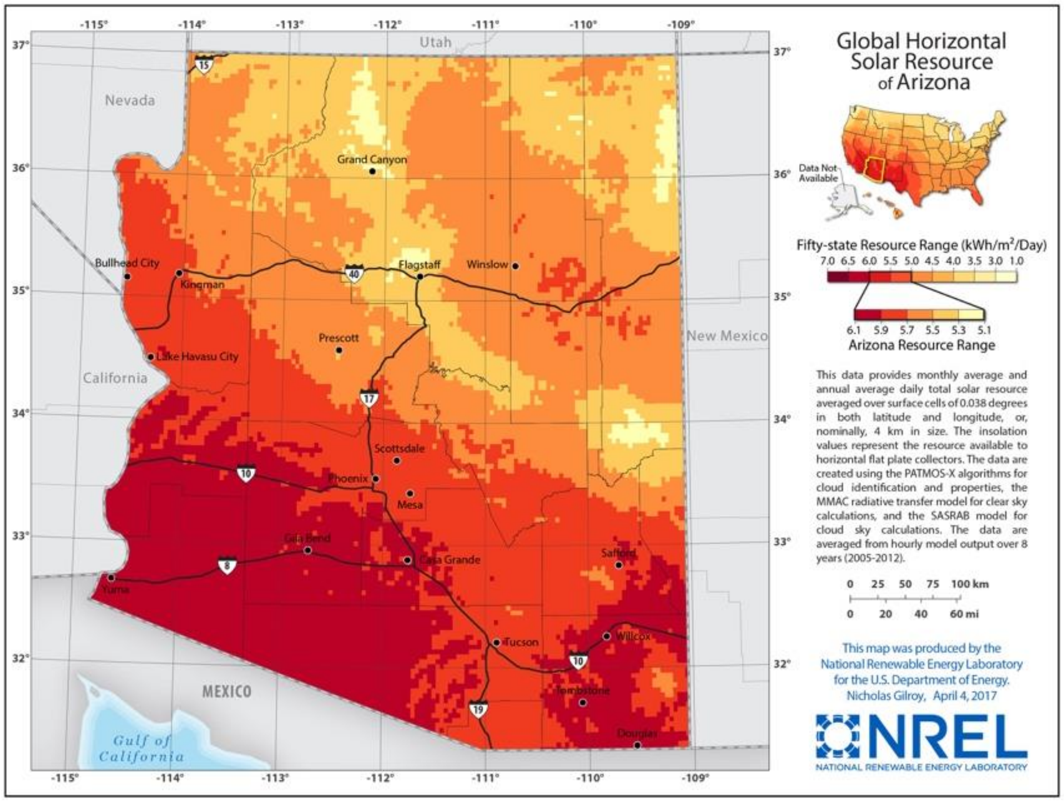

Figure 7. Global Horizontal Irradiance for Arizona, 2017 [37]

The cost per kilowatt for photovoltaics depends on location as well as application. There are varying costs within the United States for purchasing solar panels. There are also differences among residential, commercial, and utility-scale use.

Residential systems are eligible for a tax credit in 36 states and the District of Columbia. The federal government currently provides a tax credit of 26% return on a purchase for residential use through 2020 [39]. This tax credit is subsequently reduced until 2022, meaning residential systems will be less expensive to procure. A 10kW system cost would be between \$17,094 and \$29,600, thus making the system cost range from \$1,710 - \$2,960 per kW [40]. Utility scale is least expensive in \$/kW whereas residential is the most expensive. The assumed benchmark for residential solar in 2017 was \$2.13/W_{ac} [41], which is within the range described for 2020.

Commercial application differs from residential solar because projects are typically larger, and the total system weight is heavier. Unlike utility-scale, commercial solar typically has ballasted racking with a fixed tilt, which is why they are heavier [41]. A commercial system is within the 10 kW – 2 MW range; however, the difference to utility-scale only means that the system is fixed with at least one-axis tracking [41]. It is plausible for a commercial system to be larger than 2 MW. The 2 MW HCE Moore I solar farm was constructed for roughly $3M, costing $1,500 /kW$_{ac}$ [42], [43]. The assumed benchmark for commercial solar in 2017 was $1.34/W$_{ac}$ [41]. Unfortunately, not many smaller projects report their final cost; however, a cost between $1.34 - $1.5/W$_{ac}$ does appear to be the current price of commercial photovoltaics.

Utility-scale photovoltaic application is considered as a ground-mounted system, with at least one-axis tracker, a tilt, and is at minimum a 2 MW system [41]. The largest system in the United States is Antelope Valley's 253 MW$_{ac}$ solar ranch [42]. It was built for a total cost of $1.36B, which averages to $5,375/kW in 2014. This appears to be an overestimate. Currently, the 252 MW$_{ac}$ Mount Signal Solar Farm at $365M and the 50 MW$_{ac}$ Innovative Solar 54 at 72.6M were constructed in 2019 with the cost ranging from $1,448/kW$_{ac}$ to $1,452/kW$_{ac}$ [42], [44]. The assumed benchmark for utility-scale solar in 2017 was $1.44/W$_{ac}$ [41], which is just below the range of projects completed in 2019. Table 2 summarizes the results of the parameters found for PV panels and compares them against diesel generators.

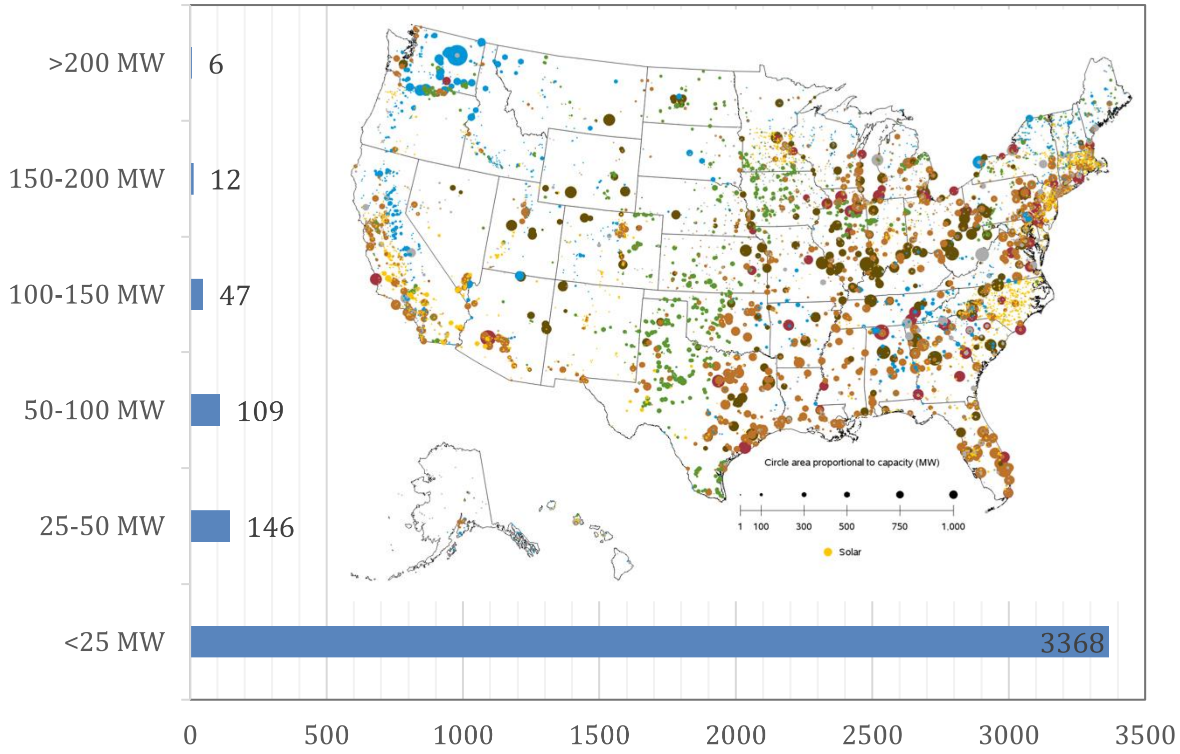

Figure 8. Solar facilities in the United States and capacity by facility size, October 2019 [42], [45]

Table 2. Photovoltaic and Diesel Generator Parameters [11], [46]–[56]

	Photovoltaics	Diesel Generator
Average Solar Irradiance (kW/m^2)	0.4408[3]	
Replacement Timeframe (yrs)	23 - 30	5 - 10
Operating Temperature	15℃ - 65℃	82℃ - 90℃
Efficiency	12% - 20%	30% - 55%
Specific Power (W/kg)	15 - 30[1]	
Operation and Maintenance (O&M) ($/kWh)	0.008	0.005 - 0.010 2 - 12 visits per year
Cost ($/kW)	1500	80 – 240[2]
Salvage Value ($/W)	0.20 - 0.27	

1. Upper limit found in the lab to be nearly 6000; however, practical commercial solar panels on Earth are heavier than residential solar panels for the same output [52][53].
2. Cost per kW derived from a 1250 kW CAT generator ranging $100,000 to $300,000 [48].
3. Average Solar Irradiance derived from Afghanistan time-series dataset.

PV Operations and Maintenance (O&M) costs are in the range of $16/kW$_{ac}$-year or $8/MWh in 2017 [51]. Interestingly, these numbers are from projects that trend away from predominately sunny regions—Global Horizontal Irradiance < 4.75 kWh/m^2/day [51]. The operational range of photovoltaics is optimal between 25℃ - 35℃; however, significant efficiency loss compounds near 65℃ [55]. The temperature coefficient and low light conditions also account for the total kWh produced.

Many commercially available photovoltaics have efficiencies between 15% and 20%, with some higher quality panels reaching 22% [54]. Some experiments have produced numbers as high as 31%, but these have not been replicated outside the lab [57]. Realistically, average priced photovoltaics are most likely 13% to 18% efficient.

End-of-life costs are another consideration for the overall economic feasibility. The recyclability of photovoltaics, as well as the salvage value, has recently gained attention. Studies suggest a net present value loss since the recycled materials are not highly valuable [58]. Salvage value for PV can range from $0.04/W to $1.26/W for the California region, with 2012 purchases ranging between $0.20/W and $0.27/W [59].

Dataset

This section will discuss the dataset used in the model. The dataset contains hourly times series estimates for a solar irradiance profile and a load requirement [60]. The data describes the profile for a FOB in Afghanistan—located in the Helmand province [60]. The FOB is a typical 1100-person United States Air Force enduring location that utilizes Basic Expeditionary Airfield Resources (BEAR) mobile assets [60]. Of the 8760 hours total, 4007 hours produced zero energy—46% of the data.

The solar irradiance profile contains 8760 data points ordered from January to December. Each data point corresponds to the hourly solar irradiance in kW/m^2. The maximum solar irradiance is 1.15 kW/m^2, with an average of 0.24 kW/m^2. The data ranges from 0.34 kWh/m^2/day - 9.26 kWh/m^2/day when converted to the Global Horizontal Irradiance (GHI). The average GHI is 5.74 kWh/m^2/day, which is within the range of a desert climate [37]. Figure 9 shows the daily changes and yearly trend of the data. The outliers are most likely from cloudy days or bad weather events. The monthly averages are also shown in Table 3. They show the irradiance peaking in June and reaching a minimum in December.

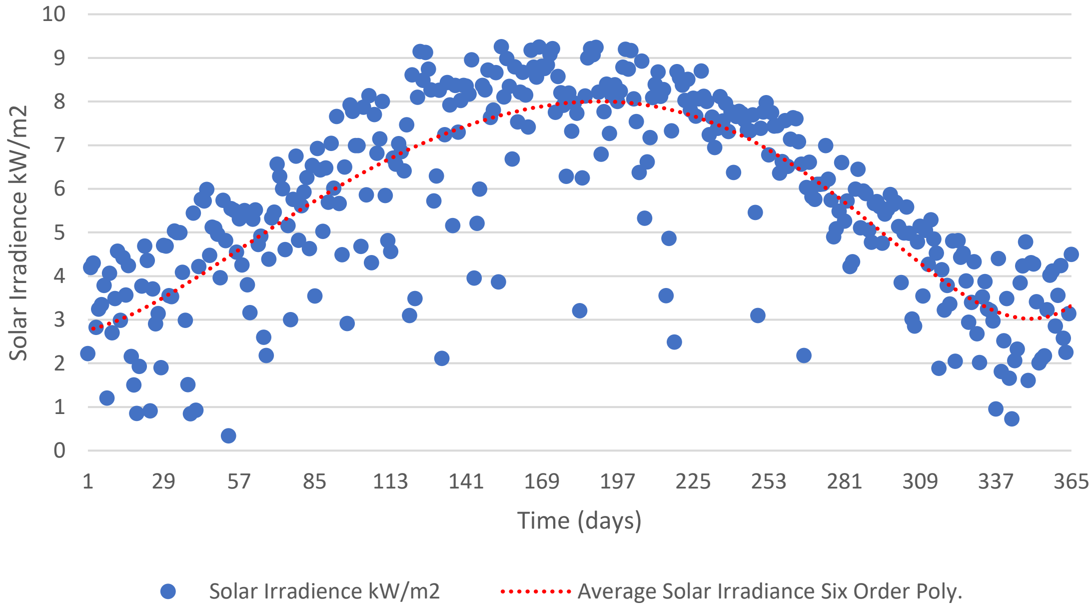

Figure 9. Average Global Horizontal Irradiance over One Year: Afghanistan (estimate) [60].

Table 3. Monthly Global Horizontal Irradiance Averages (kWh/m^2/day)

Jan	3.22
Feb	4.33
Mar	5.14
Apr	6.33
May	7.37
Jun	8.18
Jul	7.87
Aug	7.44
Sept	6.63
Oct	5.46
Nov	3.84
Dec	3.01

The load requirement profile also contains 8760 data points ordered from January to December. Each data point corresponds to the hourly power demand in kW. The daily data points output a power requirement from 70,451 kW to 96,113 kW throughout the year. The average daily loading is 77,689 kW. Figure 10 shows how the average power demand changes each month during the year. Typically, the summer will require more power because Heating, Ventilation, Air Conditioning (HVAC) units are operating more frequently and for longer periods with an increase in ambient temperature. The most demanding month is June. The dataset averages about 2350 MWh of energy use per month. As shown in Figure 11, this also fluctuates throughout the year. This totals approximately 28,400 MWh per year.

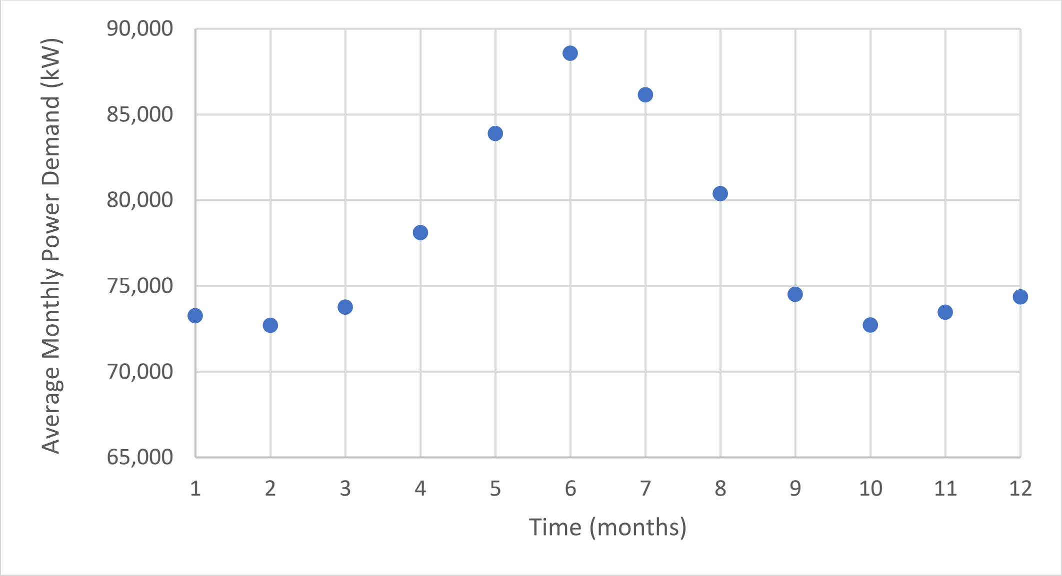

Figure 10. Average Monthly Power Demand (kW)

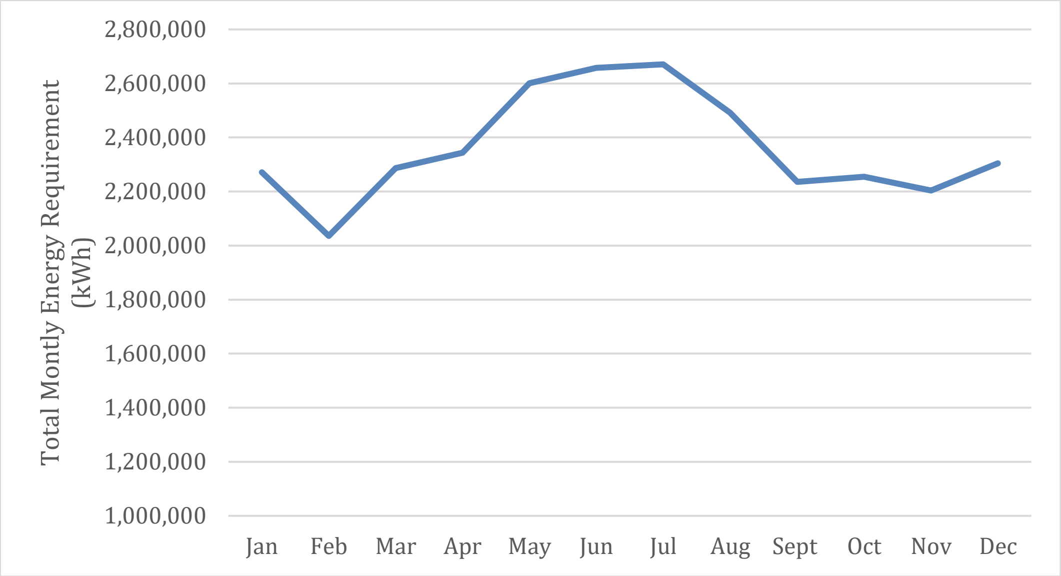

Figure 11. Total Monthly Energy Requirement (kWh)

Parameter Tables for Photovoltaics and Batteries

This section presents the tabulated parameters discussed in the previous sections. Based on the source material, physical data was selected before theoretical models. The three battery systems—VRFB, Li-Ion, and Lead-acid—are compared here along with diesel fuel and diesel generators.

Table 4. Comparison of the Physical Parameters [8], [14], [23], [24], [26], [30], [34], [47], [61]–[66]

	VRFB	Li-Ion (NMC/Gr)	Lead-acid	Diesel Fuel
Energy Density (Wh/L) Volumetric	15 - 70	250 - 360	54 - 95	9700
Energy Density (Wh/kg) Gravimetric	10 - 30	110 - 175	30 - 40	11,600
Power Output (W/L) (Power Density)	1 - 2	100 - 10,000	10 - 700	
Efficiency	60% - 80%	92% - 97%	75% - 82%	
Depth of Discharge (DoD)	100%	80% - 95%	50% - 60%	
Cycle count	12,000[1]- 14,000	1900 - 10,000	300 - 1500	2500 - 12,500[3]
Operating Temperature Range	10℃ - 40℃	10℃ - 55℃	- 40℃ - 60℃	82℃ - 90℃
Charging Temperature Range	15℃ - 35℃	5℃ - 45℃	- 20℃ - 55℃	
Ambient Temperature Range	-20℃ - 50℃	-20℃ - 50℃	20℃ - 30℃	- 50℃ - 50℃[2]
Self-discharge (% per day)	0 - 1%	0.09% - 0.36%	0.09% - 0.4%	

1. Theoretical limit assumed as low as 3000 cycles [23]. Real-life tests, as of 2016, show cycle count as low as 12,000 [24], also showed a minimal calendar life of 5 years as opposed to the theoretical 20 years.
2. Range includes additives/methods to mitigate gelatinous diesel at temperatures lower than 40℃ [61].
3. Numbers derived for diesel generator running 4-hour cycles. Typical generator life-cycle expected is 10,000 to 50,000 hours [62].

Table 5. Comparison of Cost Parameters [8], [12], [17], [21], [23], [24], [28], [31], [35], [50], [67]

	VRFB	Li-Ion (NMC/Gr)	Lead-acid	Diesel Fuel
Energy Storage ($/kWh)	315-1050	200-840	105-473	1.9-2.64[1]
Operation and Maintenance	7% min. 4 visits per year	3% min. 4 visits per year	2% min. 4 visits per year	
Salvage Value	$11.57/kg[2]	$43/kWh	$0.82/kg - $0.88/kg	

1. Diesel Energy Storage derived from Fully Burdened Cost of Fuel FBCF at $15-42/ gal [12] plus storage cost of $1.5/kWh [17] using a conversion ratio of 36.6 kWh/gal.
2. Approximate weight conversion of 10 tonnes per MWh must be used with this amount.

Logistics

Understanding how an asset is transported to a location in a contingency environment is critical for determining the total system cost. For enduring locations, there are specific ways to move assets to their final destination. The logistics of transporting a photovoltaic-battery system can be complex. There are multiple ways to ship and stage equipment to optimize this cost. This section will investigate three means of transportation and the assets involved with ground transportation military airlift, and sealift. This section will not cover contractor transportation, beyond sealift, since this method can have a contract-specific price based on carrier, region, ability, contracting agency policy, etc. Figure 13 shows some of the avenues possible for transporting assets.

Generally, cargo ships are the most cost-effective long-distance transportation method for large assets. Many companies offer discounts when shipping large quantities and include cost estimation calculators for port-to-port transportation [68]. For standard transportation, the 20 ft and 40ft CONEX box are industry standards [69], [70]. Table 6 shows the typical standards for a 40 ft CONEX from two different companies.

Table 6. Typical size and payload 40 ft CONEX [69], [70]

Capacity	Company A	Company B
Max Gross Weight	30,480 kg	
Tare Weight	3655 kg	
Payload	26,825 kg	26,500 kg
Dimensions		
Length	12,192 mm	12,050 mm
Width	2,348 mm	2,350 mm
Height	2,358 mm	2,360 mm

The cost of shipping also depends on which port transports the assets. In the United States, Los Angeles and New York are the primary ports for transportation companies. Table 7 summarizes some destination costs for a 40 ft CONEX box from Los Angeles and New York. Typically, Los Angeles transportation costs are lower for many destinations. Figure 12 visually shows the different costs of transporting 40’ containers.

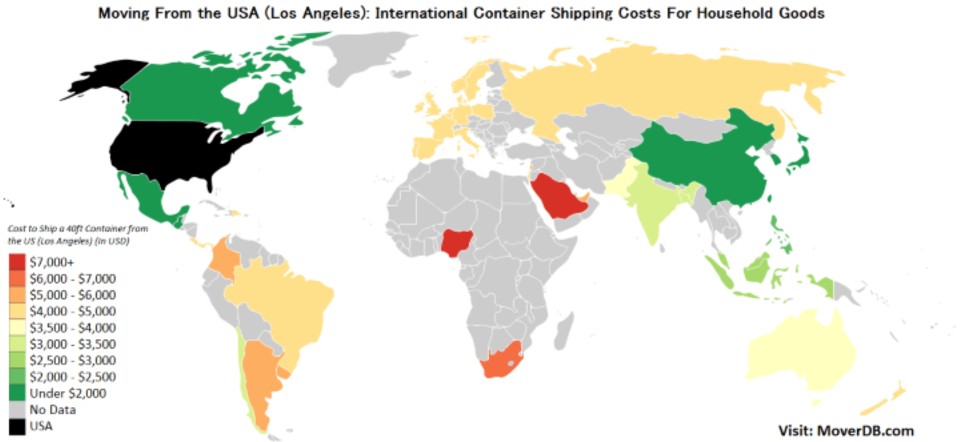

Figure 12. Transportation Cost of a 40 ft CONEX from Los Angeles [71].

Table 7. Cost to ship a 40 ft Container from New York and Los Angeles to Various Locations [71].

	New York	Los Angeles
Australia (Sydney)	$4,175	$1,879
Argentina (Buenos Aires)	$2,975	$3,774
Brazil (Rio de Janeiro)	$2,313	$3,160
India (Mumbai)	$1,245	$1,553
Nigeria (Apapa)	$7,436	$4,519
Russia (Vladivostok)	$1,254	$715
Saudi Arabia (Jeddah)	$4,606	$3,397
South Korea (Busan)	$1,112	$579
UAE (Zayed)	$2,572	$2,880
United Kingdom (London)	$1,772	$2,684
Note 1. Cost accurate as of 2017 [71]. Cost estimated on 50,000 USD port-to-port shipment.		

Combining Tables 6 and 7 results in an estimated cost. For example, it would cost $0.16 per kg to ship cargo from New York to Australia and $0.07 per kg to ship cargo from Los Angeles to Australia. For cost estimation, the port of origin and final destination must be known.

Military airlift is another option to transport assets across vast distances; however, this method is generally more expensive than shipping by sea. The main reason to use this method is for saving time. The two primary transportation airframes in the United States Air Force are the C-5 Super Galaxy and the C-17 Globemaster.

The C-5 has a cargo capacity of 127,460 kg [72]. With an unloaded range of more than 7,000 mi, it operates between $16,408 and $78,818 per flight hour [72], [73]. The lower cost assumes a fuel price of $2.98 per gallon. The upper cost is most likely closer to the FBCF to operate, maintain, and crew the aircraft—$15 per gallon.

The C-17 has a cargo capacity of 77,519 kg [74]. With aerial refueling, it has the range to go anywhere on the planet without landing [74]. It operates between $15,342 and $23,811 per flight hour [73], [75]. The lower and upper cost assume the fuel price is $2.98 per gallon and $15 per gallon, respectively. The C-5 has more capacity; however, it does require a very long runway. The C-17 is designed for use on short and unpaved runways [74].

Military ground transportation is the last form than can move assets. The United States Army and Marine Corps primarily transport assets by ground using the LSVR MKR-18 Cargo Variant or the M1070A1 Tractor and M1000 trailer.

The Oshkosh LSVR MKR-18 Cargo Variant is a heavy armored all-terrain vehicle with a maximum cargo capacity of 20,412 kg [76]. This vehicle is used in situations where combat is likely and may not be the first choice for transportation in less hostile environments.

The M1070A1 tractor and M1000 trailer are built to transport the M1A1 Abrams; however, they can also support heavy cargo [77]. This vehicle has an impressive cargo capacity of 68,027 kg [78]. The Technical Manual for the vehicle describes its capability:

> Normal operating range is 325 mi (523 km), based on 250 gal. (946 L) of fuel and 250,911 lbs (113 914 kg) gross combination weight rating (GCWR) when operated at an average speed of 30 mph (48 km/h). Varying loads, prolonged idle, use of Power Takeoff (PTO), off-road driving, and climatic conditions affect operating range [77].

Table 8 summarizes the air and ground vehicle parameters used in this research. The other way to transport assets to an FOB is by helicopter; however, this form of transportation will not be discussed as the FOB modeled will have a functional runway.

Table 8. Vehicle Parameters [72]–[79]

Vehicle	Maximum Cargo Capacity (kg)	Operating Expense ($/hour) at $2.98/gal	Range	Fuel Consumption Rate	Avg. Speed
C-17	77,519	$15,352 - $23,811	5,524 mi		
C-5	127,460	$16,408 - $78,818	7,273 mi		
LVSR MKR-18 Cargo Variant	18,371 - 20,412	$44.7 - $225	300 mi	2 mi/gal	30 mph
M1070A1 Tractor M1000 Trailer	68,027	$68.77 - $346.15	325 mi	1.3 mi/gal	30 mph

Note 1. Ground Vehicle transportation costs derived from a fuel cost of $2.98 per gal on the low end and an FBCF of $15 per gal on the high end. Each fuel price is then multiplied by the average speed and divided by the fuel consumption rate.

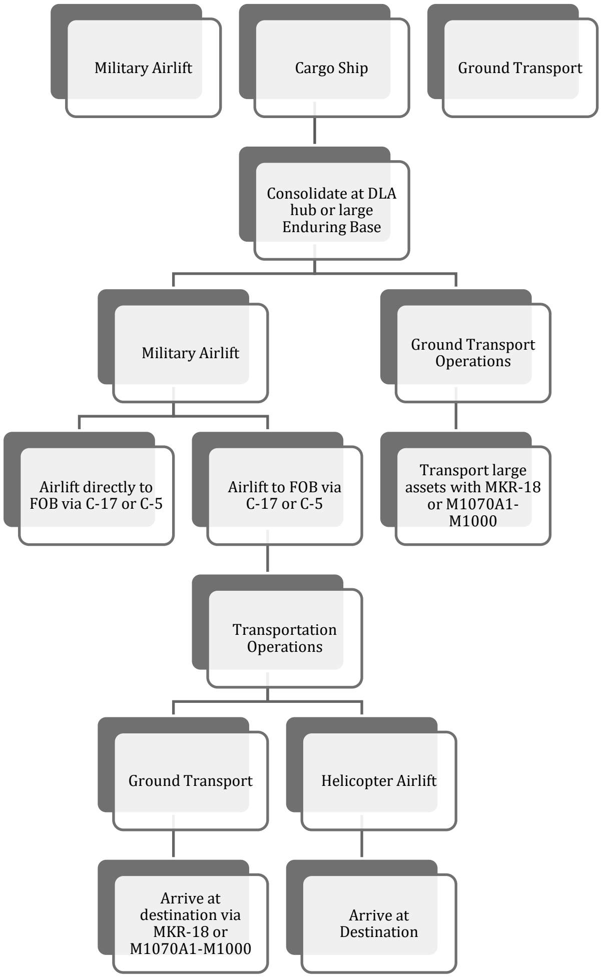

Figure 13. Transportation of Assets from the United States to a Forward Operating Location [80], [81]

In certain instances, United States law requires procurement of highly technical assets from the United States and shipped to location. This includes assets that cannot be procured locally or assets that are sensitive to mission success. The electrical power of a base could be considered mission-critical if it has a computer system included in its operation.

There are several means to procure an asset from the United States. One way is to use military airlift. It is effective and fast, but very expensive. The second is contracts, which include the costs for the vendor to ship to a certain location; however, these can be expensive and lead to the government losing control over when an asset will be delivered.

The most practical way to get a significant amount of heavy assets from the United States to an FOB is by cargo ship, but this method is slower. Shipments would need to take place well in advance and be stored until required. DLA maintains global distribution centers where materials can be stored and distributed [82].

Resilient Energy Infrastructure

Base Resilience refers to the ability of installation infrastructure to be adaptive, fiscally sustainable, and assure combat readiness after an attack [6]. This means that a resilient installation could lose a critical asset—like commercial power—and still be able to perform its mission with or without a certain level of degradation. Thus, resilience is a scale that depends upon the level of mission degradation caused by losing one or more critical assets.

The ability of the base to recover after attack is important to increasing base resilience. Certain characteristics in Li-Ion disallow safe shutdown if the unit receives damage. This can lead to thermal runaway. VRFB have systems that allow for safe shutdown if the unit receives damage. For an enduring base, there is potential for attack. Assets that could be dangerous if damaged may not be suited for forward operating bases.

Conclusion

There are three challenges that VRFB face. First, there is minimal data available for large scale projects because interest in the technology is relatively new. Second, the biggest speculation on the full cost of a utility-scale VRFB network is dependent upon the price of the material vanadium [83]. This mineral is utilized in steel manufacturing and a change to this market could impact the potential savings that VRFB batteries may have over their life-cycle. Third, the technology is so new that many believe that it is too early to know whether other issues with the technology could reduce its theoretical parameters enough to be competitive. Figure 14 shows how Li-Ion costs have dropped over time. In that time, its energy density, cycle count, Depth of Discharge, and efficiency have all increased. Given more time, VRFB may show the same trend. VRFB's low energy density will be a logistics problem, especially when both have similarly expected life-cycles.

Figure 14. Learning Curve Projection for Li-Ion Costs to 2030 [33]

Source: BloombergNEF

There are several differences between VRFB and Li-Ion. VRFB has lower roundtrip efficiency but does not degrade as Li-Ion does with frequent use [22]. VRFB does not have a risk of thermal runaway; Li-Ion can experience thermal runaway near 80°C [26]. VRFB is better for energy applications, but Li-Ion is better for power application.

From a safety standpoint, VRFB and Li-Ion contrast in several ways as summarized in Table 9. First, there is minimal chance of fire in VRFB as thermal runaway is the main cause of battery fires [84]. VRFB can shut down if there is a significant deviation from the safe operating parameters [84]. This makes VRFB better against Li-Ion if the battery is damaged with stranded energy and cannot properly discharge [84]. On an FOB that could be attacked, the ability to maintain safety on damaged systems is crucial. Both batteries have the potential to off-gas toxic fumes from the combustion of hydrocarbons in the event of a fire [84]. This is only compounded if the battery systems are placed indoors or without proper ventilation.

Table 9. Hazardous Comparison of Batteries [84]

Risk	Lithium-ion	Flooded Cell	Sodium Sulfur	VRB Flow Battery
Voltage	X	X	X	
Arc-Flash/Blast	X	X	X	
Toxicity	X	X	X	X
Fire	X	X	X	
Deflagration	X	X		
Stranded Energy	X	X	X	

Solar panel networks have more data to support their results. The panel's effective energy conversion rate is slowly increasing with the development of better materials. Investigations are showing promise for regions that may never have considered solar panels a decade ago.

The salvage value is essentially dependent upon location and market demand. Several companies will purchase PV panels and Lead-acid batteries in the US, Europe, and China. It is reasonable to assume that companies in the future would purchase Li-Ion batteries and VRFB. Without assuming metrics, the most reasonable salvage value would be the expense to ship the decommissioned batteries to the nearest Defense Logistics Agency site for disposition services. Determining a proper salvage value outside of the final transportation cost is beyond the scope of this research.

Methodology

In Chapter 3, we will discuss the creation of the model using the parameters found and discussed in the literature review. The purpose will be to model different utility-scale photovoltaic-battery systems and determine the economic viability of each on a forward operating base (FOB) over the life-cycle of that asset. Photovoltaic panels will be able to power the grid directly, or store the excess energy into a supplemental battery energy storage system. The logistics model will identify practical scenarios to support a transportation cost that can be integrated into the total cost of the systems.

III. Methodology

Introduction

The purpose of this research is to compare different utility-scale photovoltaic-battery systems and determine the economic viability of each on a forward operating base (FOB) over the life-cycle of that asset. Utility-scale refers to the power grid of the entire FOB. This section details the methods used to address the research questions described in Chapter I. The batteries to be compared are Vanadium redox flow (VRFB), Lithium-ion (Li-Ion), and Lead-acid. A minimal number of diesel generators are included within the model to be used if the photovoltaic network cannot provide power and the batteries are not charged.

Theory

Two parts comprise the final cost for each system—the total cost for optimal size and the cost of logistics. First, the parameters found in the literature review are integrated into MATLAB models to optimize the size of the battery and photovoltaic network. This outputs total cost and size for each component. Second, a logistics analysis is conducted with tangible and intangible parameters to show the full scope of the expenses. A model is then built to show transportation costs of the assets from the United States to the 1100-person FOB via airlift, sealift, and ground transport. These parameters factor in location-specific details and will be defined.

The first part of the model builds upon existing MATLAB code developed for photovoltaic system optimization in austere locations [11], [17], [85] The data includes one year of solar irradiance in hourly intervals for a fictitious 1100-person FOB in Afghanistan [60]. It also provides a time-series load requirement for the FOB on an hourly interval for one-year. The parameters used in this research are summarized in Tables 2, 4, 5, 8, & 10. Additional clarification is provided in Chapter II.

Table 2. Photovoltaic and Diesel Generator Parameters [11], [46], [55], [56], [47]–[54]

	Photovoltaics	Diesel Generator
Average Solar Irradiance (kW/m^2)	0.4408[3]	
Replacement Timeframe (yrs)	23 - 30	5 - 10
Operating Temperature	15℃ - 65℃	82℃ - 90℃
Efficiency	12% - 20%	30% - 55%
Specific Power (W/kg)	15 - 30[1]	
Operation and Maintenance O&M ($/kWh)	0.008	0.005 - 0.010 2 - 12 visits per year
Cost ($/kW)	1500	80 - 240[1]
Salvage Value ($/W)	0.20 - 0.27	

1. Upper limit found in the lab to be nearly 6000; however, practical commercial solar panels on Earth are heavier than residential solar panels for the same output [52][53].
2. Cost per kW derived from a 1250 kW CAT generator ranging $100,000 to $300,000 [48].
3. Average Irradiance derived from Afghanistan time-series dataset.

Table 4. Comparison of the Physical Parameters [8], [14], [23], [24], [26], [30], [34], [47], [61]–[66]

	VRFB	Li-Ion (NMC/Gr)	Lead-acid	Diesel Fuel
Energy Density (Wh/L) Volumetric	15 - 70	250 - 360	54 - 95	9700
Energy Density (Wh/kg) Gravimetric	10 - 30	110 - 175	30 - 40	11,600
Power Output (W/L) (Power Density)	1 - 2	100 - 10,000	10 - 700	
Efficiency	60% - 80%	92% - 97%	75% - 82%	
Depth of Discharge (DoD)	100%	80% - 95%	50% - 60%	
Cycle count	12,000[1]- 14,000	1900 - 10,000	300 - 1500	2500 - 12,500[3]
Operating Temperature Range	10°C - 40°C	10°C - 55°C	- 40°C - 60°C	82°C - 90°C
Charging Temperature Range	15°C - 35°C	5°C - 45°C	- 20°C - 55°C	
Ambient Temperature Range	-20°C - 50°C	-20°C - 50°C	20°C - 30°C	- 50°C - 50°C[2]
Self-discharge (% per day)	0 - 1%	0.09% - 0.36%	0.09% - 0.4%	

1. Theoretical limit assumed as low as 3000 cycles [23]. Real-life tests, as of 2016, show cycle count as low as 12,000 [24], also showed a minimal calendar life of 5 years as opposed to the theoretical 20 years.
2. Range includes additives/methods to mitigate gelatinous diesel at temperatures lower than 40°C [61].
3. Numbers derived from 4-hour cycles. Typical generator life-cycle expected is 10,000 to 50,000 hours [62].

Table 5. Comparison of Cost Parameters [8], [12], [17], [21], [23], [24], [28], [31], [35], [50], [67]

	VRFB	Li-Ion (NMC/Gr)	Lead-acid	Diesel Fuel
Energy Storage ($/kWh)	315-1050	200-840	105-473	1.9-2.64[1]
Operation and Maintenance	7% min. 4 visits per year	3% min. 4 visits per year	2% min. 4 visits per year	
Salvage Value	$11.57/kg	$43/kWh	$0.82/kg - $0.88/kg	

1. Diesel Energy Storage derived from Fully Burdened Cost of Fuel FBCF at $15-42/ gal [12] plus storage cost of $1.5/kWh [17] using a conversion ratio of 36.6 kWh/gal.

Table 8. Vehicle Parameters [72]–[79]

Vehicle	Maximum Cargo Capacity (kg)	Operating Expense ($/hour) at $2.98/gal	Range	Fuel Consumption Rate	Avg. Speed
C-17	77,519	$15,352 - $23,811	5,524 mi		
C-5	127,460	$16,408 - $78,818	7,273 mi		
LVSR MKR-18 Cargo Variant	18,371 - 20,412	$44.7 - $225	300 mi	2 mi/gal	30 mph
M1070A1 Tractor M1000 Trailer	68,027	$68.77 - $346.15	325 mi	1.3 mi/gal	30 mph
Note 1. Ground Vehicle transportation costs derived from a fuel cost of $2.98 per gal on the low end and an FBCF of $15 per gal on the high end. Each fuel price is then multiplied by the average speed and divided by the fuel consumption rate.					

Table 10. Comparison of Practical Consideration Parameters [8], [24]

	VRFB	Li-Ion (NMC/Gr)	Lead-acid
Replacement Timeframe (yr)	5 - 20[1]	5 - 20[1]	3 - 15
Operating Timeframe (yrs)	5, 10, 20	5, 10, 20	5, 10, 20
Assumed Battery Loss for round-trip and Self-Discharge	8%	8%	8%
1. Theoretical constraint assumed from ideal conditions.			

The second part of the model constructs the logistics costs incurred by transporting a system to an austere location. It then models the transportation requirement for a theoretical 1100-person FOB via airlift, sealift, and ground transport. Parameters for the logistics are shown in Table 8. The sealift costs are calculated using a shipping calculator for bulk cargo and is only introduced for the theoretical Alpha FOB. The model will run air only, sea only, and ground only costs. Then it combines these as the outcomes shown in Figure 18. These combinations are:

- Military airlift direct from Holloman AFB to Alpha FOB
- Sealift to port Mina Salman, Bahrain and then military airlift to Alpha FOB
- Sealift to port Mina Salman, Bahrain and then ground transport to Alpha FOB

Materials and Equipment

This model utilizes the MATLAB 2018b software. The photovoltaic data collected real-world measurements for one year at an FOB. This includes hourly solar irradiance data and load requirements for the 1100-person base for one year. The dataset can be accessed through the AFIT network drive with password ‘fennell’ : J:\20M\ENV\Fennell\dataset

Procedures and Processes

The model works in several ways. First, it determines the optimal size and weight of each battery and photovoltaic network. Then it compares logistical costs associated with the transportation, maintenance, and removal of the assets. Finally, it compares the results between battery systems as well as diesel generators using a theoretical base. Then it can determine the feasibility of these systems from an economic and resiliency standpoint.

The first pass of the cost surface model investigates the different outputs of the battery systems by varying the Fully Burdened Cost of Fuel (FBCF), the battery efficiency, and the cost of the battery in \$/kWh. Pass refers to running different iterations of the parameters to find common outputs. A cost surface plot shows where areas within a set range are less expensive with different colors. The pass starts at five years for each battery and then increases to 10 and 20 years. The second pass looks for minimal optimal battery size and PV area, for the varying FBCFs, to see how changes in fuel price affect the optimal size. The third pass investigates if the battery system has an optimal point—regardless of the FBCF, efficiency, and \$/kWh. The final pass on the cost surface model investigates the range where each battery system trends.

The first pass of the fixed battery model investigates the common size found for all five-year. This size is inputted to determine the optimal PV area. In the second pass, the PV area is then inputted in the fixed PV model. This determines what size battery would be optimal for that area. This process continues iterations until both models output the same results for battery size and PV area, which show minimal total cost.

The optimal size for five years is the starting point for 10 years, and the process repeats until each model outputs the same result. Then the 10-year optimal PV area and battery size are used as the starting point for the 20-year optimal sizing.

The logistics model utilizes the weights of each optimal battery system determined through an iterative process of the first model. With the weight of the optimal array and battery, the ground, air, and sea economic costs associated with the systems cab be shown. To further show how this impacts the overall cost, a theoretical 1100-person FOB is created with a known location. This determines a cost for the transportation for the batteries and the photovoltaics. Finally, the optimal cost and the transportation cost is added to the Operations and Maintenance cost and salvage value. All these values added together make up the total cost. A new $/kWh for the battery and $/kW for the PV array can be derived from this. The differences in cost can then be discussed between the batteries and years.

Assumptions

The model assumes that the forward operating base will have a minimum life of five years as part of ongoing operations. The reason for the minimum time is that there is a certain amount of time that is required for any battery system to be economically feasible. Anything less than five years would most likely be impractical. The assumption here is that the current United States stance for enduring FOBs trends towards 5, 10, or 20-year operation.

The current Fully Burdened Cost of Fuel (FBCF) is assumed to be a fixed cost throughout the duration of the model. The model also includes diesel generators to be used as back-up. The reason the generators are included is that the batteries could fully discharge and there could be insufficient conditions for the photovoltaic panels to absorb energy for use. There will always be a minimal cost on the system of $240k per generator, as well as fuel costs to operate them. The theoretical Alpha FOB is capable of accepting airlifted assets as well as ground transported assets.

Energy density is not dependent upon the overall quality and cost of the battery. Therefore, averages of volumetric and gravitational energy densities is used for the batteries when calculating the optimal size. Also, the specific power of the photovoltaic array for the logistics model is averaged.

The logistics model assumes that the means of transportation to the Alpha FOB will be by military vehicle except for sealift. Sealift is estimated by commercial costs. The total system cost cannot account for all possible expenditures. Things such as the reduced cost of maintenance, replacement of transformers, replacements of power lines, etc. are not accounted for within the model.

Model Development

The MATLAB code includes three sections for to find battery size and photovoltaic (PV) area: the objective function, the cost surface area model, and the fixed battery or PV array size model. The logistics model uses Excel spreadsheets to translate the optimal weight from the first model to a cost per kWh that can be added to the final monetary figure.

Objective Function Description

The objective function's primary purpose is to investigate the dataset and output specific results for the other two sections. The function outputs total cost, solar cost, diesel cost, wasted kWh, and battery energy history. It assumes an 8% loss of energy in the battery from grid transmission losses, self-discharges, and other factors. The function also requires inputs defined by the models. These inputs include two passed variables, diesel cost per kWh, solar cost per kWh, battery cost per kWh, solar panel efficiency, expected years at location, and Depth of Discharge (DoD). The two passed variables are model specific and are defined as the PV area(s) and battery size(s). This will be discussed in detail for the code of the other two models.

The function defines a for-loop to look at the load requirement and the total solar irradiance on the system at all points in the data. The total load is pulled directly from the dataset. The total solar is pulled from the dataset then multiplied by the panel efficiency and the array area.

The array area is an input variable from the other two models that defines a range of potential areas for the function to simulate. It then categorizes these points as an energy shortage or an energy surplus on the system. The energy surplus increases the storage battery energy until the battery is fully charged. From there, the function will output any unused energy to the models. The energy shortage will draw from the battery until the battery reaches its DoD. If the battery energy storage falls below DoD, then diesel generator's power the remainder of the load requirement for that point. The diesel generators cost depends on the cost of diesel fuel per kWh. This for-loop continues until all 8760 data points are read from both the solar profile and the load estimate. Results are sent to the cost surface and one-variable models.

Cost Surface Model Description

The cost surface area model outputs the total costs for a defined range of PV and battery systems. It identifies where optimal solutions are using colors. Just as topographical maps show elevation, the valley of the output is where the system expense is minimized. This model defines the inputs required in the objective function. This includes diesel cost per kWh, diesel kW per gallon, solar cost per kW, battery cost per kWh, DoD, PV efficiency, modeled years, PV area indices, and battery size indices. The indices define PV area (m^2) and battery sizes (kWh) between 1000 and 11000, with respective units.

The model then defines a for-loop that varies the sizes and areas of the battery and PV, respectively, using the objective function's inputs and outputs. A graphical representation outputs the results of this loop, accounting for all variables described above. Figure 15 shows a typical output.

The top graph provides a 3D representation of the valley in the cost topography. The bottom graph is the top-down view of that cost topography. The title between each graph provides information about the input values for the simulation. It includes the PV cost of \$1500/kW, the battery cost at \$840/kWh, a 95% battery DoD, the Fully Burdened Cost of Fuel (FBCF) at \$2.64/kWh, the equivalent cost per gallon and liter, and the length of the simulation in years.

The y-axis labels areas from 1000 m^2 to 110,000 m^2, and the x-axis labels battery sizes from 1000 kWh to 110,000 kWh. The colors define the range of total cost values. The graph on the bottom right shows the range of total costs from approximately \$200M to over \$450M. Darker blue means the system is the least expensive. This occurs between the coordinates 30 kWh, 75,000 m^2 and 60 kWh, 82,000 m^2.

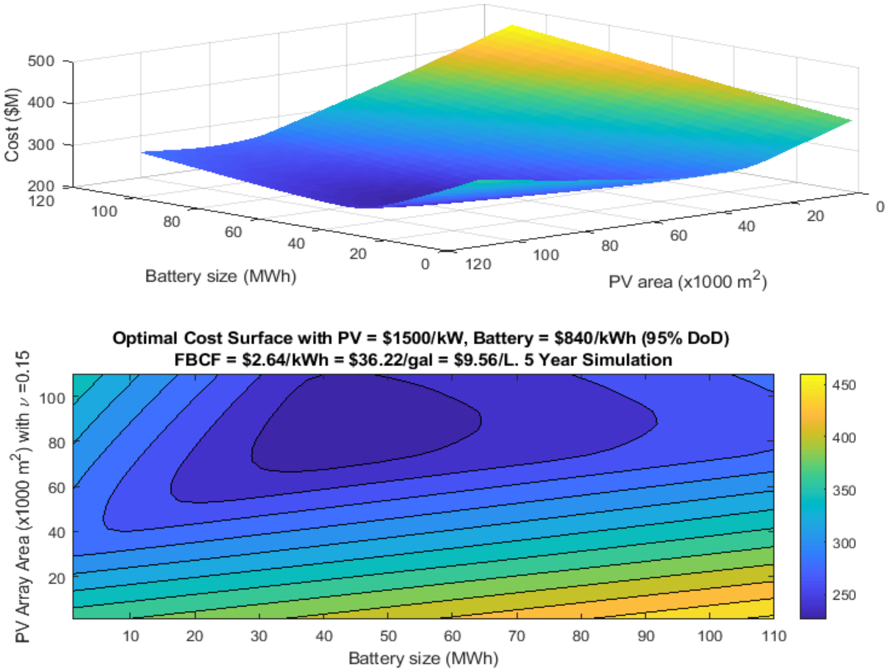

Figure 15. Typical Output of the Cost Surface Model

One-variable Optimization Model Description

The one-variable battery/PV optimization model outputs where a fixed battery size, or fixed PV area, optimizes the other variable. It finds a single point where cost is minimized. The code also outputs the total weight and volume of the battery systems as well as the weight of the PV array. The code for the two sections is nearly identical, except one varies the PV area and the other varies the battery size while fixing the opposite variable input to a single number.

This model defines the inputs required in the objective function. This includes the diesel cost per kWh, the kW per gallon of diesel, the solar cost per kW, the battery cost per kWh, the DoD, the average solar irradiance, the fixed PV area or fixed battery size, and the indices to vary the non-fixed variable. The inputs also include logistics parameters, including the volumetric energy density of the battery (Wh/L), the gravimetric energy density of the battery (Wh/kg), and the density of the PV panel (W/kg).

The model defines a for-loop to vary the indices from 10 to 150,000—with the units of the non-fixed variable. This loop utilizes the inputs and outputs of the objective function to plot several lines and output the optimal value. The code then takes the optimal value and converts that size and area into a weight and volume.

Figure 16 is a typical output of the fixed battery code, and Figure 17 is a typical output of the fixed PV area code. The title provides information about the input values for the simulation. It includes the PV cost of \$1500/kW, the battery cost at \$315/kWh, a 100% battery DoD, the Fully Burdened Cost of Fuel (FBCF) at \$1.90/kWh, the equivalent cost per gallon and liter, and the length of the simulation at 5 years. Depending on which simulation is running, the fixed 50,000 kWh battery or the fixed 80,000 m^2 solar area will appear on the last line of the title. The final value produced is the optimal PV area, or battery size, determined as the minimum cost. In this case, cost is minimized with a 77,775 m^2 array and a 40,445-kWh energy storage system, respectfully.

The left y-axis is always cost ($M). The right y-axis is always the total unused solar energy (MWh). The x-axis either shows the changing PV area or the changing battery sizes. Both figures plot the same lines: the total cost, the PV array cost, the fuel cost, the unused solar, and the optimal point value. The optimal value for a fixed battery is approximately $180M and for fixed PV, it is approximately $185M.

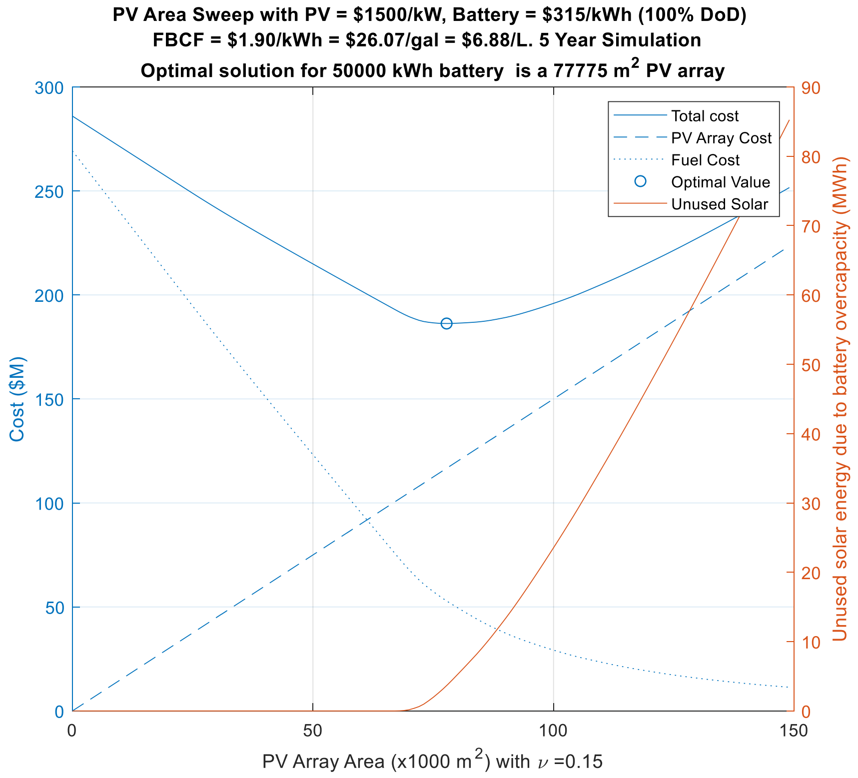

Figure 16. Typical Output of the Fixed Battery Optimization Model

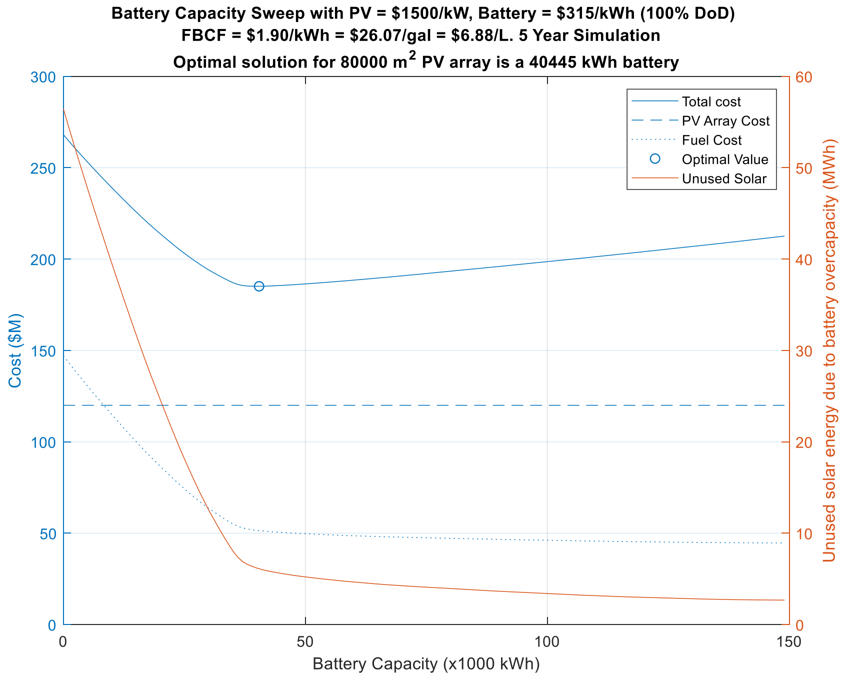

Figure 17. Typical Output of the Fixed PV Optimization Model

Logistics Model Description

The first part of the model incorporates the various optimal sizes of each battery system over 5, 10, and 20 years and derives shipping cost. The model description looks at how much each mode of transportation could cost to ship from Jeddah, Saudi Arabia to Mina Salman, Bahrain. These two places were chosen for relative distance to each other as well as their ability to transport the assets by land, air, and sea. Any political or import/export issues that arise from crossing the border are ignored.

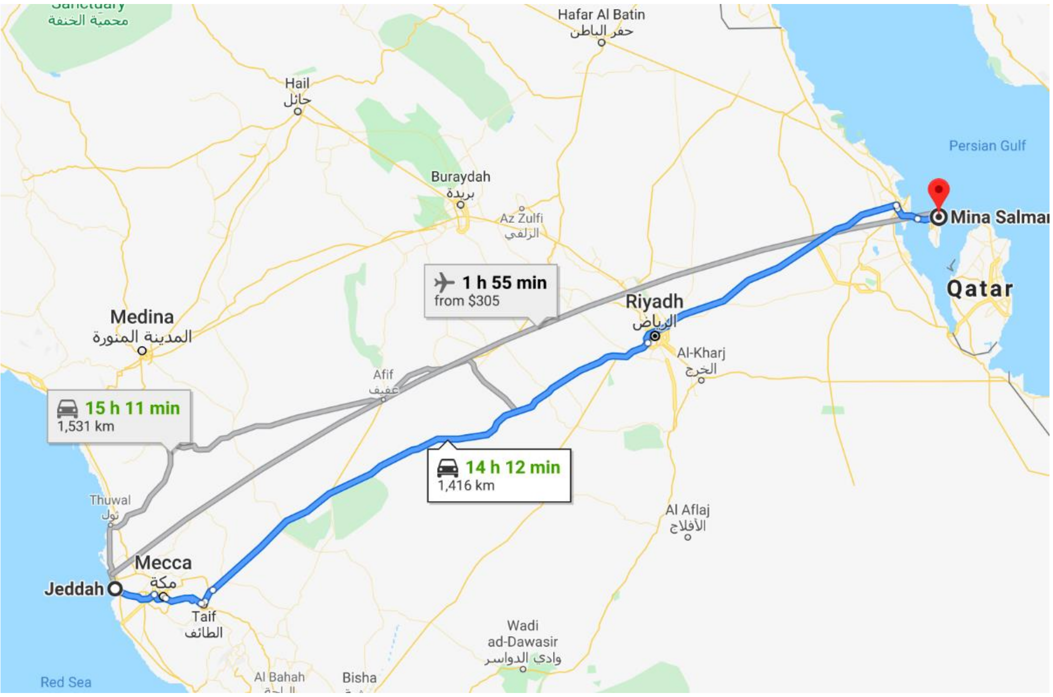

Figure 18. Route Jeddah, Saudi Arabia to Mina Salman, Bahrain [86]

For 5 years, VRFB total PV weight and total battery weight are provided in Table 11 from the optimization model in Chapter IV. This will be used in the following example.

Table 11. 5-year VRFB Optimized Weight and Volume

	Total PV Weight (kg)	Total Battery Weight (kg)	Total System Weight (kg)	Total Battery Volume (L)
VRFB	1,708,000	1,964,000	3,672,000	925,000

There are approximately 880 miles between Jeddah and Mina Salman by road. When averaging 30 mph, it will take approximately 30 hours to make the trip. This model also assumes that the PV and batteries can be shipped on each vehicle at the vehicle’s maximum allowable payload. It is also assumed that there is no issue with refueling the ground vehicles during the 880 mi trip. The total cost will be determined from the minimum of the two vehicle options for ground and air. Table 12 summarizes the results of the route shown in Figure 18.

Table 12. Route Total Transportation Cost for VRFB 5-year Optimization from Jeddah to Mina Salman

	Sea	Air	Ground (30 mph)
Anticipated Time		2 hrs	30 hrs
C17 cost ($/hr)		$23,811	
C5 cost ($/hr)		$78,818	
MKR-18 cost ($/hr)			$225.00
M1070A1 ($/hr)			$346.15
PV Weight	1,707,531	1,707,531	1,707,531
Battery Weight	1,964,150	1,964,150	1,964,150
# of C-17 sorties needed to transport PV system		23	
# of C-17 sorties needed to transport battery system		26	
# of C-5 sorties needed to transport PV system		14	
# of C-5 sorties needed to transport battery system		16	
# of MKR-18 required to transport PV system			84
# of MKR-18 required to transport battery system			97
# of M1070A1 required to transport PV system			26
# of M1070A1 required to transport battery system			29
Total PV Transportation Cost	$3.0M- $3.3M	$2.2M - $4.4M	$540k - $1.2M
Total Battery Transportation Cost	$601k- $665k	$2.5M - $5.1M	$603k - $1.3M
Total Transportation Cost to system	$3.6M- $4M	$4.7M - $9.5M	$1.2M - $2.5M

The results show that the cost of transporting the PV-battery system from Jeddah to Mina Salman varies depending upon mode of travel. In this case, ground transportation is the least expensive at not more than $2.5M. This number includes return trips at a FBCF of $15/gal. Cargo ship is next at no more than $4M. Finally, air transport is the greatest expense at no more than $9.5M. These results are to be expected for short distances—880 mi from Jeddah to Mina Salman. Even at this mileage, shipping is still more cost effective than airlift.

The actual transportation model investigates costs from Holloman AFB to Alpha FOB, which will be located near Samawah, Iraq—roughly the same latitude and climate as Afghanistan. Since this model is only the five-year optimization, no replacement battery systems are included in the final transportation cost. This will not be the case with the 10 and 20-year models.

Energy Resilience

Batteries and photovoltaics eventually fail. How long their life-cycle is before they fail depends on temperature, usage, technology, Depth of Discharge, and cycle-count. The first step to finding a total cost is defining how many times the batteries, diesel generators, and photovoltaics need to be replaced on a 20-year timeframe. Table 13 summarizes the range of replacements possible for a given timeframe.

Table 13. Battery Replacement Time and Possible Number of Replacement Cycles Required [8], [24], [56]

Battery	Expected Life	Number of Replacement Cycles for 5 years	Number of Replacement Cycles for 10 years	Number of Replacement Cycles for 20 years
VRFB	5-20	0	0-1	0-4
Li-Ion	5-20	0	0-1	0-4
Lead Acid	3-15	0-1	0-3	1-6

Chapter IV discusses the results from modeling the optimal battery size, optimal photovoltaic area, and the logistics costs. The total cost is equal to the optimal system cost plus the logistics costs, maintenance costs, the cost to replace the assets after n years, and any salvage value the assets could expect. This new cost can show a more accurate $/kWh for batteries and $/kW for photovoltaics.

IV. Results and Analysis

This chapter begins by discussing the results of the MATLAB model for the first research question for each battery type. It then discusses the logistics analysis for the optimal size of the battery system. For the second research question, the chapter presents a scenario to show how much cost airlift, ground transportation, and sealift would incur. Finally, the chapter answers the third research question detailing how much additional cost per kWh would be added if energy resilience were added to the system.

VRFB Optimization Results

The first pass looks at all five-year models when varying FBCF, efficiency, and \$/kWh. Figures 19-22 show that all four models share a common battery size at 40 MWh and an array area of 75,000 m^2. These will be the starting values for the fixed PV area and fixed battery models. Figure 21 shows the minimal optimal size was for high battery cost and low FBCF. The results show the minimum is a 9 MWh battery with a 45,000 m^2 PV area. The low battery cost and high FBCF results show the maximum optimal size is a 120 MWh battery with a 90,000 m^2 PV area.

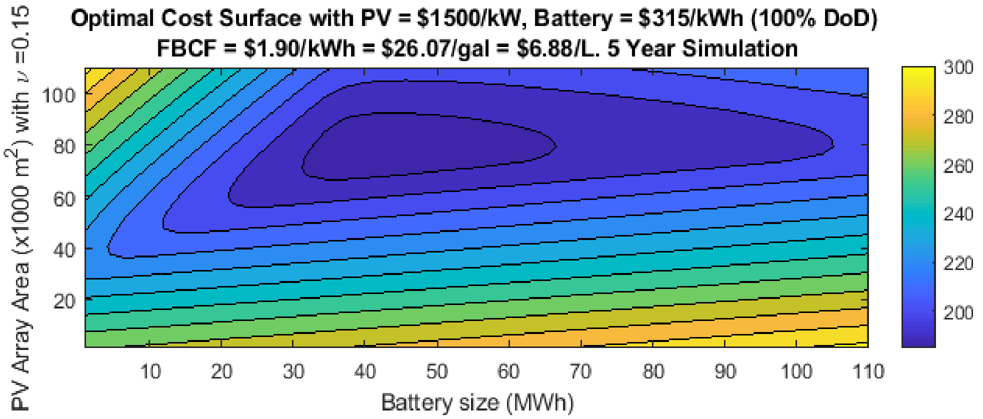

Figure 19. VRFB Cost Surface Low FBCF – Low \$/kWh

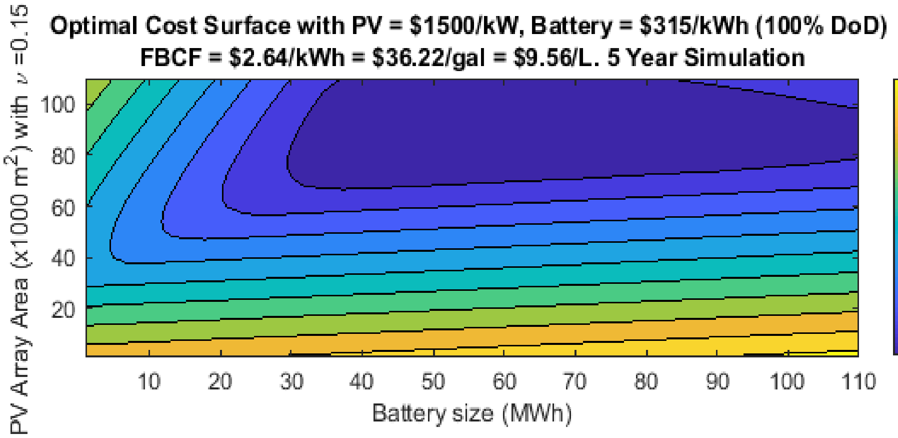

Figure 20. VRFB Cost Surface High FBCF – Low $/kWh

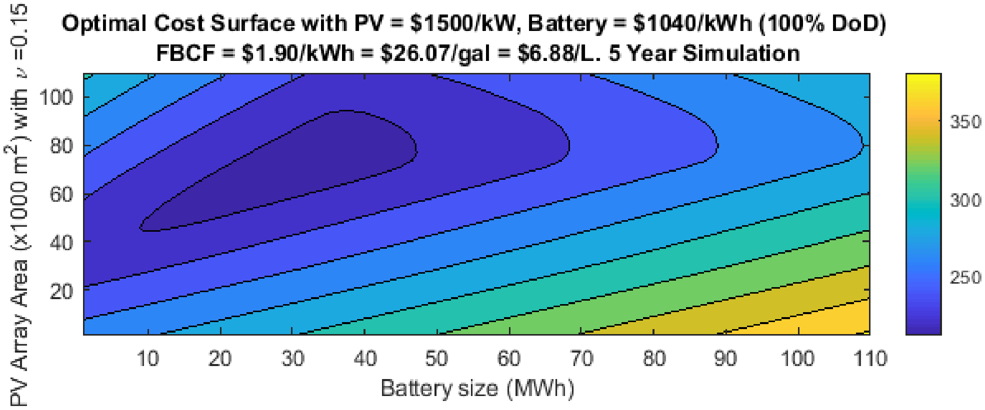

Figure 21. VRFB Cost Surface Low FBCF – High $/kWh

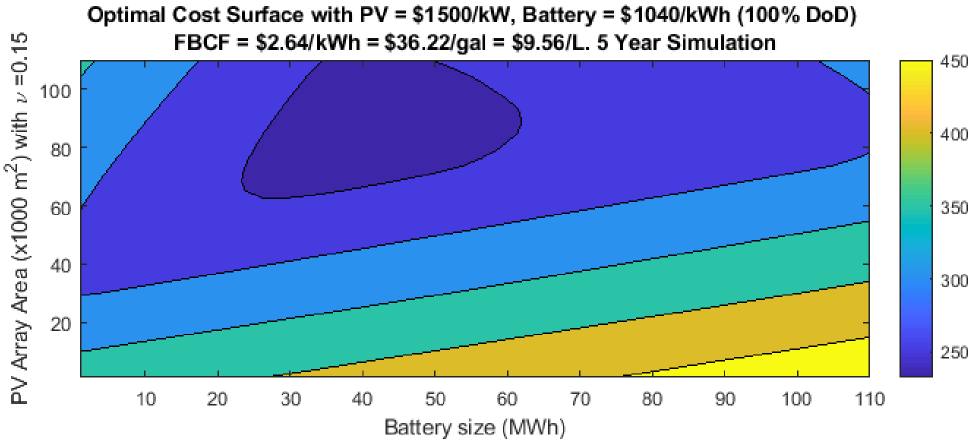

Figure 22. VRFB Cost Surface High FBCF – High $/kWh

After modeling 10 and 20 years and comparing the results, a trend begins to show that VRFB systems are optimal, for an 1100-person FOB, at a battery size between 30 MWh and 60 MWh. The photovoltaic area is optimal for an area between 60,000 m^2 and 100,000 m^2.

The optimal sizes of each system and their cost for 5, 10, and 20 years are summarized in Table 14. Figures 23-28 show the optimal PV-Battery size outputs from MATLAB. Over a 20-year life-cycle, the total cost to fuel an 1100-person FOB on diesel fuel would be approximately $1B.

Table 14. VRFB Optimal PV-Battery Size for 5, 10, & 20 years

Life-cycle (years)	Battery Size (kWh)	PV Area (m^2)	Total Cost	System Cost per year
5	39,283	77,475	$184.9M	$37.0M
10	55,461	97,318	$225.0M	$22.5M
20	67,018	123,947	$268.2M	$13.4M

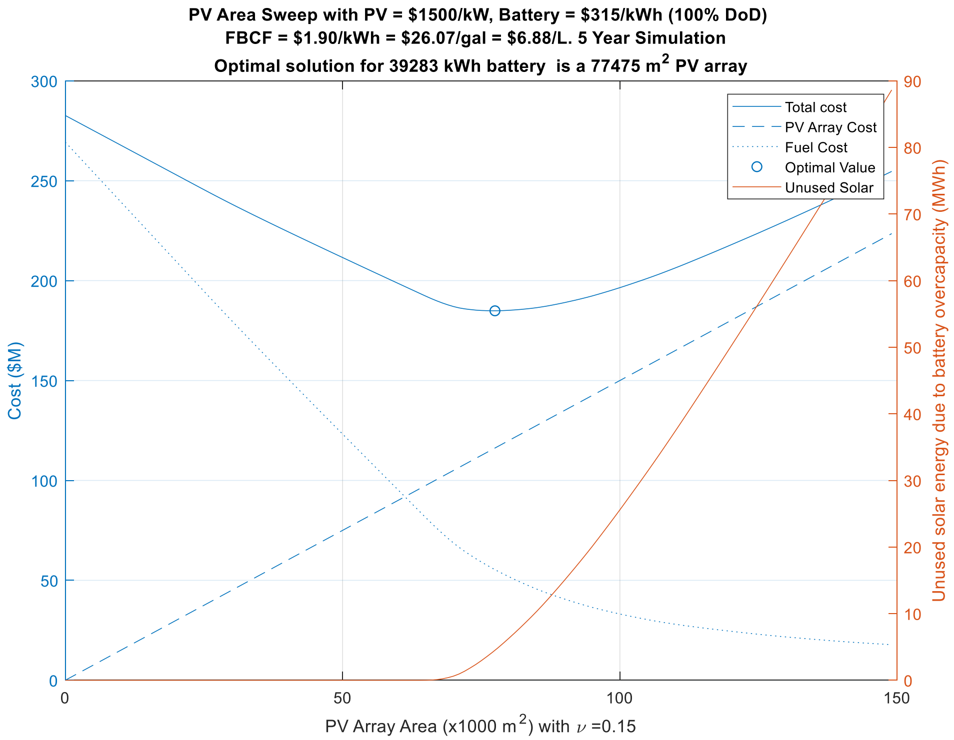

Figure 23. 5-year VRFB Optimal PV Area given Battery Size 39,328 kWh

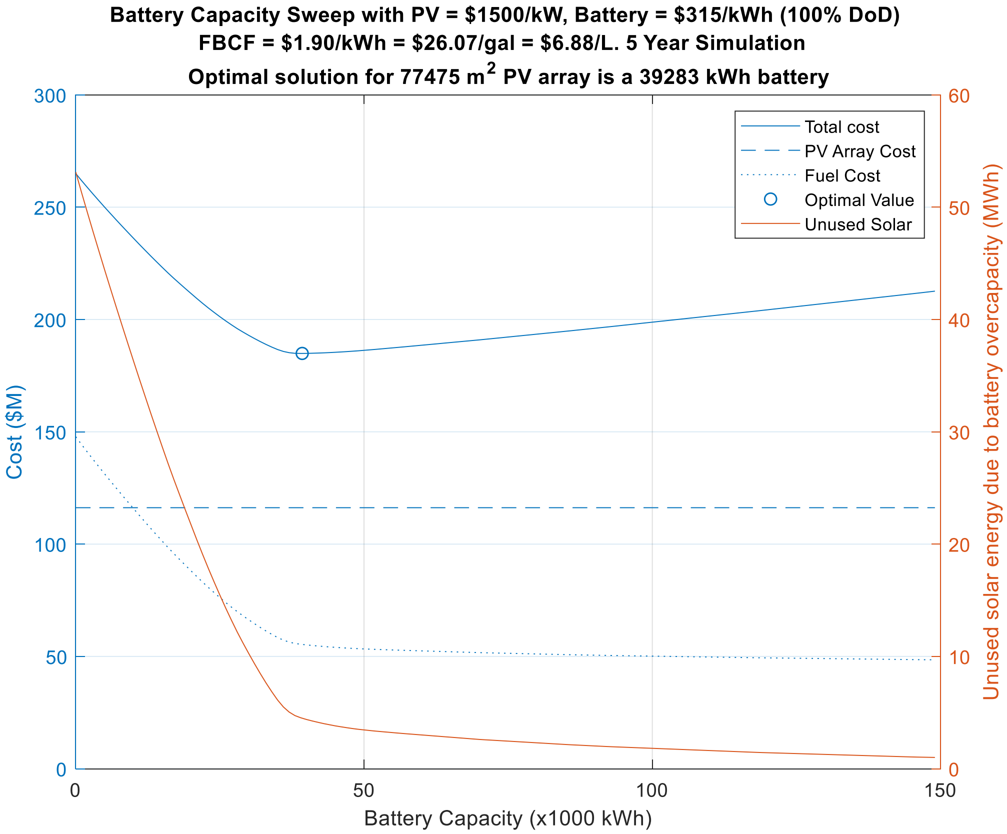

Figure 24. 5-year VRFB Optimal Battery Size given PV Area of 77,745 m^2

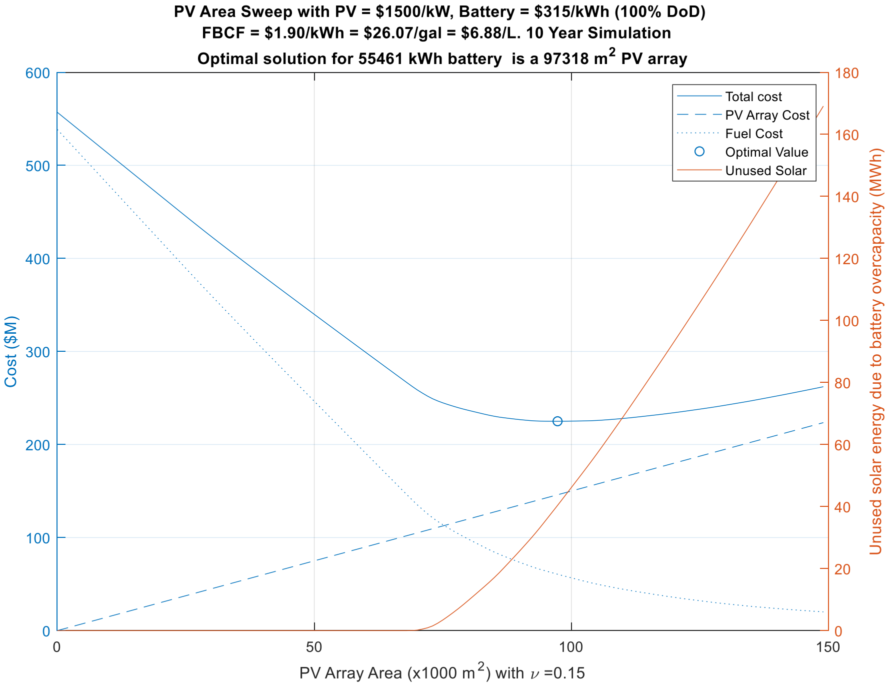

Figure 25. 10-year VRFB Optimal PV Area given Battery Size 55,461 kWh

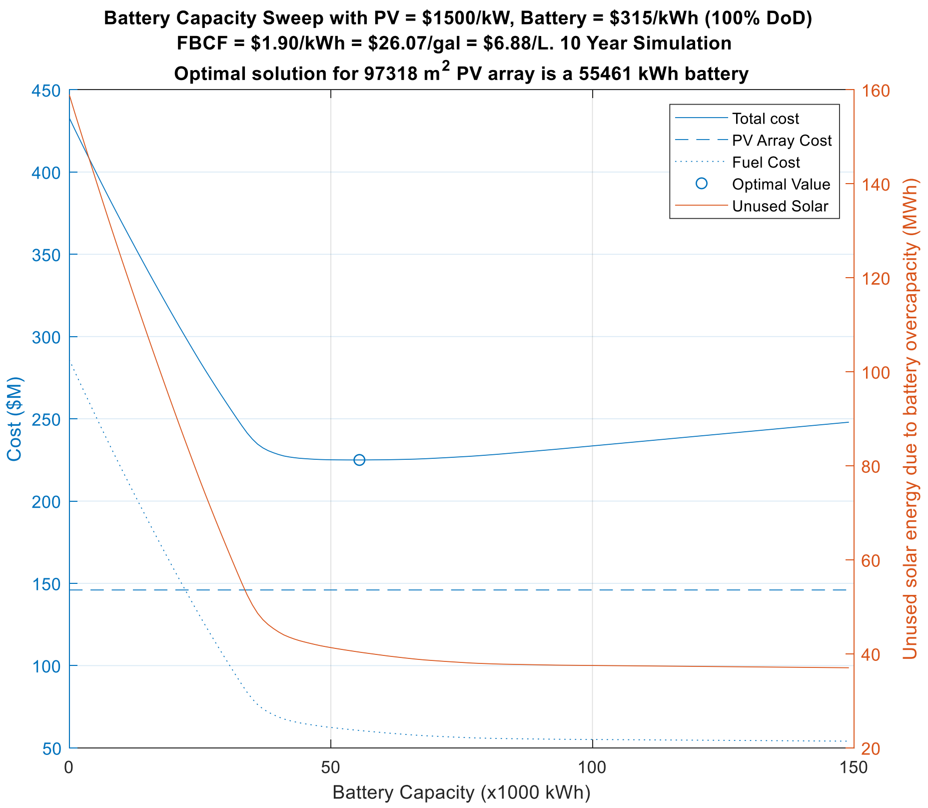

Figure 26. 10-year VRFB Optimal Battery Size given PV Area of 97,318 m^2

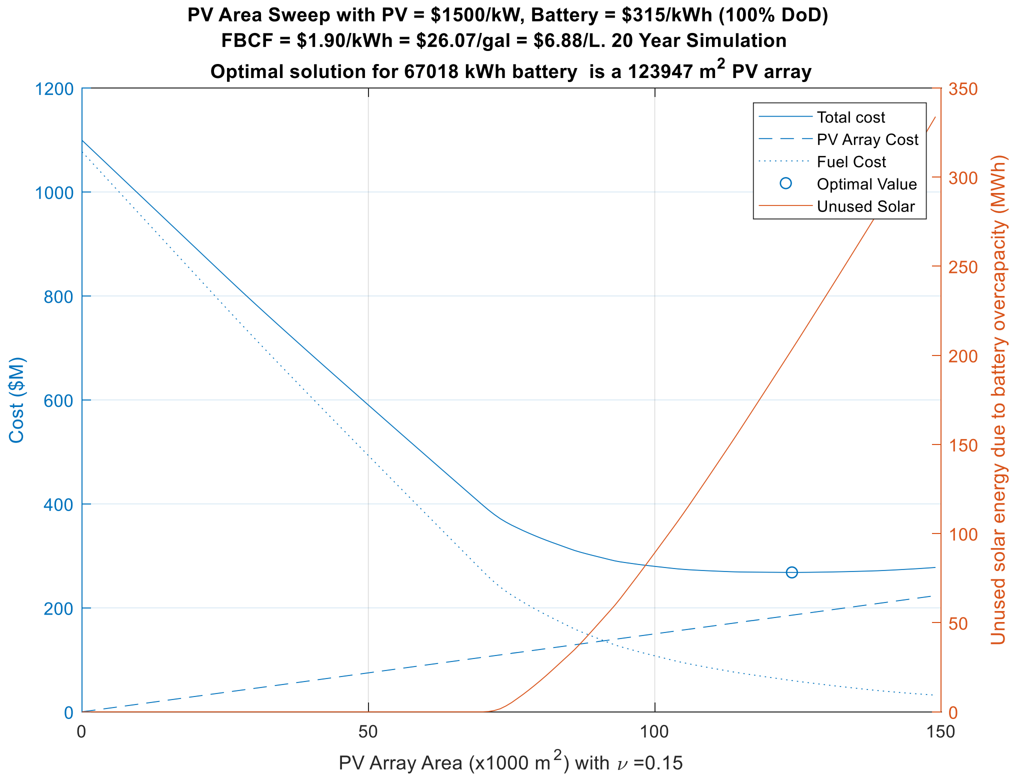

Figure 27. 20-year VRFB Optimal PV Area given Battery Size 67,018 kWh

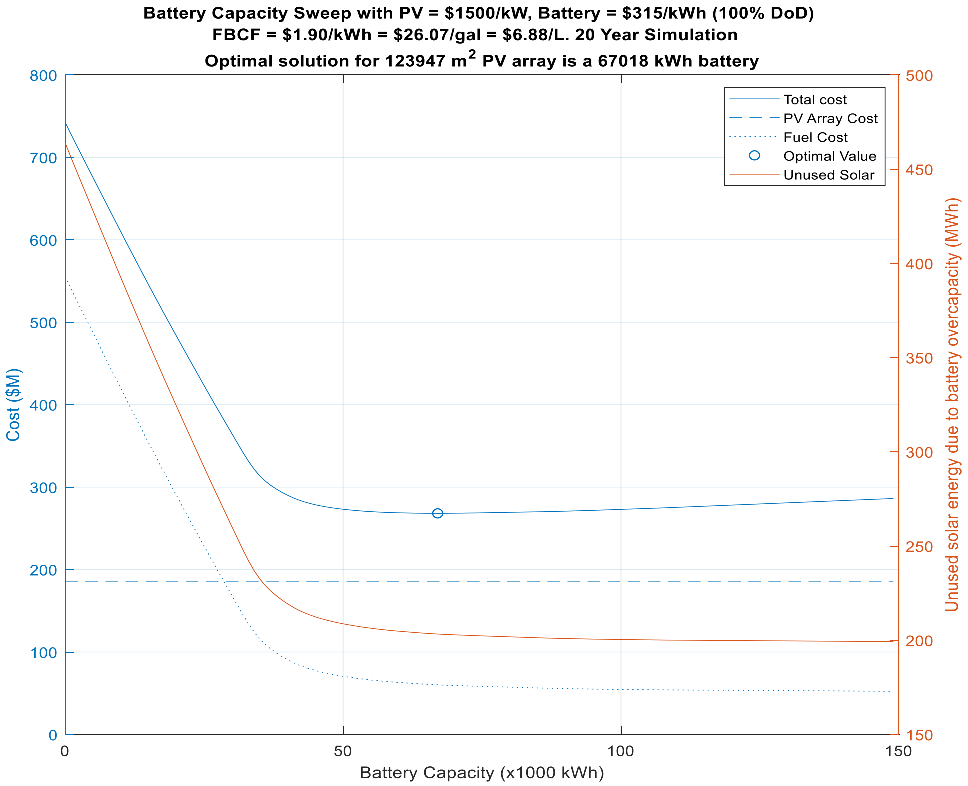

Figure 28. 20-year VRFB Optimal Battery Size given PV Area of 123,947 m^2

Li-Ion Optimization Results

The first pass looks at all five-year models when varying FBCF, efficiency, and $/kWh. As seen in Figures 29-32, all four models share a common battery size of 40 MWh and an array area of 70,000 m^2. These will be the starting values for the fixed PV area and fixed battery models. Figure 31 shows the minimal optimal size was for high battery cost and low FBCF. The results show the minimum is a 7 MWh battery with a 42,900 m^2 PV area. The low battery cost and high FBCF results show the maximum optimal size is a 130 MWh battery with a 100,000 m^2 PV area.

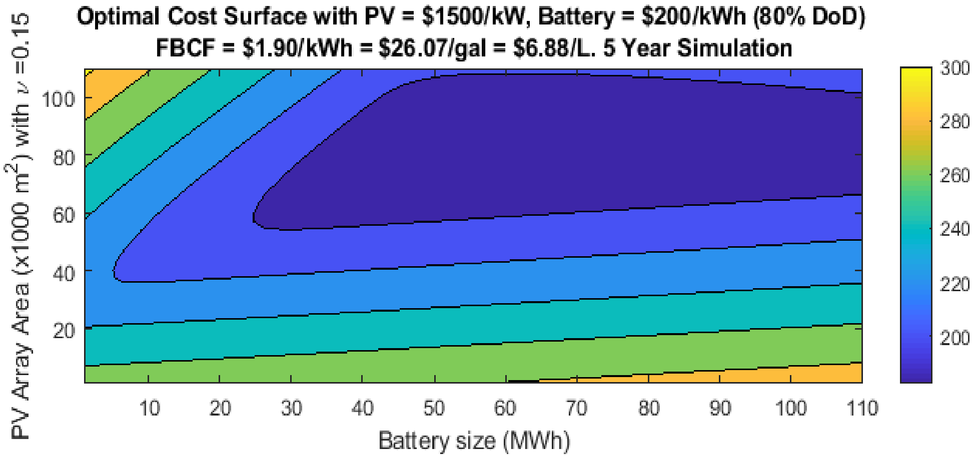

Figure 29. Li-Ion Cost Surface Low FBCF – Low $/kWh

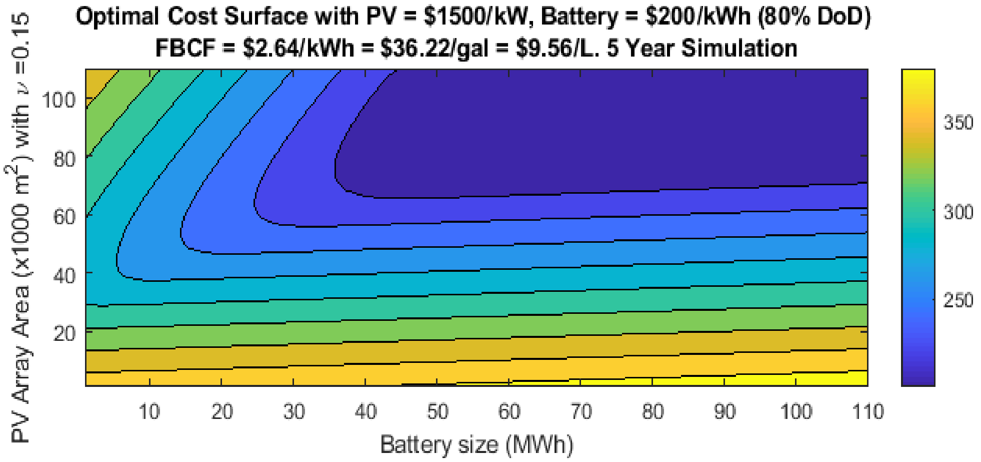

Figure 30. Li-Ion Cost Surface High FBCF – Low $/kWh

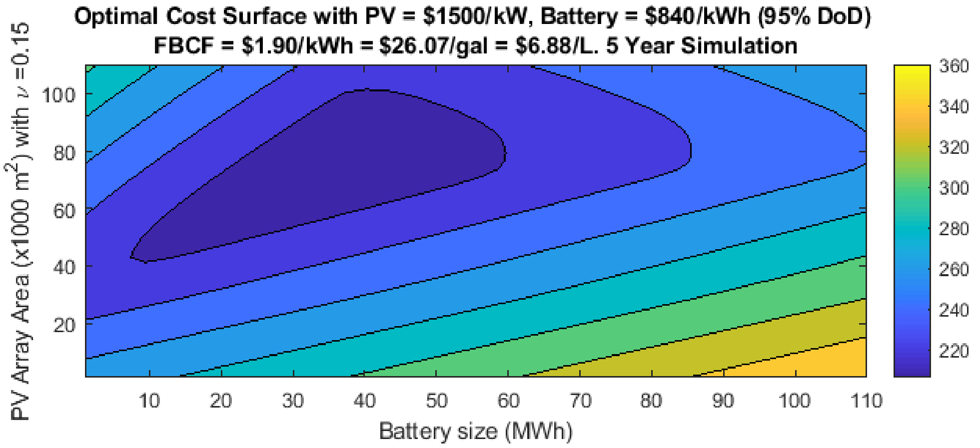

Figure 31. Li-Ion Cost Surface Low FBCF – High $/kWh

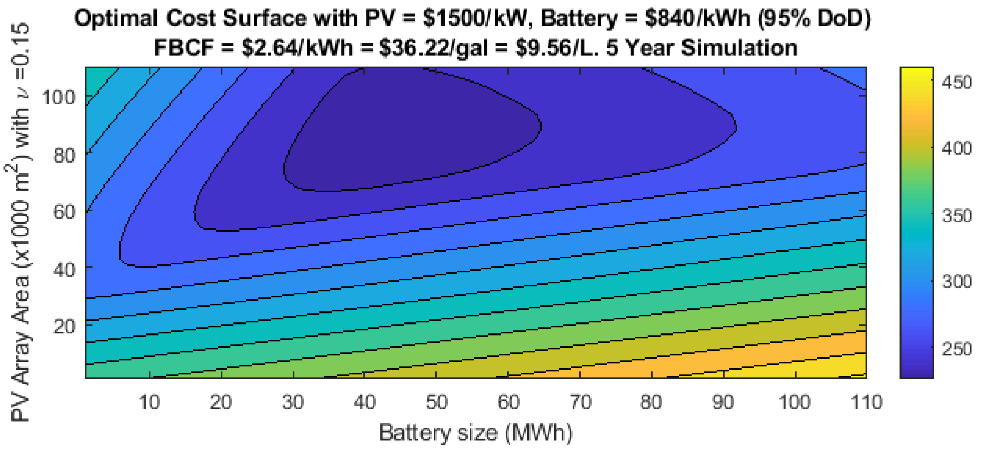

Figure 32. Li-Ion Cost Surface High FBCF – High $/kWh

After modeling 10 and 20 years and comparing the results, a trend begins to show that Li-Ion battery systems are optimal, for an 1100-person FOB, at a battery size between 30 MWh and 90 MWh. The photovoltaic area is optimal for an area between 60,000 m^2 and 100,000 m^2.

The optimal sizes of each system and their cost for 5, 10, and 20 years are summarized in Table 15. Figures 33-38 show the optimal PV-Battery size outputs from MATLAB.

Table 15. Li-Ion Optimal PV-Battery Size for 5, 10, & 20 years

Life-cycle (years)	Battery Size (kWh)	PV Area (m^2)	Total Cost	System Cost per year
5	48,730	77,475	$181.4M	$36.3M
10	75,312	97,147	$219.8M	$22.0M
20	84,015	124,983	$262.3M	$13.1M

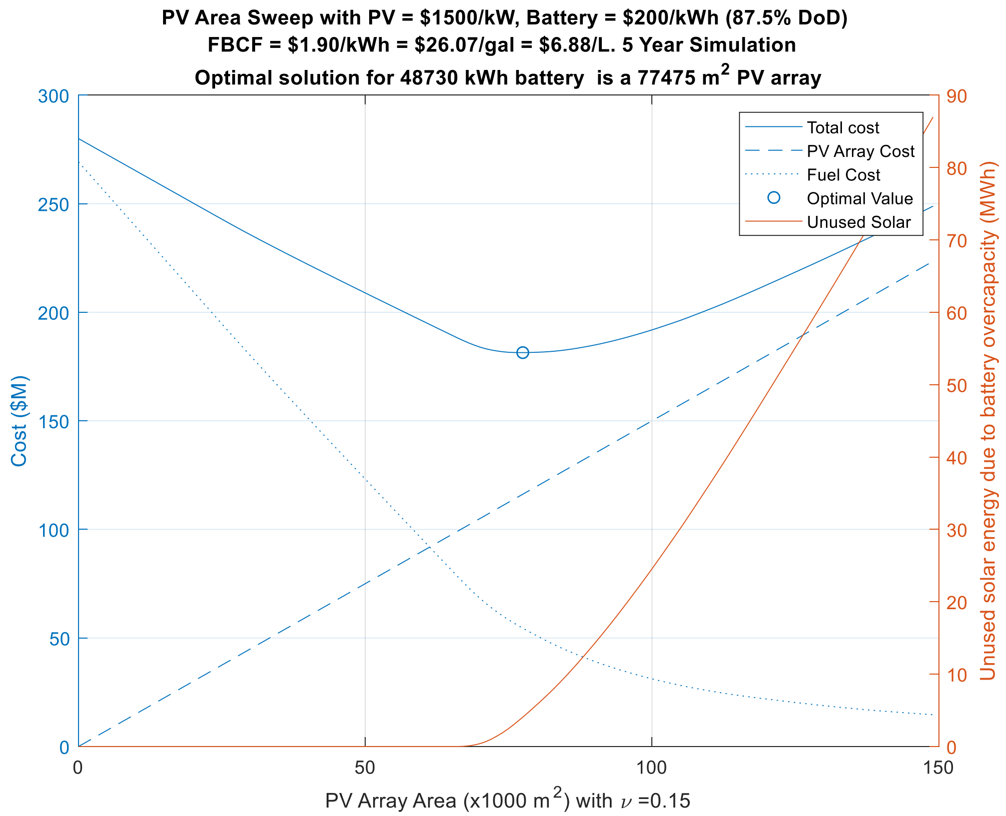

Figure 33. 5-year Li-Ion Optimal PV Area given Battery Size 48,730 kWh

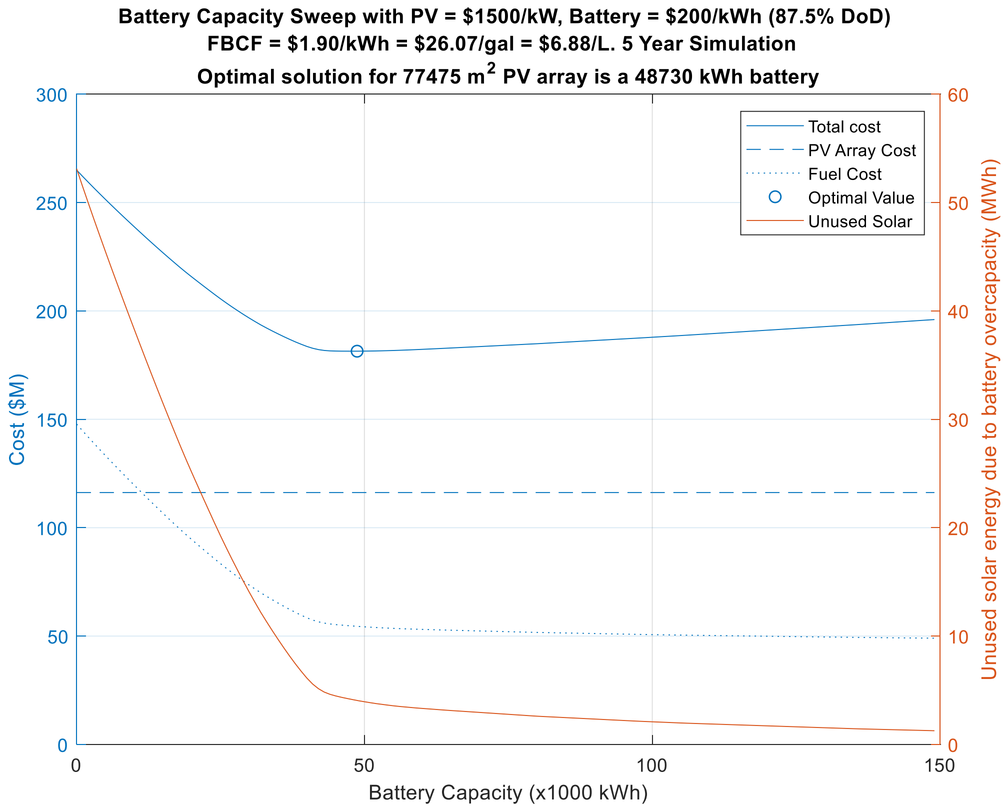

Figure 34. 5-year Li-Ion Optimal Battery Size given PV Area of 77,475 m^2

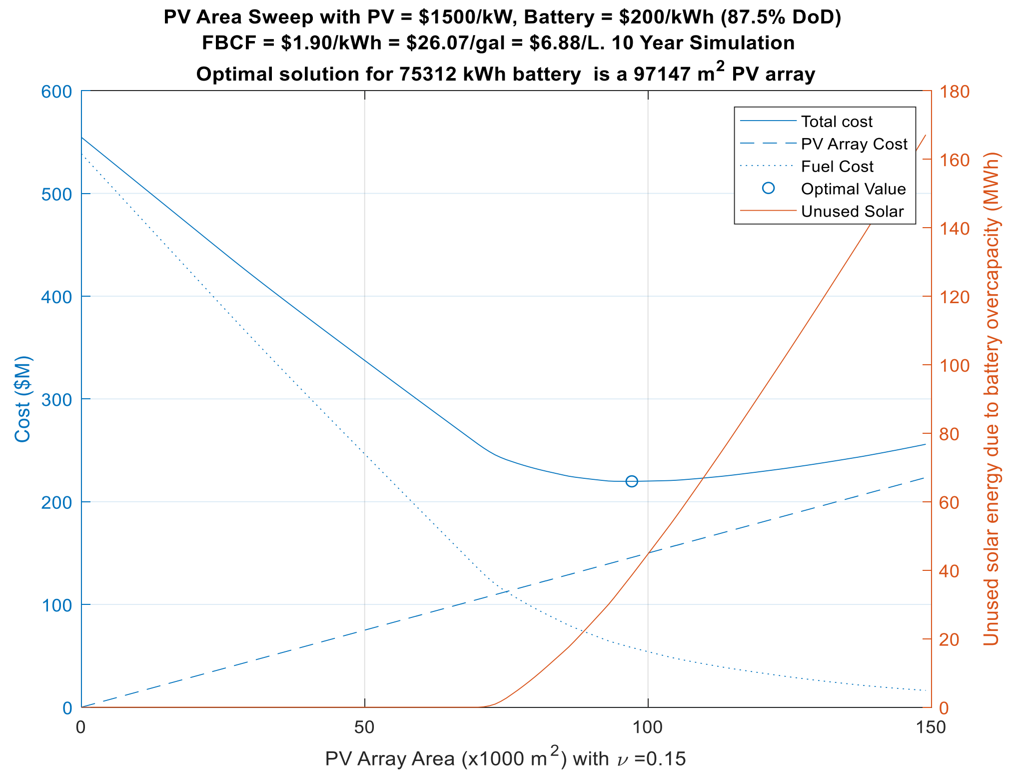

Figure 35. 10-year Li-Ion Optimal PV Area given Battery Size 75,312 kWh

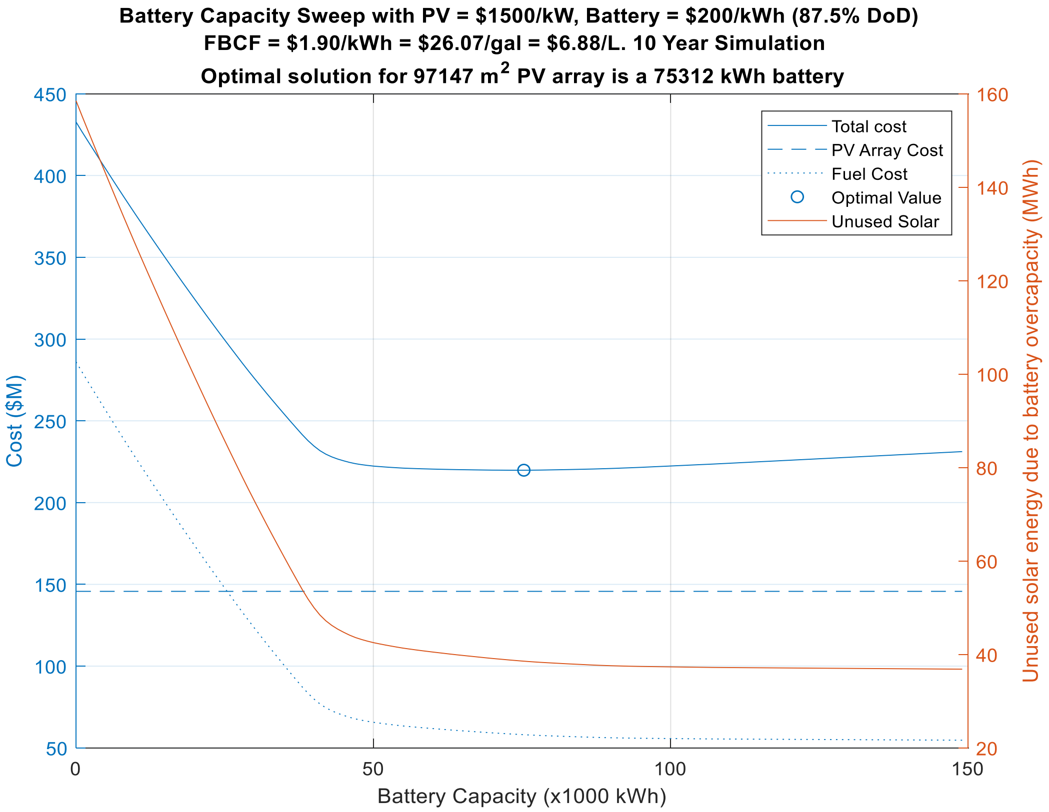

Figure 36. 10-year Li-Ion Optimal Battery Size given PV Area of 97,147 m^2

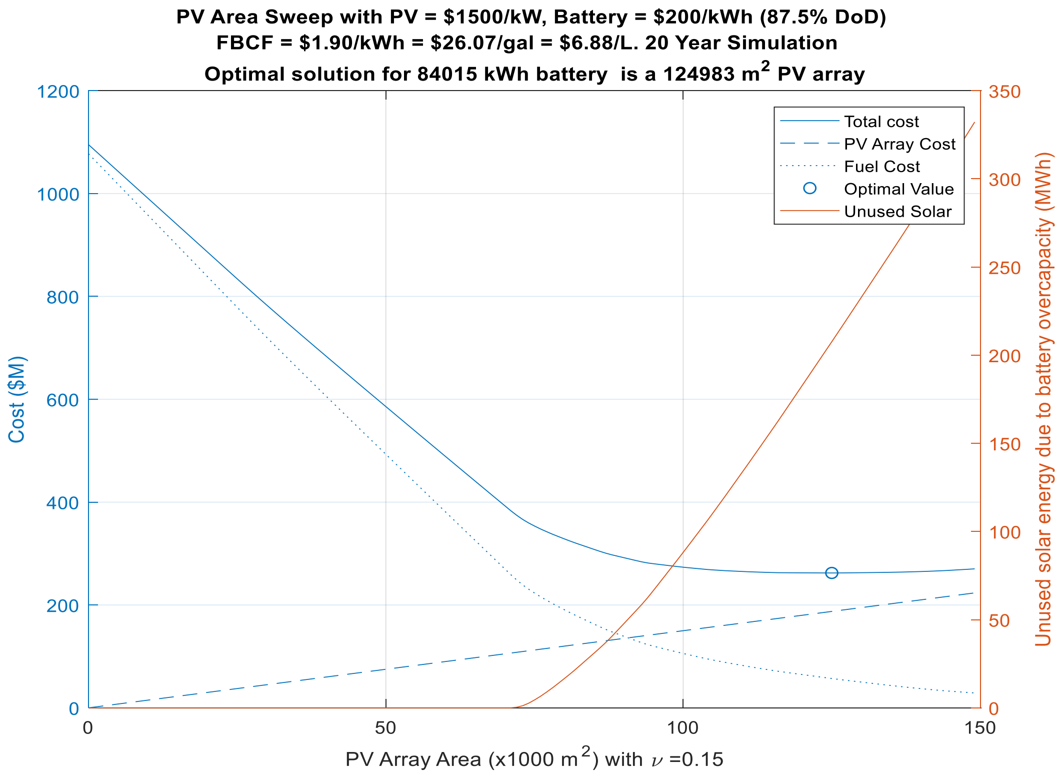

Figure 37. 20-year Li-Ion Optimal PV Area given Battery Size 84,015 kWh

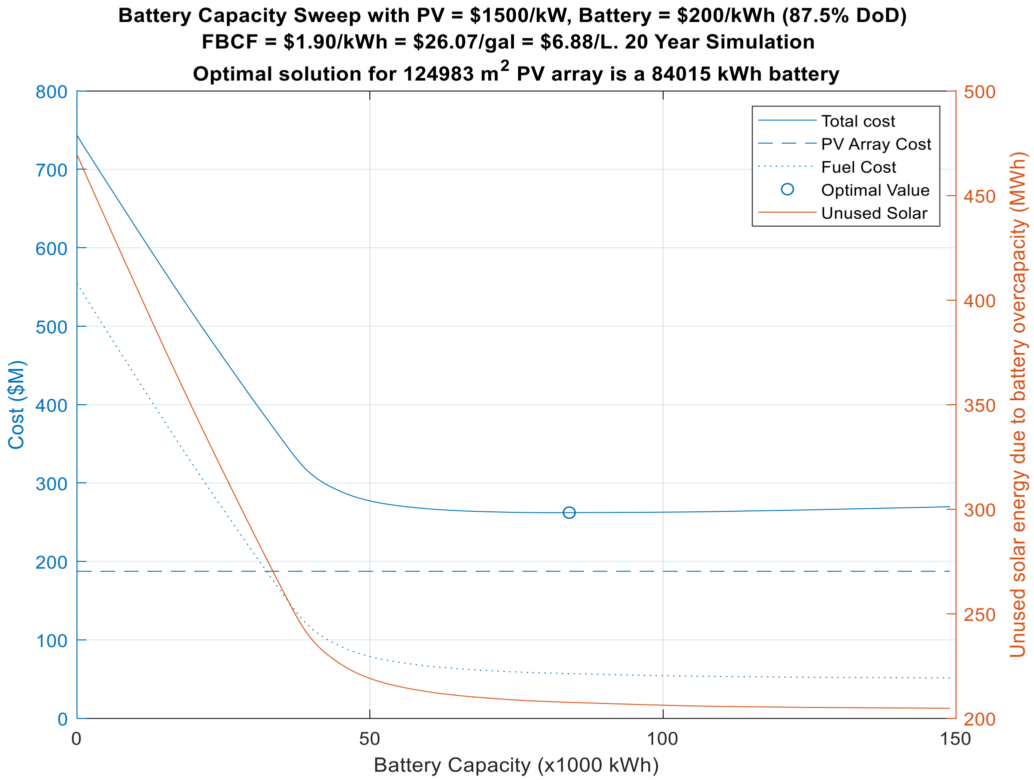

Figure 38. 20-year Li-Ion Optimal Battery Size given PV Area of 124,983 m^2

Lead-acid Optimization Results

The first pass looks at all five-year models when varying FBCF, efficiency, and \$/kWh. As seen in Figures 39-42, all four models share a common battery size of 93 MWh and an array area of 90,000 m^2. These will be the starting values for the fixed PV area and fixed battery models. Figure 41 shows the minimal optimal size was for high battery cost and low FBCF. The results show the minimum is an 11.2 MWh battery with a 41,900 m^2 PV area. The low battery cost and low FBCF results show the maximum optimal size is a 220 MWh battery with an 82,000 m^2 PV area.

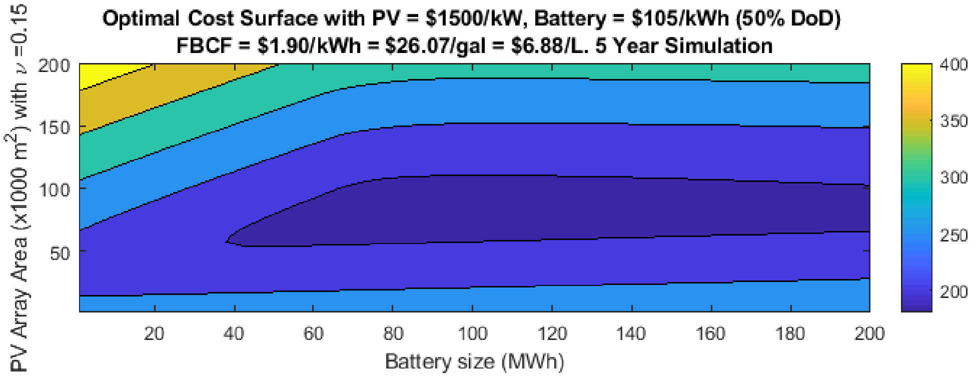

Figure 39. Lead-acid Cost Surface Low FBCF – Low \$/kWh

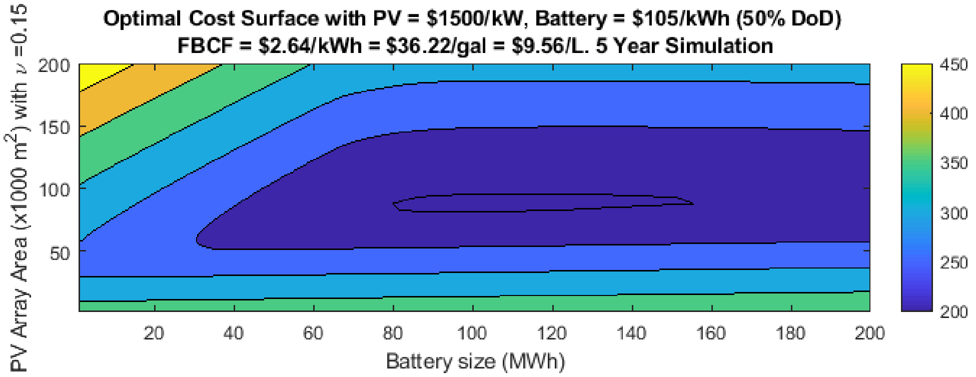

Figure 40. Lead-acid Cost Surface High FBCF – Low \$/kWh

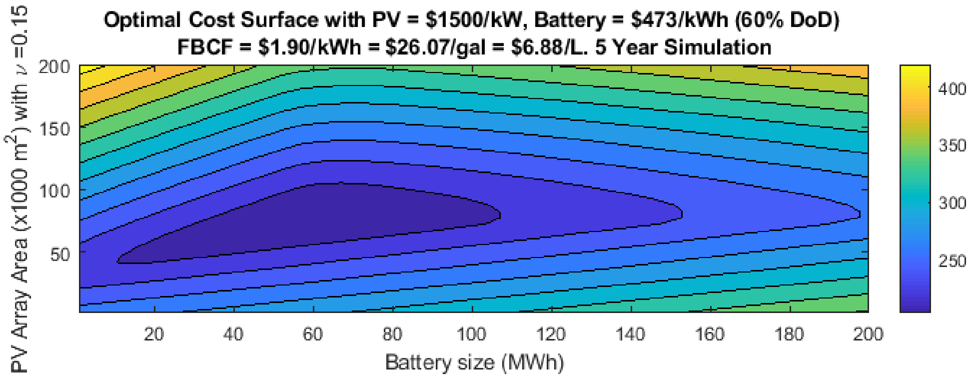

Figure 41. Lead-acid Cost Surface Low FBCF – High $/kWh

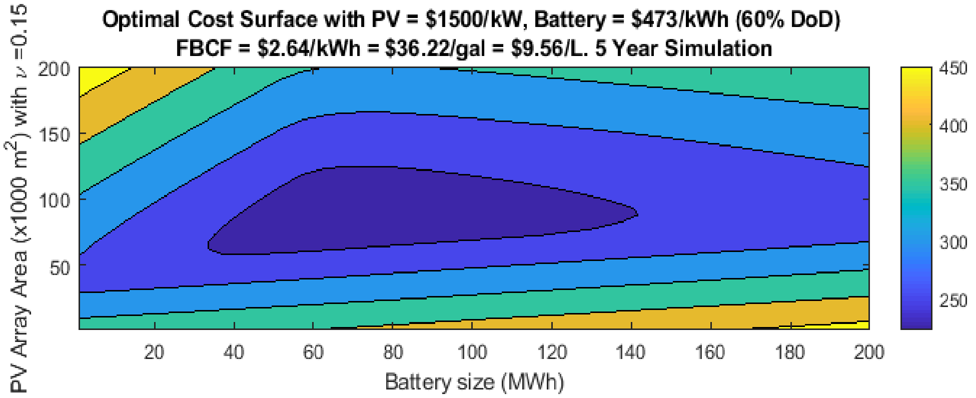

Figure 42. Lead-acid Cost Surface High FBCF – High $/kWh

After modeling 10 and 20 years and comparing the results, a trend begins to show that Lead-acid battery systems are optimal, for an 1100-person FOB, at a battery size between 80 MWh and 200 MWh. The photovoltaic area is optimal for an area of 80,000 m^2 to 130,000 m^2.

The optimal sizes of each system and their cost for 5, 10, and 20 years are summarized in Table 16. Figures 43-48 show the optimal PV-Battery size outputs from MATLAB.

Table 16. Lead-acid Optimal PV-Battery Size for 5, 10, & 20 years

Life-cycle (years)	Battery Size (kWh)	PV Area (m^2)	Total Cost	System Cost per year
5	75,163	77,475	$179.9M	$36.0M
10	115,449	96,141	$216.2M	$21.6M
20	142,134	124,983	$259.5M	$13.0M

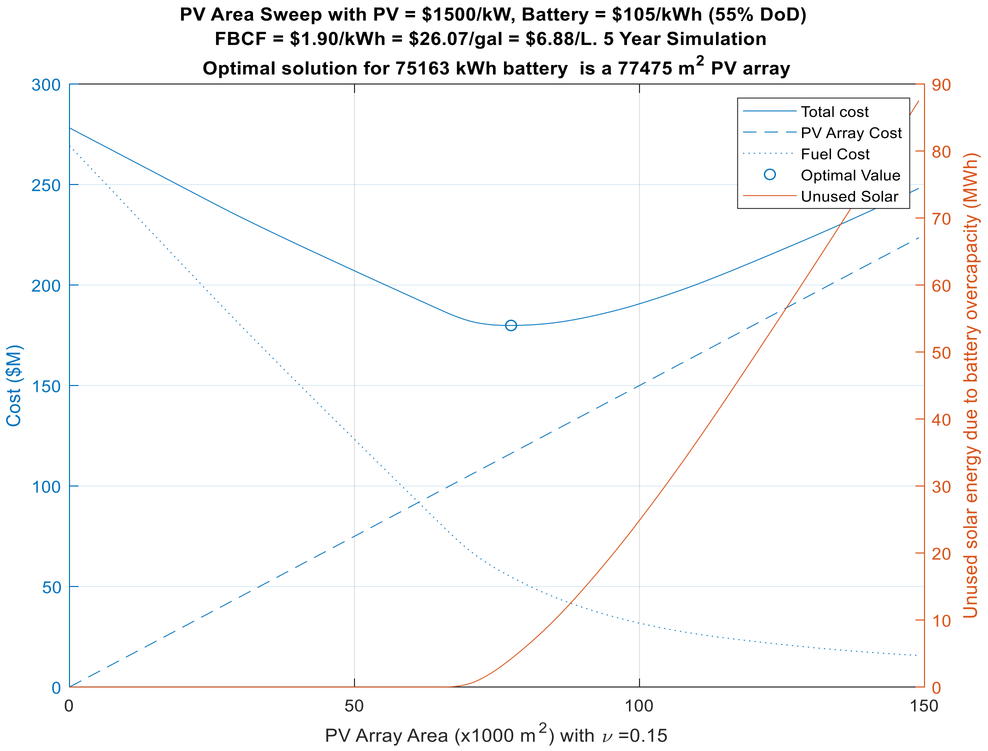

Figure 43. 5-year Lead-acid Optimal PV Area given Battery Size 75,163 kWh

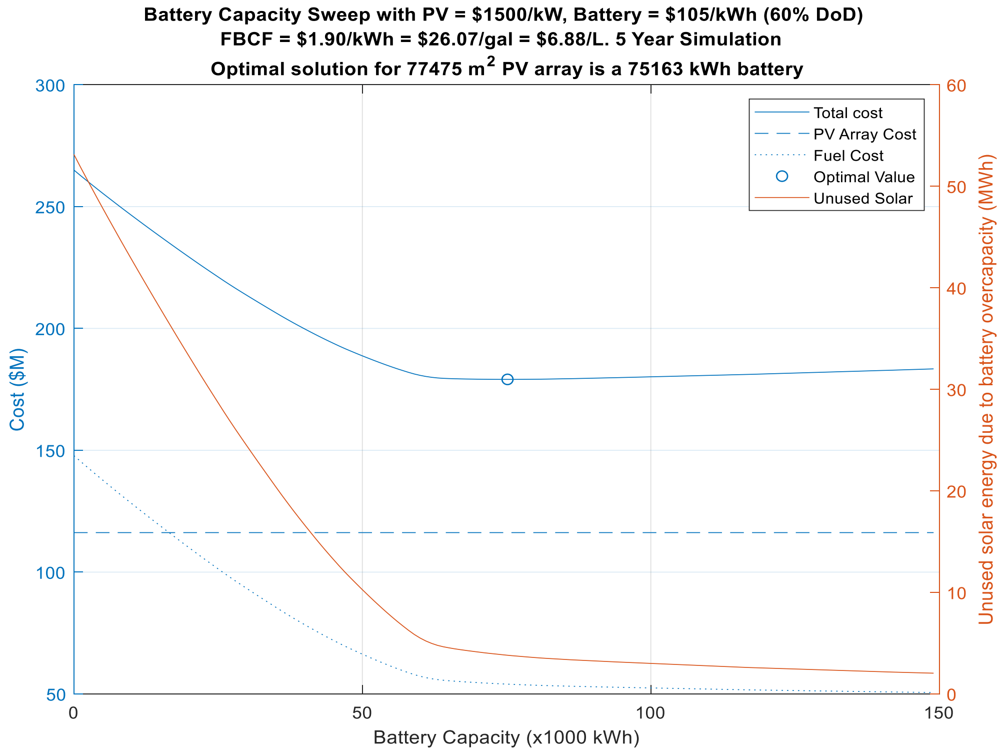

Figure 44. 5-year Lead-acid Optimal Battery Size given PV Area of 77,745 m^2

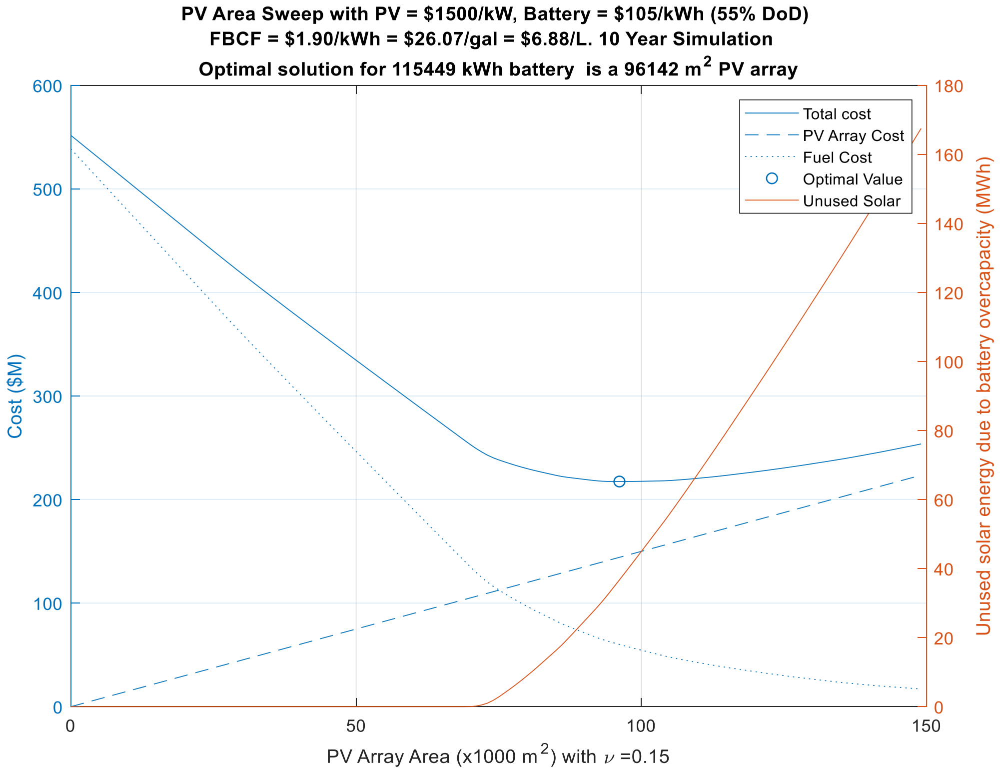

Figure 45. 10-year Lead-acid Optimal PV Area given Battery Size 115,449 kWh

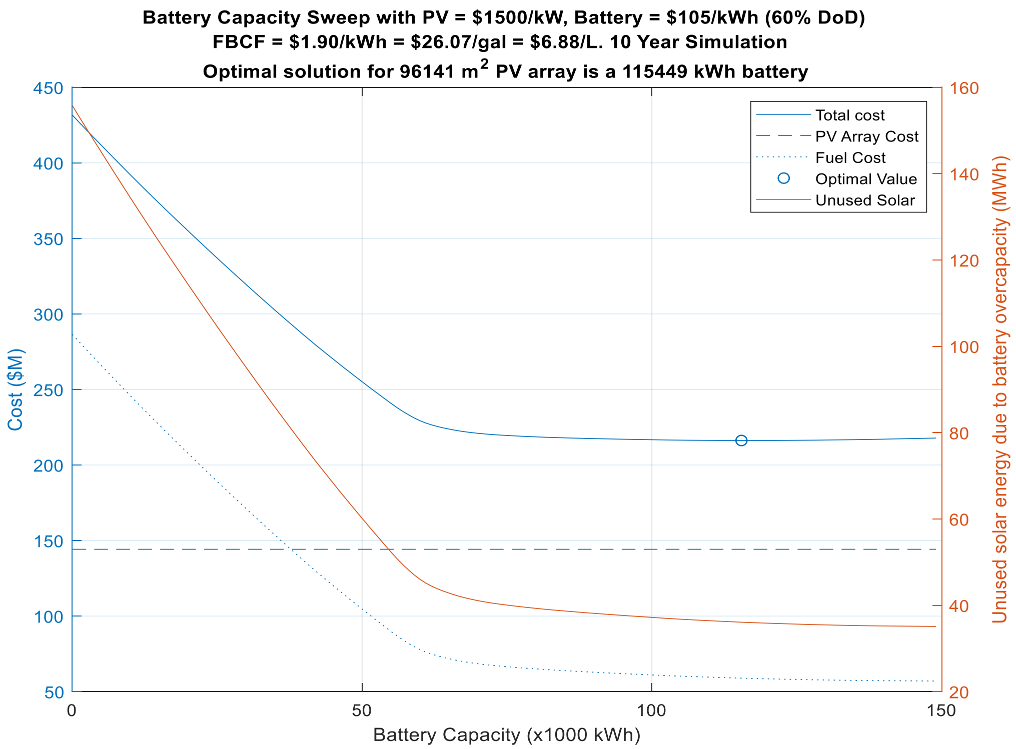

Figure 46. 10-year Lead-acid Optimal Battery Size given PV Area of 96,141 m^2

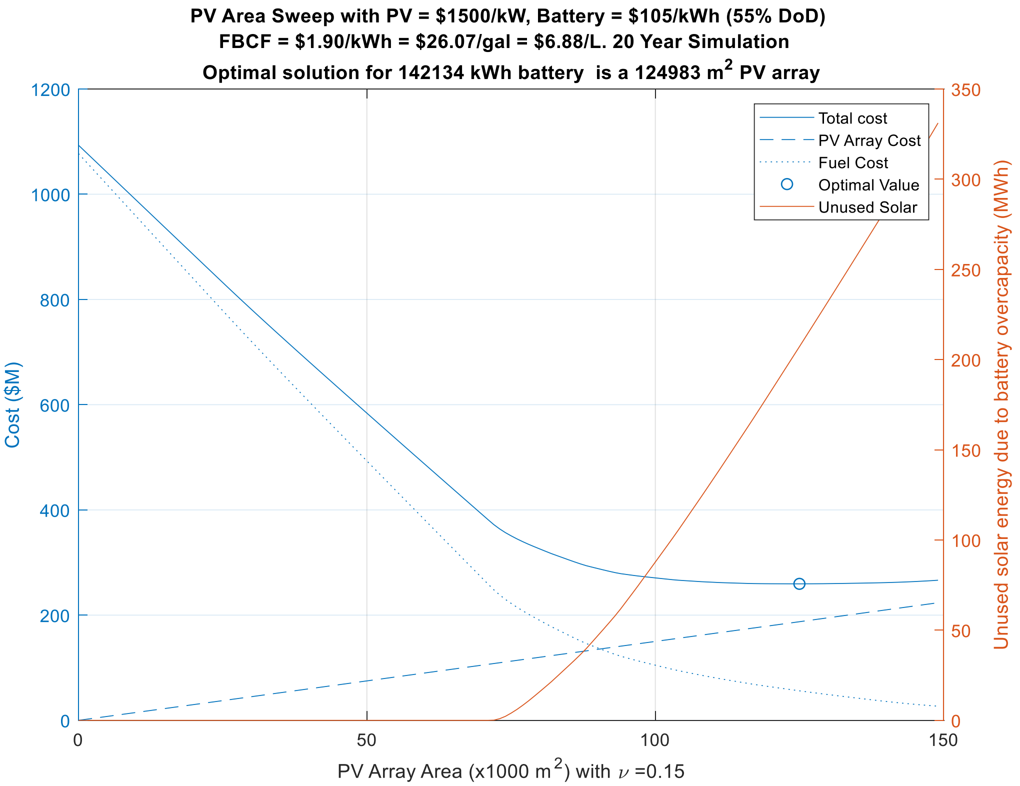

Figure 47. 20-year Lead-acid Optimal PV Area given Battery Size 142,134 kWh

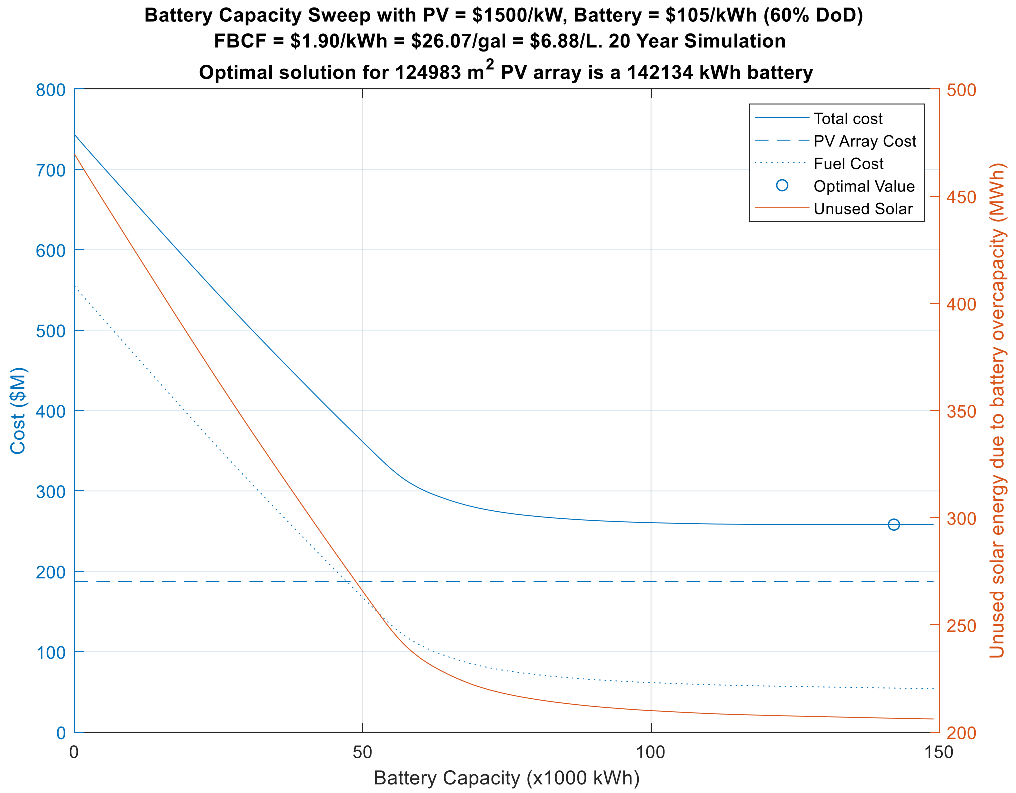

Figure 48. 20-year Lead-acid Optimal Battery Size given PV Area of 124,983 m^2

Additional Analysis of the Photovoltaic (PV)-Battery Systems

All PV-battery systems trend towards larger PV areas and bigger batteries as time increases. This is most likely because diesel fuel is the most expensive component of the diesel generator system. As time increases, diesel fuel costs increase rapidly, making larger PV areas and bigger batteries optimal. Figures 49-51 shows how the optimal battery size and photovoltaic area output increase for VRFB as the time the asset is required increases. The figures also show that the optimal area shifts and expands in size with respect to time.

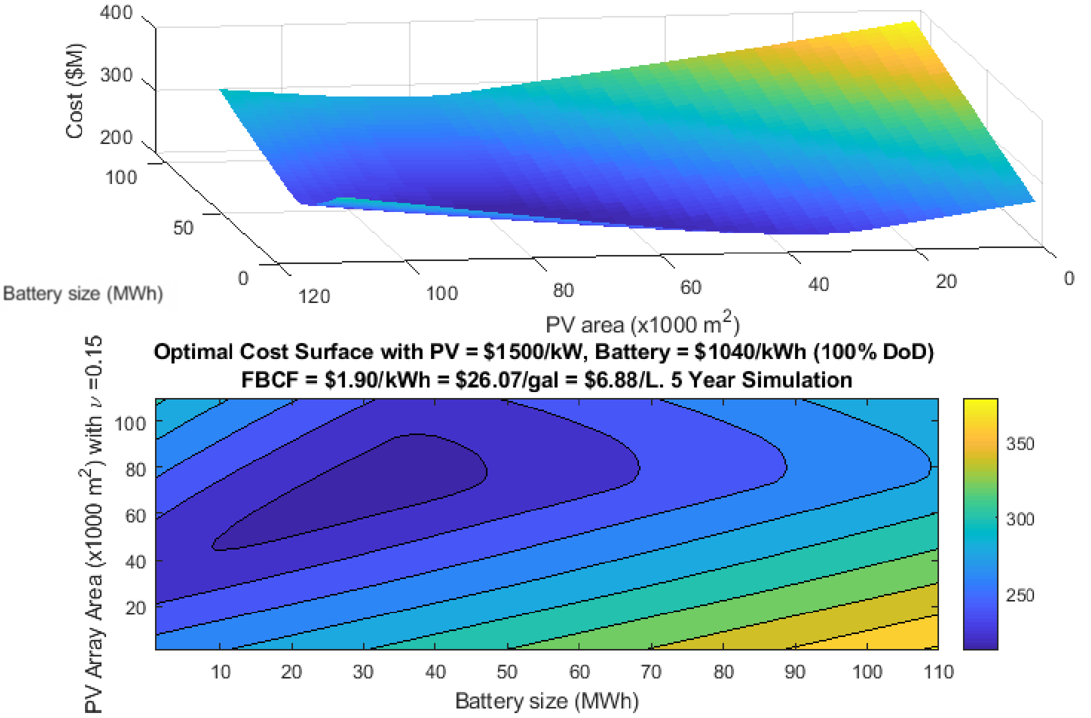

Figure 49. 5-year Cost Surface for VRFB

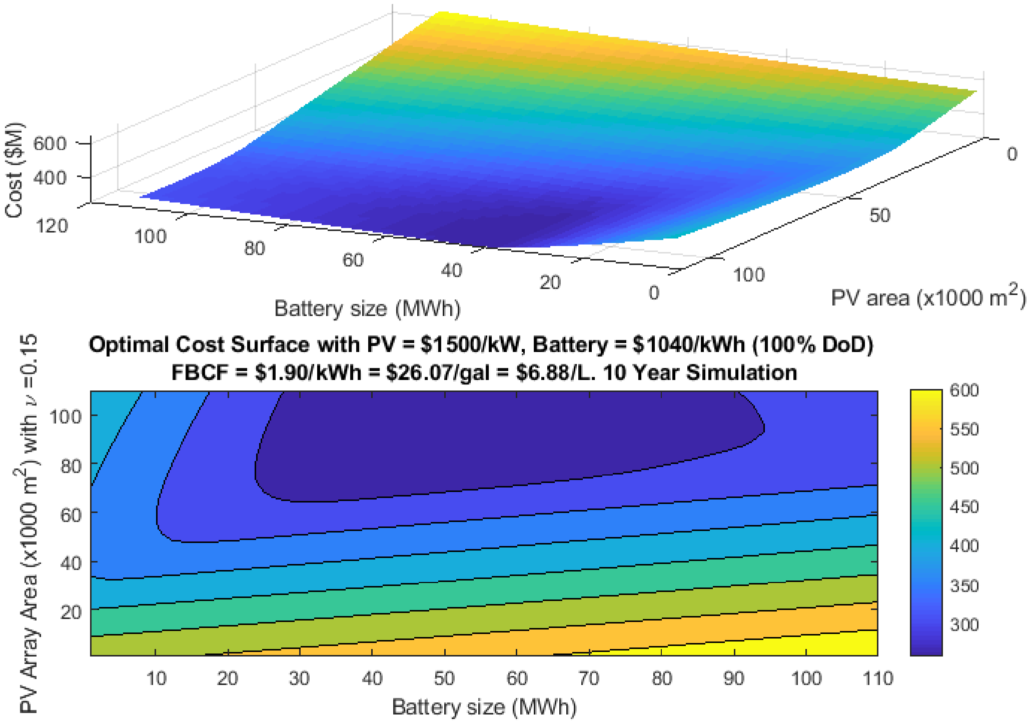

Figure 50. 10-year Cost Surface for VRFB

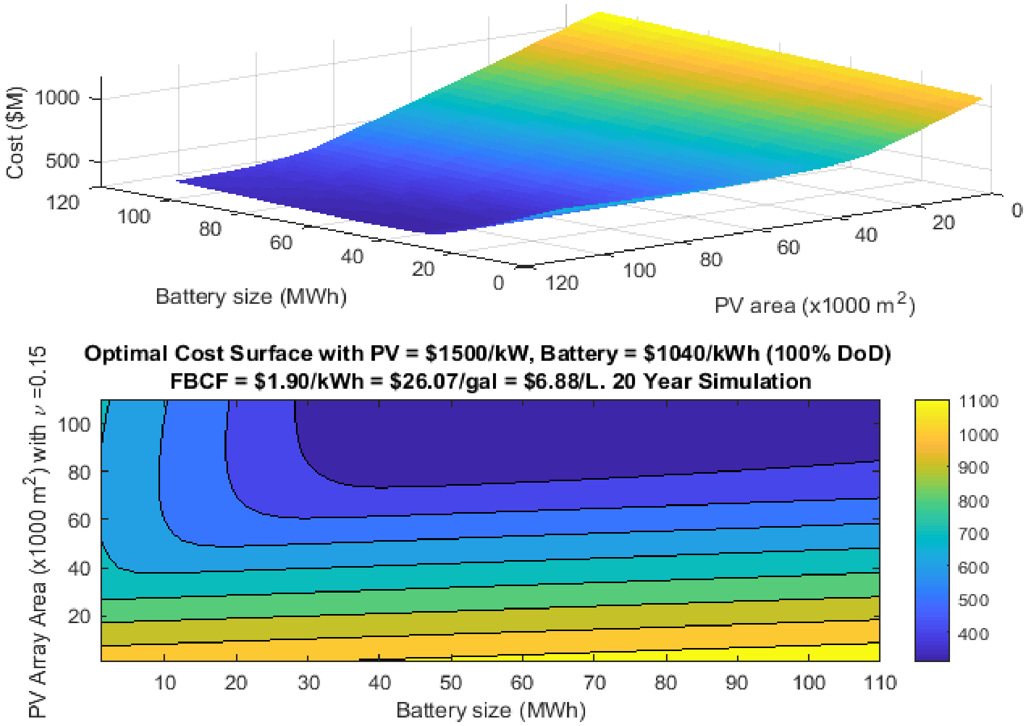

Figure 51. 20-year Cost Surface for VRFB

Replacement time is another factor to consider when investigating different battery systems. Its impact could be minimal on the overall system dollar per kilowatt-hour. The logistics portion may increase the life-cycle cost and optimal solution for size. At the end of the asset's life, removal and recycling may also increase the final cost or create a hazardous waste situation.

VRFB batteries can last up to 20 years without replacement [24]. Li-Ion batteries usually last up to 10 years [8], [24]. Lead-acid batteries need to be replaced as early as three years [24]. Diesel generators, utilized as prime power, do not last longer than five years. As back-up power, they can be replaced every 10 years. The life-cycle depends on how deep each discharge cycle is, how often the battery discharges, how many cycles the typical battery is rated for, and the temperatures at which the battery consistently operates. Photovoltaics have more reliability, and many manufacturers guarantee a 10 to 20-year warranty on their products [56]. The overall cost of the system may be impacted by these replacement times.

Table 17 defines the replacements required for the Alpha FOB. Assuming temperature is not a factor, then the expected yearly usage is estimated at a little more than once per day for VRFB, given its long discharge cycles—up to 10 hrs. The expected yearly usage for Li-Ion and Lead-acid are an average of 1.5 times a day because of their shorter discharge cycles—4 hrs. Diesel generators will only be used if the load cannot be supported by the PV-battery network, so this usage is expected to be less than once every two days. Lead-acid batteries were minimized to three-year replacements despite the very low average cycle count supporting replacement between 1.5 and 2 years.

Table 17. Component Replacement Time and Number of Replacement Cycles for Alpha FOB

System	Expected Yearly usage	Average Cycle Count	Expected Life (yrs)	# of replacement cycles for 5 years	# of replacement cycles for 10 years	# of replacement cycles for 20 years
VRFB	400	13,000	20	0	0	0
Li-Ion	550	5,950	12	0	0	1
Lead Acid	550	900	3	1	3	6
Diesel Generators	150	7500	10	0	0	0
PV	▨	▨	20	0	0	0

The Operations and Maintenance expense as well as the salvage value expected for these systems are shown in Table 18. Example calculations are shown in Appendix A. VRFB and Li-Ion metrics are derived from estimated parameters. The salvage value for the batteries includes the additional replacements.

Table 18. Expected O&M Costs and Salvage Values

Optimal VRFB-PV	PV O&M Cost per year	Battery O&M Costs per year	PV Salvage Value per system	Battery Salvage Value per system
5-year	$1.3M	$868k	-$15.4M	-$4.6M
10-year	$1.6M	$1.3M	-$19.4M	-$6.5M
20-year	$2.1M	$1.5M	-$25.4M	-$7.8M
Optimal Li-Ion-PV				
5-year	$1.3M	$294k	-$15.4M	-$2.1M
10-year	$1.6M	$453k	-$19.4M	-$3.3M
20-year	$2.1M	$504k	-$25.4M	-$3.6M
Optimal Lead-Acid-PV				
5-year	$1.3M	$158k	-$15.4M	-$616k
10-year	$1.6M	$242k	-$19.4M	-$946k
20-year	$2.1M	$298k	-$25.4M	-$1.2M

Logistics Analysis

The total weight of each optimal photovoltaic-battery system for 5, 10, and 20 years is summarized in Tables 19-21. These numbers were integrated into the logistics model for transportation costs to Alpha FOB. For all three battery systems and the photovoltaics, a typical 40 ft CONEX box will reach the maximum weight before the maximum volume is reached. This means that the total weight controls the cost of transporting the PV-battery system, not the volume.

Table 19. Five-Year PV and Battery Optimal Solution Weight and Volume

	Total PV Weight (kg)	Total Battery Weight (kg)	Total System Weight (kg)	Total Battery Volume (L)
VRFB	1,708,000	1,964,000	3,672,000	925,000
Li-Ion	1,708,000	342,000	2,050,000	160,000
Lead-acid	1,708,000	2,148,000	3,855,000	1,009,000

Table 20. 10-Year PV and Battery Optimal Solution Weight and Volume

	Total PV Weight (kg)	Total Battery Weight (kg)	Total System Weight (kg)	Total Battery Volume (L)
VRFB	2,145,000	2,773,000	4,918,000	1,305,000
Li-Ion	2,141,000	529,000	2,670,000	247,000
Lead-acid	2,119,000	3,299,000	5,417,000	1,550,000

Table 21. 20-Year PV and Battery Optimal Solution Weight and Volume

	Total PV Weight (kg)	Total Battery Weight (kg)	Total System Weight (kg)	Total Battery Volume (L)
VRFB	2,732,000	3,351,000	6,083,000	1,577,000
Li-Ion	2,755,000	590,000	3,344,000	275,000
Lead-acid	2,755,000	4,061,000	6,816,000	1,908,000

The next step was to determine the transportation cost for each combination described in Chapter III. Sealift calculations were completed as project cargo/heavy lift [68]. The ground transportation assumes that the assets can be locally procured. The combinations are:

-Military airlift direct from Holloman to Alpha FOB
-Sealift to Port Mina Salman, Bahrain
    - Military airlift to Alpha FOB
    - Ground transport to Alpha FOB

Table 22 to 24 show the transportation results for each of these scenarios. The transportation cost in the table accounts for a single trip. Transportation expenses are repeated for battery systems that require replacements within the expected life-cycle. For example, Li-Ion requires a replacement after 12 years. The total transportation cost includes the initial $6.7M, then adds $820k for transporting the new assets at 12 years, and finally adds $657k for removal of the assets at 20 years.

The route to Alpha FOB from Bahrain is shown in Figure 52. Airlift directly from Holloman AFB to the Alpha FOB is roughly 20 hours. Airlift from Bahrain to the Alpha FOB is roughly 1.5 hours. The ground route traverses several countries and it is roughly 909 km in length. Both ground vehicles average approximately 30 mph when fully loaded. Appendix A shows example calculations used for the ground transportation. The total transportation cost includes the summation of the minimal value of either airframe and either ground vehicle. Typically, the C17 and M1070A1 have minimal costs compared to the C5 and MKR-18, respectively.

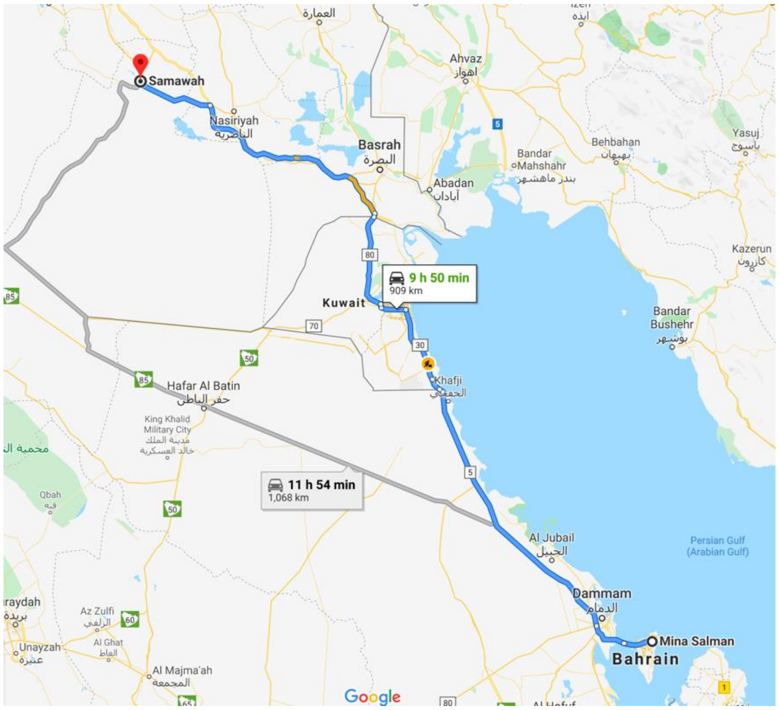

Figure 52. Route Mina Salman, Bahrain to Alpha FOB [87]

Table 22. Route Total Transportation Costs Optimization Direct Flight from Holloman AFB to Alpha FOB

	VRFB			Li-Ion			Lead-Acid		
C17	5	10	20	5	10	20	5	10	20
Cost to transport Battery	$24,763,440	$34,287,840	$41,907,360	$4,762,200	$6,667,080	$7,619,520	$26,668,320	$40,954,920	$50,479,320
Cost to transport PV	$21,906,120	$26,668,320	$34,287,840	$21,906,120	$26,668,320	$34,287,840	$21,906,120	$26,668,320	$34,287,840
C5									
Cost to transport Battery	$50,443,520	$69,359,840	$85,123,440	$9,458,160	$15,763,600	$15,763,600	$53,596,240	$81,970,720	$100,887,040
Cost to transport PV	$44,138,080	$53,596,240	$69,359,840	$44,138,080	$53,596,240	$69,359,840	$44,138,080	$53,596,240	$69,359,840
MKR-18									
Cost to transport Battery	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cost to transport PV	$0	$0	$0	$0	$0	$0	$0	$0	$0
M1070A1									
Cost to transport Battery	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cost to transport PV	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cargo Ship: Los Angeles to Mina									
Cost to transport Battery	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cost to transport PV	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Transportation Cost	$46,669,560	$60,956,160	$76,195,200	$26,668,320	$33,335,400	$41,907,360	$48,574,440	$67,623,240	$84,767,160

Table 23. Route Total Transportation Costs Optimization Ship to Bahrain, then airlift to Alpha FOB

	VRFB			Li-Ion			Lead-Acid		
C17	5	10	20	5	10	20	5	10	20
Cost to transport Battery	$1,857,258	$2,571,588	$3,143,052	$357,165	$500,031	$571,464	$2,000,124	$3,071,619	$3,785,949
Cost to transport PV	$1,642,959	$2,000,124	$2,571,588	$1,642,959	$2,000,124	$2,571,588	$1,642,959	$2,000,124	$2,571,588
C5									
Cost to transport Battery	$3,783,264	$5,201,988	$6,384,258	$709,362	$1,182,270	$1,182,270	$4,019,718	$6,147,804	$7,566,528
Cost to transport PV	$3,310,356	$4,019,718	$5,201,988	$3,310,356	$4,019,718	$5,201,988	$3,310,356	$4,019,718	$5,201,988
MKR-18									
Cost to transport Battery	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cost to transport PV	$0	$0	$0	$0	$0	$0	$0	$0	$0
M1070A1									
Cost to transport Battery	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cost to transport PV	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cargo Ship: Los Angeles to Mina									
Cost to transport Battery	$694,537	$980,393	$1,180,346	$322,293	$495,806	$551,921	$610,864	$934,307	$1,150,348
Cost to transport PV	$3,339,572	$4,209,241	$5,500,761	$3,339,572	$4,208,533	$5,505,051	$3,339,572	$4,204,367	$5,505,051
Total Transportation Cost	$7,534,326	$9,761,346	$12,395,747	$5,661,989	$7,204,494	$9,200,024	$7,593,519	$10,210,417	$13,012,936

Table 24. Route Total Transportation Costs Optimization Ship to Bahrain, then ground transport to Alpha FOB

	VRFB			Li-Ion			Lead-Acid		
C17	5	10	20	5	10	20	5	10	20
Cost to transport Battery	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cost to transport PV	$0	$0	$0	$0	$0	$0	$0	$0	$0
C5									
Cost to transport Battery	$0	$0	$0	$0	$0	$0	$0	$0	$0
Cost to transport PV	$0	$0	$0	$0	$0	$0	$0	$0	$0
MKR-18									
Cost to transport Battery	$829,350	$1,162,800	$1,410,750	$145,350	$222,300	$247,950	$906,300	$1,385,100	$1,701,450
Cost to transport PV	$718,200	$906,300	$1,145,700	$718,200	$897,750	$1,154,250	$718,200	$889,200	$1,154,250
M1070A1									
Cost to transport Battery	$381,457	$539,302	$657,685	$78,922	$105,230	$118,383	$420,918	$644,531	$789,222
Cost to transport PV	$341,996	$420,918	$539,302	$341,996	$420,918	$539,302	$341,996	$420,918	$539,302
Cargo Ship: Los Angeles to Mina									
Cost to transport Battery	$694,537	$980,393	$1,180,346	$322,293	$495,806	$551,921	$610,864	$934,307	$1,150,348
Cost to transport PV	$3,339,572	$4,209,241	$5,500,761	$3,339,572	$4,208,533	$5,505,051	$3,339,572	$4,204,367	$5,505,051
Total Transportation Cost	$4,757,563	$6,149,854	$7,878,094	$4,082,783	$5,230,487	$6,714,657	$4,713,351	$6,204,124	$7,983,923

The least expensive logistics option for this location is where the assets are shipped from Los Angeles to Bahrain on cargo ships and then transported to the Alpha FOB via M1070A1 ground vehicles. These values will be used in the total cost calculations.

Total System Cost

This section summarizes all costs to determine the equivalent annual cost (EAC) incurred by installing a battery-photovoltaic system on an enduring forward operating base. Figures 53-55 show the cash flow diagrams for the three 20-year battery systems including salvage values. Additional Cash flow diagrams as well as calculations for EAC are included in Appendix A-6–A-24. Tables 25-26 summarize the EAC for both salvage and not salvaged systems over 5, 10, and 20 years. EAC is calculated using an interest rate of 5% to account for inflation.

Li-Ion is the least expensive system with a 20-year EAC of $24.1M/yr. At 20 years, VRFB costs $24.8M/year and Lead-acid costs $28.4M/year. These numbers include a salvage value. Without salvage values, Li-Ion increase system cost to $25.2M/year for 20-years. The diesel generator baseline shown in Figure A-7 depicts a 20-year system costing $106.2M/year. This number assumes an average 1250 kW generator consumes approximately 72 gallons of fuel per hour. Lead-acid is consistently the most expensive option except for the 5-year system with salvage values included. Here, the Lead-acid battery system is $200,000 per year less expensive to implement than VRFB.

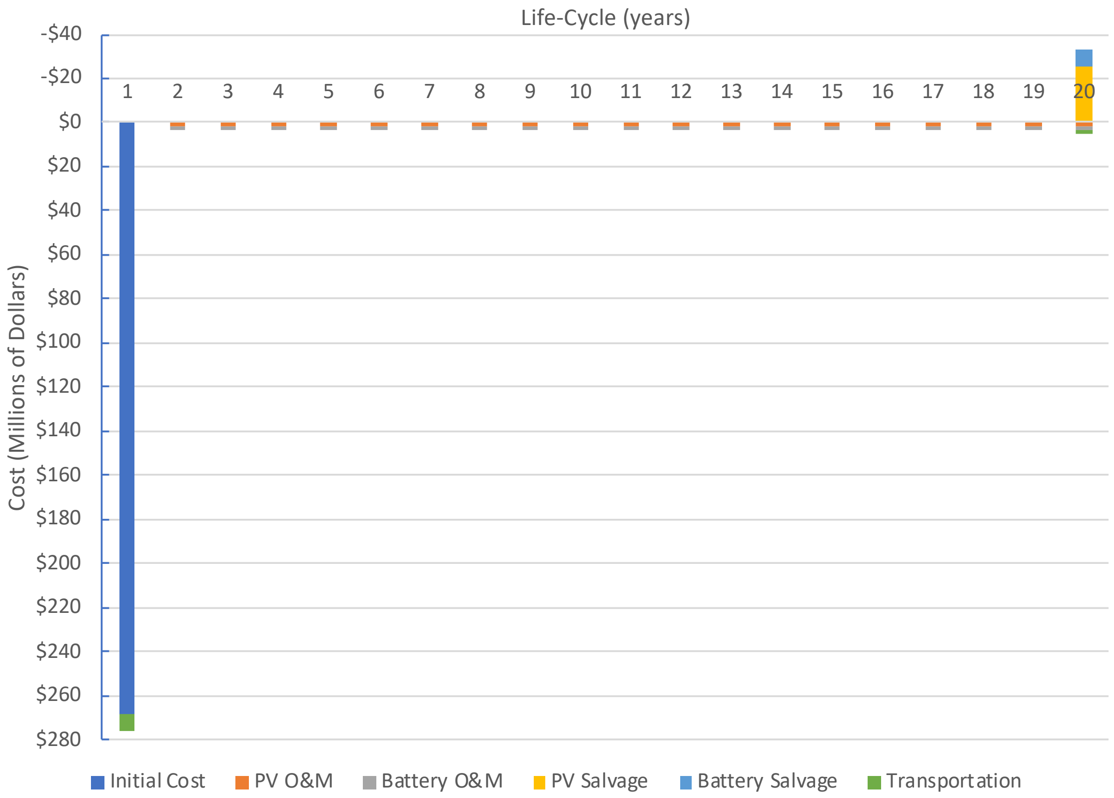

Figure 53: 20-year Cash Flow Diagram for VRFB

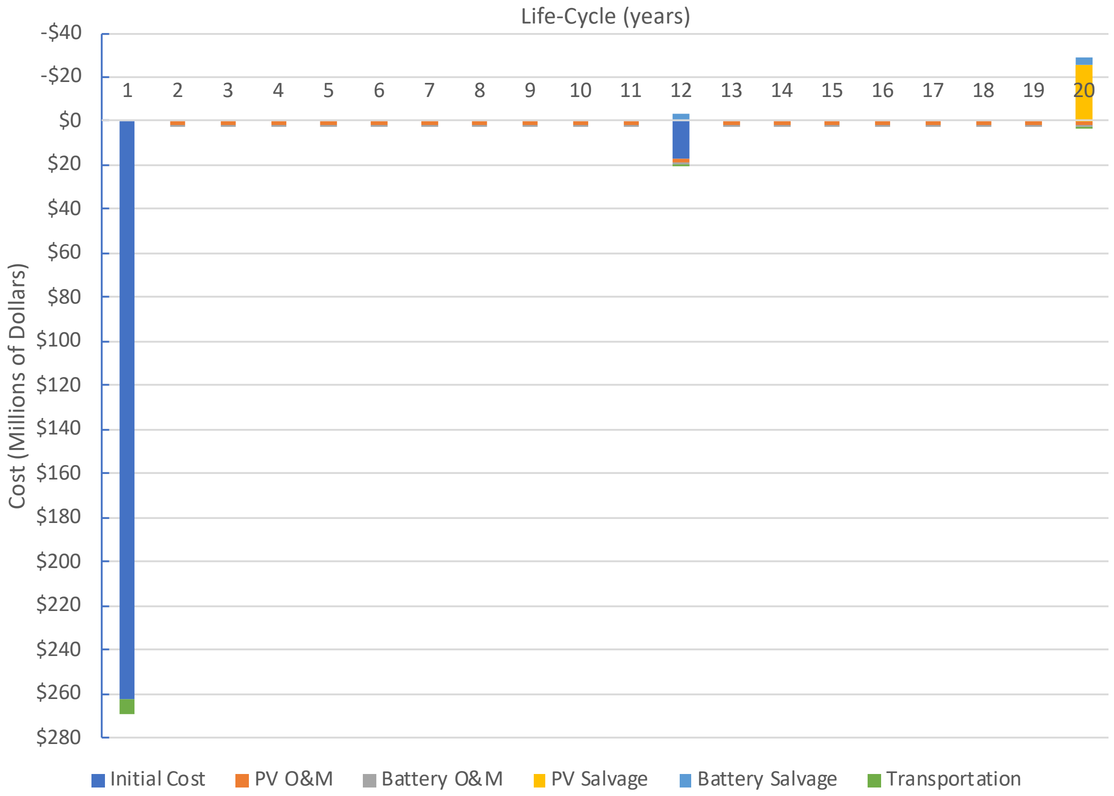

Figure 54: 20-year Cash Flow Diagram for Li-Ion

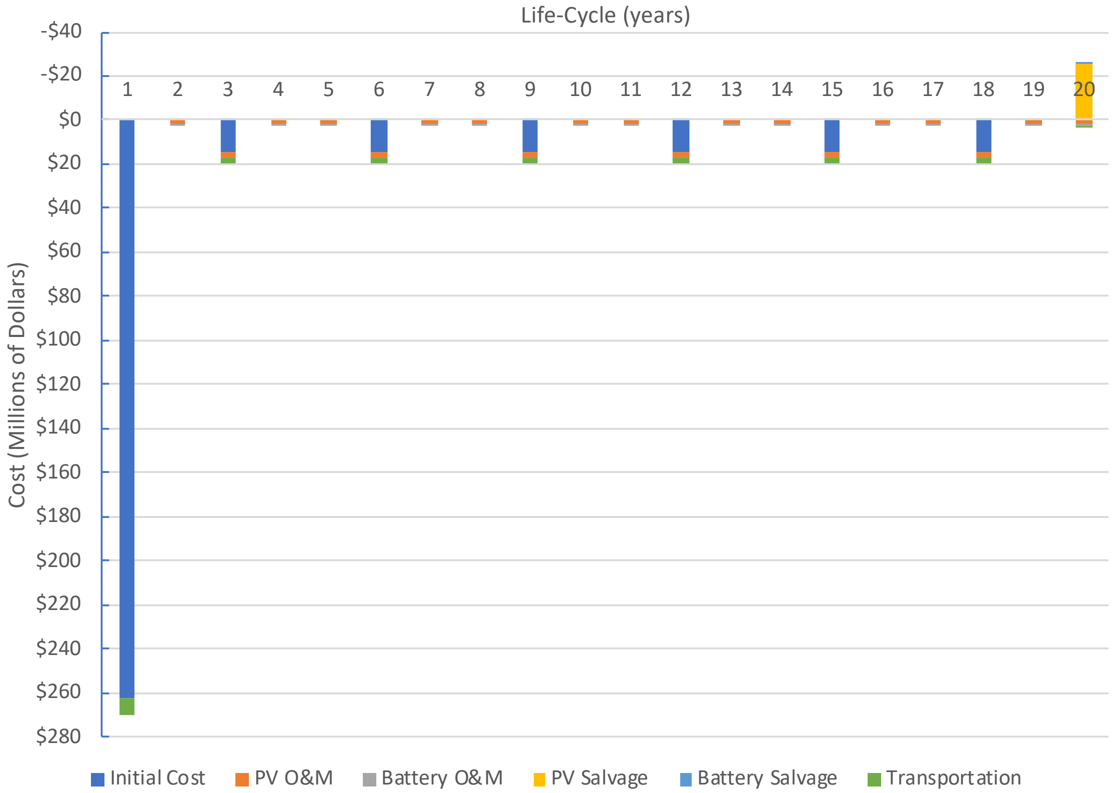

Figure 55: 20-year Cash Flow Diagram for Lead-Acid

Table 25. Total System Cost with Salvaged Components

	VRFB			Li-Ion			Lead-Acid		
Time (yrs)	5	10	20	5	10	20	5	10	20
Optimized Cost	$184.9M	$225M	$268.2M	$181.4M	$219.8M	$262.3M	$179.9M	$216.2M	$262.3M
Initial Transportation Cost	$4.8M	$6.2M	$7.9M	$4.1M	$5.2M	$6.7M	$4.7M	$6.2M	$7.9M
Battery Replacement Cost	n/a	n/a	n/a	n/a	n/a	$16.8M	$7.9M	$12.1M	$14.9M
Battery Replacement Transportation Cost	n/a	n/a	n/a	n/a	n/a	$828k	$1.42M	$2.2M	$2.7M
PV O&M Cost per yer	$1.3M	$1.63M	$2.08M	$1.3M	$1.63M	$2.09M	$1.3M	$1.63M	$2.09M
Battery O&M Cost per yer	$868k	$1.3M	$1.5M	$294k	$453k	$504k	$158k	$242k	$298k
PV Salvage Value per system	-$15.4M	-$19.4M	-$25.4M	-$15.4M	-$19.4M	-$25.4M	-$15.4M	-$19.4M	-$25.4M
Battery Salvage Value per system	-$4.6M	-$6.5M	-$7.8M	-$2.1M	-$3.3M	-$3.6M	-$616k	-$946k	-$1.2M
Transportation Cost to Salvage System	$700k	$1.0M	$1.2M	$420k	$520k	$660k	$760k	$1.1M	$1.3M
EAC at 5% interest rate	$43.5M/yr	$30.9M/yr	$24.8M/yr	$41.4M/yr	$29.5M/yr	$24.1M/yr	$43.2M/yr	$33.5M/yr	$28.4M/yr
Total Lifecycle Cost	$217.5M	$309M	$496M	$207M	$295M	$482M	$216M	$335M	$568M

Table 26. Total System Cost, No Salvage Value

	VRFB			Li-Ion			Lead-Acid		
Time (yrs)	5	10	20	5	10	20	5	10	20
Optimized Cost	$184.9M	$225M	$268.2M	$181.4M	$219.8M	$262.3M	$179.9M	$216.2M	$262.3M
Initial Transportation Cost	$4.8M	$6.2M	$7.9M	$4.1M	$5.2M	$6.7M	$4.7M	$6.2M	$7.9M
Battery Replacement Cost	n/a	n/a	n/a	n/a	n/a	$16.8M	$7.9M	$12.1M	$14.9M
Battery Replacement Transportation Cost	n/a	n/a	n/a	n/a	n/a	$828k	$1.42M	$2.2M	$2.7M
PV O&M Cost per yer	$1.3M	$1.63M	$2.08M	$1.3M	$1.63M	$2.09M	$1.3M	$1.63M	$2.09M
Battery O&M Cost per yer	$868k	$1.3M	$1.5M	$294k	$453k	$504k	$158k	$242k	$298k
EAC at 5% interest rate	$47M/yr	$32.9M/yr	$25.7M/yr	$44.5M/yr	$31.2M/yr	$25.2M/yr	$46.0M/yr	$35.1M/yr	$29.3M/yr
Total Lifecycle Cost	$235M	$329M	$514M	$222.5M	$312M	$504M	$230M	$351M	$586M

V. Conclusion and Recommendations

The model analyzed is for a theoretical Alpha FOB located in the Middle East. The region was similar to the dataset solar profile and was accessible from the port in Bahrain by land and air. The model used all optimal PV-battery system’s weight and volume to look at three scenarios for logistics and find the minimal transportation cost. The three scenarios were:

1. Military airlift direct from Holloman AFB to Alpha FOB
2. Sealift to port Mina Salman, Bahrain and then military airlift to Alpha FOB
3. Sealift to port Mina Salman, Bahrain and then ground transport to Alpha FOB

A single 1100-person FOB would require around a 60 MWh battery system. The total installed energy capacity of all utility-scale battery systems in 2017 was 225 MWh [88]. This number is well within the range of the manufacturer’s ability to build this system at market prices.

The salvage value of photovoltaics (PV) at this size turned out to be significant when determining final cost. This value is based on \$0.20/W as the 2018 average selling point for scrap PV panels in California. This salvage value equated to \$15.4M to \$25.4M from 5 to 20 years, respectively. Both five-year and 10-year O&M costs for all battery systems could be negated if the PV panels were salvaged at \$0.20/W. At half this value, the 10-year and 20-year models still show at least \$10M removed from the total cost. Still, the specific company removing the specific PV system decides the removal value per Watt. Without an industry standard, it would be up to the local contracting squadrons to negotiate removal prices if a company had that capability.

The transportation costs by ground, air, and sea are difficult to quantity. A gallon of fuel 20 years from now will not cost the same as a gallon of fuel today. The equivalent annual cost can normalize this and provide an estimate. For the model, the least expensive logistics option for this location appears to be where the assets are shipped from Los Angeles to Bahrain on cargo ships and then transported to the Alpha FOB via M1070A1 ground vehicles. The M1070's ability to carry 70 tons makes it nearly as capable for transportation as the C17, by weight. It may take longer for a ground vehicle to reach the Alpha FOB, but the M1070A1 will transport the cargo for a fraction of the cost of airlift. For scenario one, the cost to transport the five-year Li-Ion system was $26.7M. For scenario 2, the system could be transported for $5.6M. For scenario 3, the system could be transported for $4.1M at $15 FBCF. The total transportation costs are shown in Tables 22-24.

VRFB is still in its infancy. The parameters found are either theoretical or part of the early types of this battery. Just like what happened with Lead-acid and Li-Ion batteries, better parameters may appear as this type of system is implemented, tested, and researched. Data collection from a VRFB will provide better modeling accuracy with verification of the parameters collected. The most significant issue to overcome is the low energy density. Additionally, Vanadium's fluctuating price on the market and its anticipated lowered availability because of the new Chinese standard for rebar may only increase the overall cost of a VRFB [83].

Li-Ion was consistently the most inexpensive type of battery in the model. Its high energy density and low costs made it ideal for transportation and purchase. While utilizing only 88% DoD, Li-Ion has the potential to last 12 years. Even with the requirement to replace all batteries 12 year in, the system is less expensive to implement than Lead-acid. Li-Ion is less expensive than VRFB for a shorter life-cycle, but it is roughly the same cost for 10 and 20 years for VRFB.

Lead-acid parameters have not changed enough to make this option competitive. The battery was consistently the most complex system to use. Its low cycle count produced a low life expectancy. Its low energy density made it heavy to transport; however, it was less expensive to procure and maintain than VRFB if there was no salvage value for a 5-year lifecycle. The Lead-acid system was the least expensive option from the optimization model, but it quickly increased in cost because of the logistics to transport this system up to six times in 20 years.

Future Research

Further research could determine if there is a quantifiable economy of scale for battery systems that can potentially lower total costs and affect the optimized system parameters. VRFB has not been widely implemented on a utility-scale for researchers to see if a 10-kWh battery system is more expensive per kWh than a 100-MWh battery system. Metrics like this may support a different least expensive battery system.

The salvage value at end-of-life requires further research to determine a better total cost. The metrics for this variable were assumed from research suggesting that the raw materials could be reused. These metrics should be expected to change when utility-scale battery systems start requiring replacement. These metrics should also be expected to change with the value of the raw materials and how easily these materials can be extracted from the battery. Eventually, the industry will need to set standards for expected salvage value.

Energy resilience is a difficult topic to quantify. Industry standards need to be implemented to determine what needs to resist exterior forces, for how long, and to what degree. For instance, thermal runaway is a concern because damaged batteries might not be capable of shutting down. In a contingency environment, this is concerning because these batteries could be damaged in an attack. Asset dispersal could increase resilience, but there could be an added cost to the total optimized system. Placing the assets indoors can help with thermal management, but the added cost of HVAC and facility maintenance would possibly make these systems unattractive for implementation. A resilient energy system should be able to resist attack without causing serious risk personnel located near it. Further research could determine if there is an added cost to make energy infrastructure more resilient.

Appendix A: Supplemental Information

A-1: Calculations for MKR-18 and M1070A1 Operational Cost $/hr:

MKR-18

($2.98 / gal) x (gal / 2 mi) x (30 mi / hr) = $44.70/hr

($15 / gal) x (gal / 2 mi) x (30 mi / hr) = $225.00/hr

M1070A1

($2.98 / gal) x (gal / 1.3 mi) x (30 mi / hr) = $68.77/hr

($15 / gal) x (gal / 1.3 mi) x (30 mi / hr) = $346.15/hr

A-2: Example O&M PV Cost Derivation

= (5.74 kWh/m^2/day x $0.008 / kWh) x (365 days / 1 yr) x (n yrs) x (b m^2)

A-3: Example Salvage Value for PV

= ($ PV Cost) x (kW / $1500) x (1000 W / kW) x ($0.2 / W)

A-4: Example Salvage Value for VRFB

= ($ 11.57 / kg) x (1000 kg / 1 metric ton) x (10 metric tons / 1 MWh)
x (1 MWh / 1000 kWh) x (n kWh)

A-5: Ground Vehicle calculations for Alpha FOB

= (909 km * .4546 mi/km) / (30 mph) = 19 hours

A-6: Diesel Calculations

The 20-year Li-Ion-PV system results show that with 0 m^2 of PV, the fuel baseline is approximately $1060M.

124,983 m^2 array (0.4408 kW/m^2) = 55,092 kW => 44 generators at 1250 kW

44 generators * $220k/generator = $9.7M

355,704,698 gal / ((8760 hrs/year) x (20 years)) = 3184 gal/hr

3184 gal/hr / (44 generators) = 72 gal/hr/gen

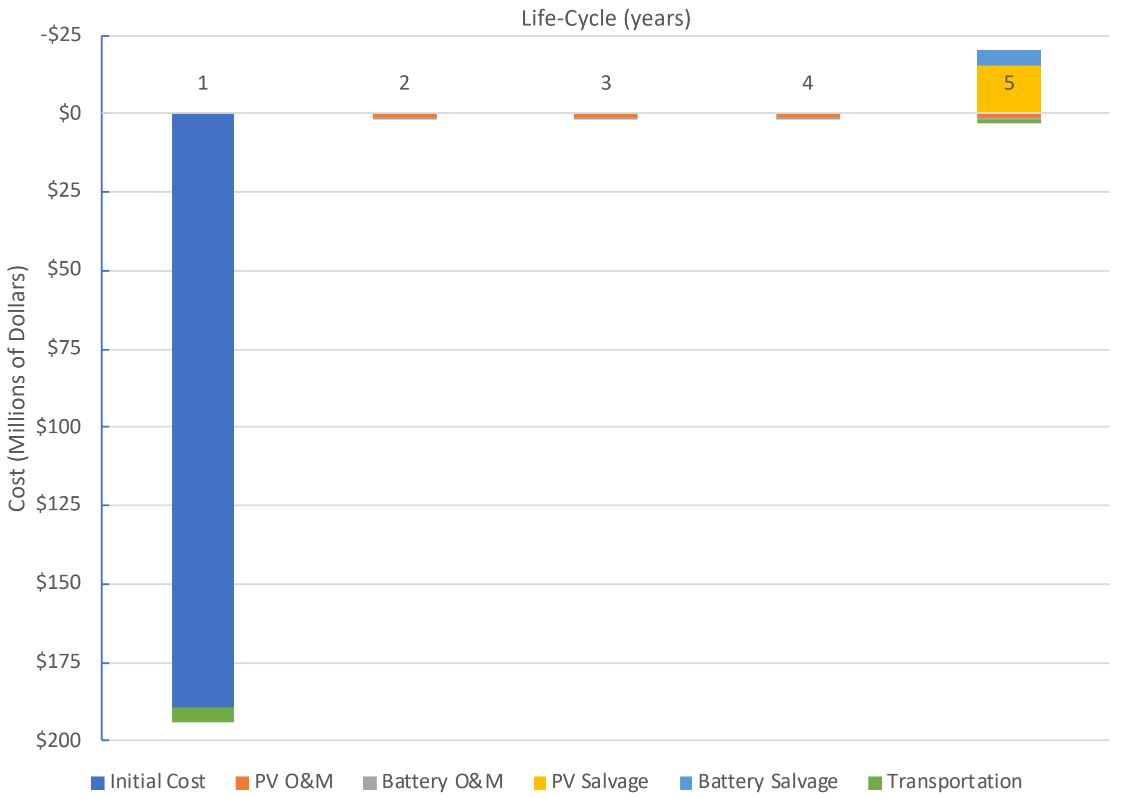

Figure A-1: 5-year Cash Flow Diagram for VRFB with Salvage Values

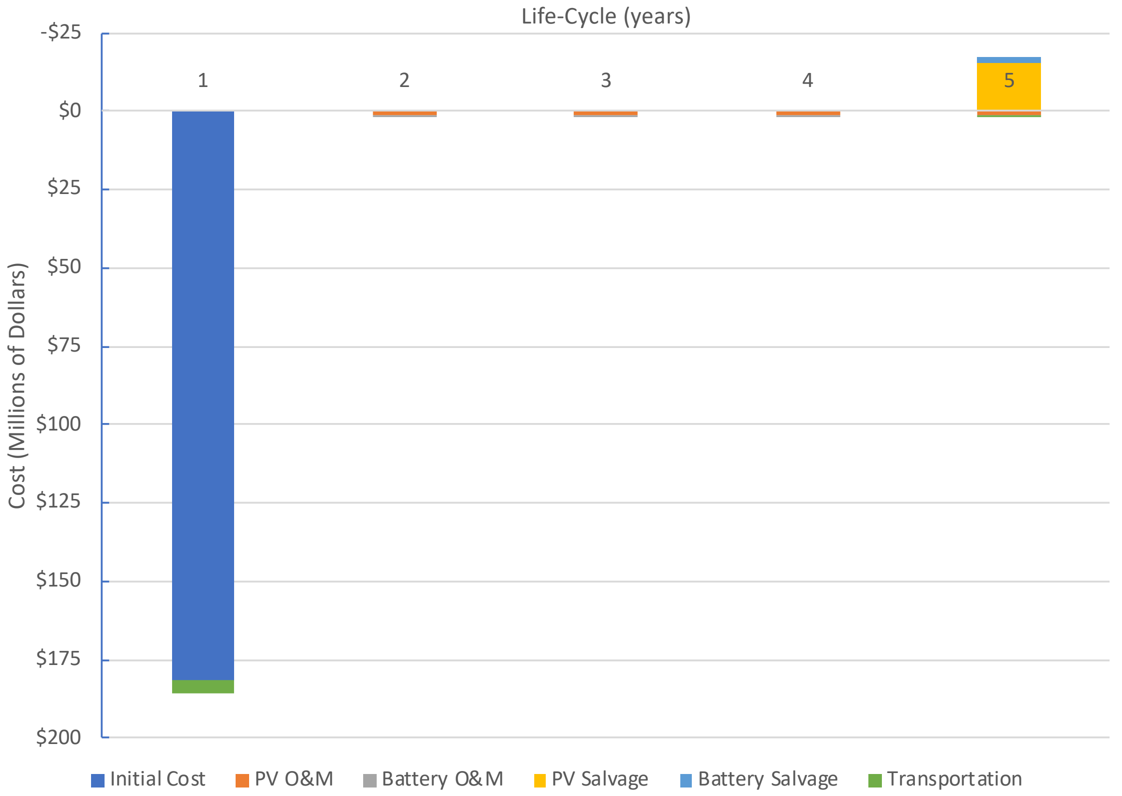

Figure A-2: 5-year Cash Flow Diagram for Li-Ion with Salvage Values

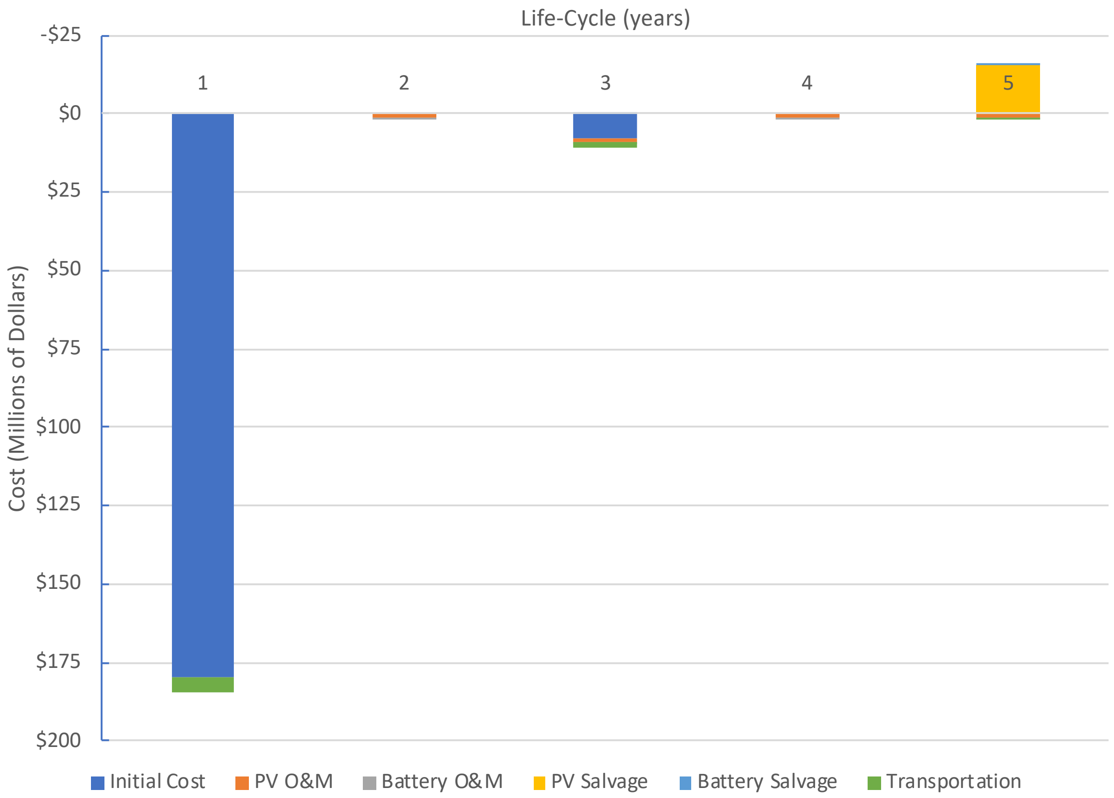

Figure A-3: 5-year Cash Flow Diagram for Lead-Acid with Salvage Values

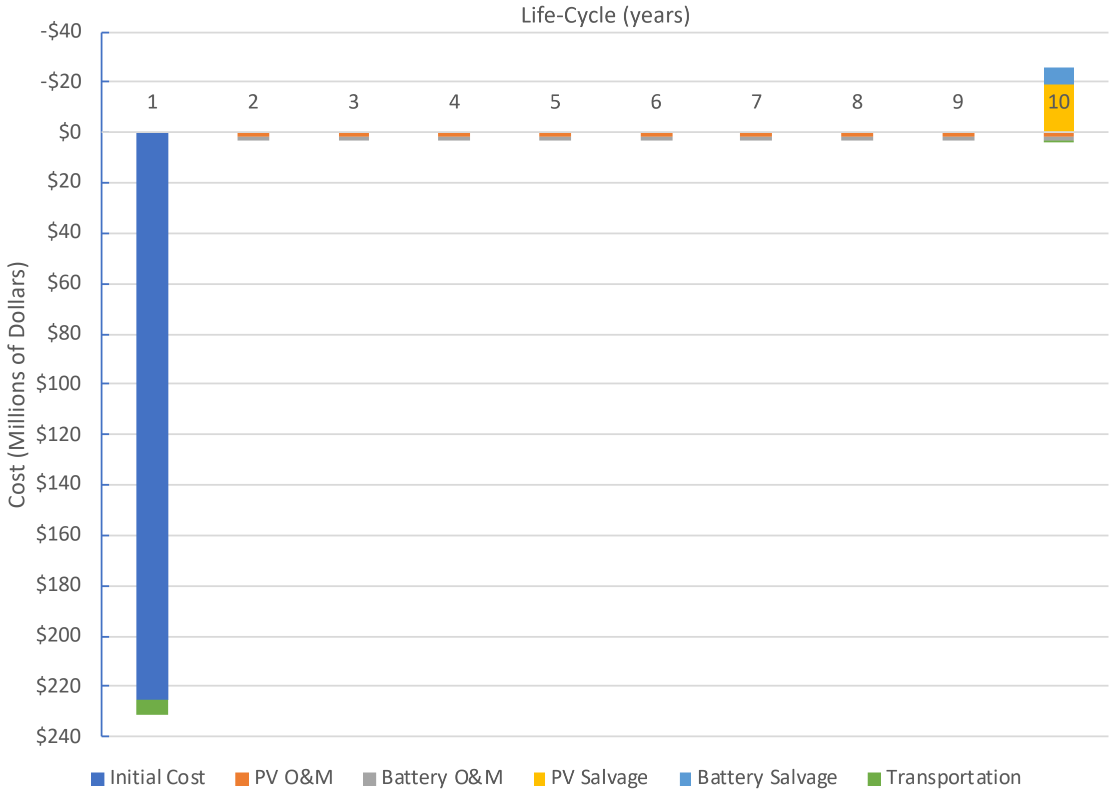

Figure A-4: 10-year Cash Flow Diagram for VRFB with Salvage Values

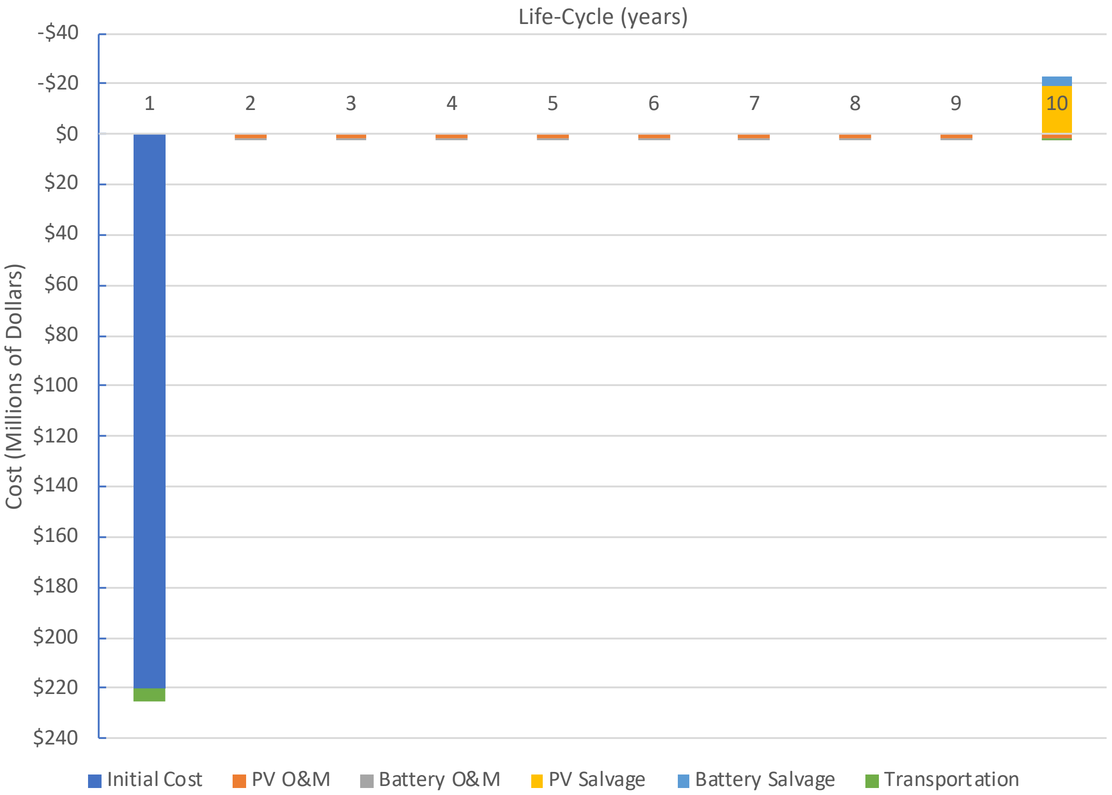

Figure A-5: 10-year Cash Flow Diagram for Li-Ion with Salvage Values

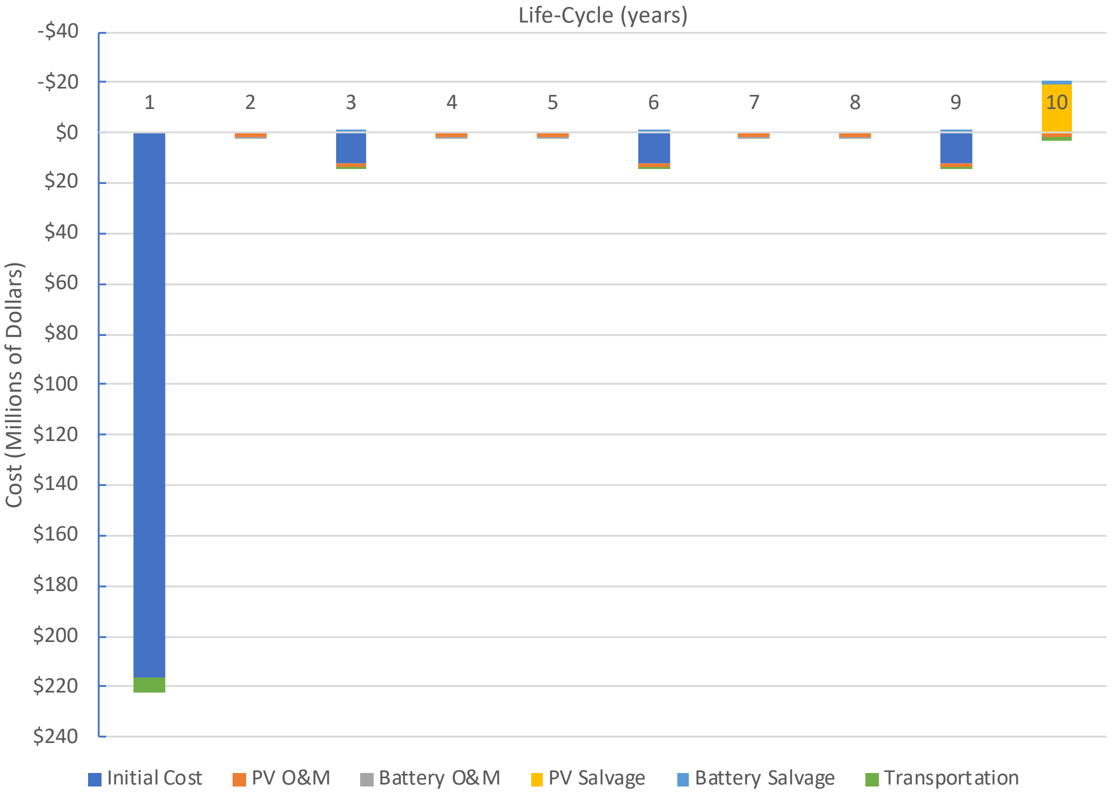

Figure A-6: 10-year Cash Flow Diagram for Lead-Acid with Salvage Values

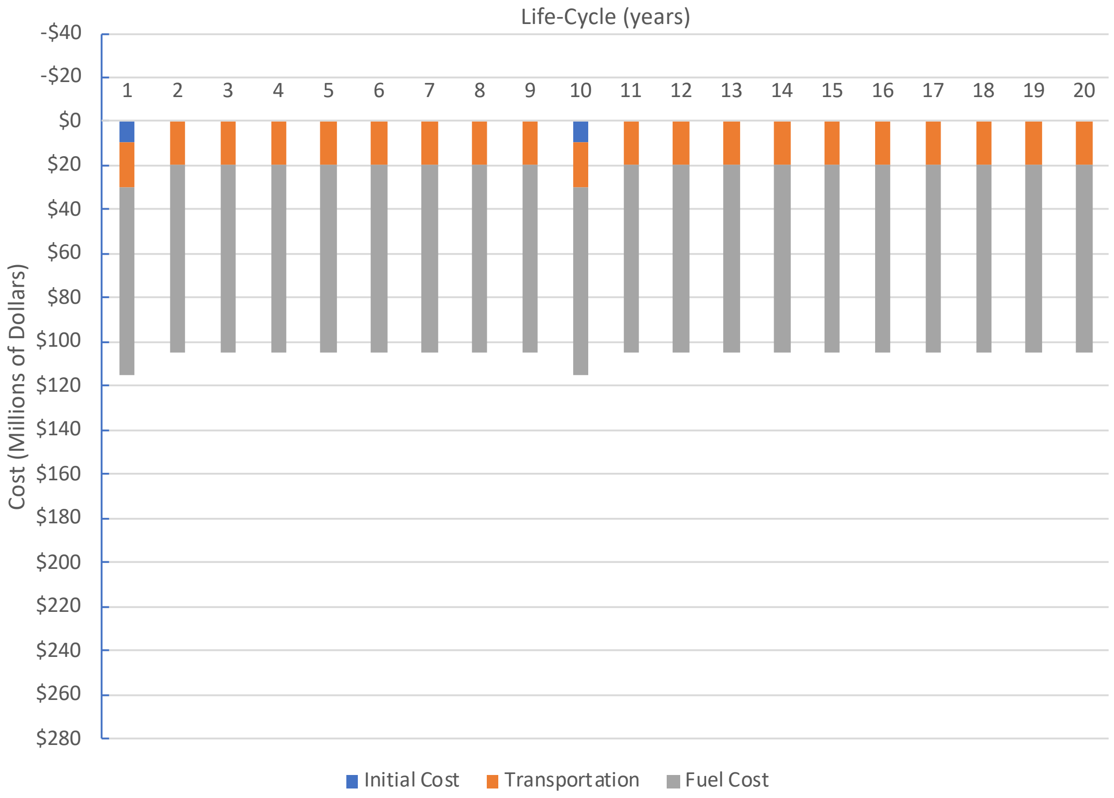

Figure A-7: 20-year Diesel Generator and Fuel Cash Flow Diagram

A-7: 5-year VRFB EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 5) + (PV O&M)
+ (Battery O&M) + (Cost Salvage Transportation) x (A/F, 5%, 5)
– (Battery Salvage Value + PV Salvage Value) x (A/F, 5%, 5)

(189.4M + 4.8M) x (0.231) + 1.3M + 0.868M + (0.7M) x (0.181)
– (4.6M + 15.4M) x (0.181) = $43.5M/yr

A-8: 5-year Li-Ion EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 5) + (PV O&M)
+ (Battery O&M) + (Cost Salvage Transportation) x (A/F, 5%, 5)
– (Battery Salvage Value + PV Salvage Value) x (A/F, 5%, 5)

(181.4M + 4.1M) x (0.231) + 1.3M + 0.294M + (0.42M) x (0.181)
– (2.1M + 15.4M) x (0.181) = $41.4M/yr

A-9: 5-year Lead-Acid EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 5) + (PV O&M)
+ (Battery O&M) + (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 3) x (A/F, 5%, 5)
– (Battery Salvage Value + PV Salvage Value – Cost Salvage Transportation) x (A/F, 5%, 5)

(179.9M + 4.7M) x (0.231) + 1.3M + 0.158M + (7.9M + 1M + 0.42M – 0.616M) x (1.158) x (0.181) + (0.76M – 0.616M – 15.4M) x (0.181) = <u>$43.2M/yr</u>

A-10: 10-year VRFB EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 10) + (PV O&M)
+ (Battery O&M) + (Cost Salvage Transportation) x (A/F, 5%, 10)
– (Battery Salvage Value + PV Salvage Value) x (A/F, 5%, 10)

(225M + 6.2M) x (0.1295) + 1.63M + 1.3M + (1.0M) x (0.0795)
– (6.5M + 19.4M) x (0.0795) = <u>$30.9M/yr</u>

A-11: 10-year Li-Ion EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 10) + (PV O&M)
+ (Battery O&M) + (Cost Salvage Transportation) x (A/F, 5%, 10)
– (Battery Salvage Value + PV Salvage Value) x (A/F, 5%, 10)

(219.8M + 5.2M) x (0.1295) + 1.63M + 0.453M + (0.52M) x (0.0795)
– (3.3M + 19.4M) x (0.0795) = <u>$29.5M/yr</u>

A-12: 10-year Lead-Acid EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 10) + (PV O&M)
+ (Battery O&M) + (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 3) x (A/F, 5%, 10)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 6) x (A/F, 5%, 10)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 9) x (A/F, 5%, 10)
– (Battery Salvage Value + PV Salvage Value – Cost Salvage Transportation) x (A/F, 5%, 10)

(216.2 + 6.2M) x (0.1295) + 1.63M + 0.242M + (12.1M + 1.5M + 0.7M – 0.946M) x (1.158) x (0.0795) + (12.1M + 1.5M + 0.7M – 0.946M) x (1.34) x (0.0795)
+ (12.1M + 1.5M + 0.7M – 0.946M) x (1.551) x (0.0795) + (1.1M – 0.946M – 19.4M) x (0.0795) = <u>$33.5M/yr</u>

A-13: 20-year VRFB EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 20) + (PV O&M)
+ (Battery O&M) + (Cost Salvage Transportation) x (A/F, 5%, 20)
– (Battery Salvage Value + PV Salvage Value) x (A/F, 5%, 20)

(268.2M + 7.9M) x (0.0802) + 2.08M + 1.5M + (1.2M) x (0.0302)
– (7.8M + 25.4M) x (0.0302) = $24.8M/yr

A-14: 20-year Li-Ion EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 20) + (PV O&M)
+ (Battery O&M)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 12) x (A/F, 5%, 20)
+ (Cost Salvage Transportation) x (A/F, 5%, 20)
– (Battery Salvage Value + PV Salvage Value) x (A/F, 5%, 20)

(262.3M + 6.7M) x (0.0802) + 2.09M + 0.504M + (16.8M + 0.7M + 0.118M – 3.6M) x (1.796) x (0.0302) + (0.66M) x (0.0302) – (3.6M + 25.4M) x (0.0302) = $24.1M/yr

A-15: 20-year Lead-Acid EAC calculation

= (Initial Cost + Initial Transportation) x (A/P, 5%, 20) + (PV O&M)
+ (Battery O&M) + (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 3) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 6) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 9) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 12) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 15) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost + Cost Salvage Transportation – Battery Salvage Value) x (F/P, 5%, 18) x (A/F, 5%, 20)
– (Battery Salvage Value + PV Salvage Value – Cost Salvage Transportation) x (A/F, 5%, 20)

(262.3 + 7.9M) x (0.0802) + 2.09M + 0.298M + (14.9M + 1.9M + 0.8M – 1.2M) x (1.158) x (0.0302) + (14.9M + 1.9M + 0.8M – 1.2M) x (1.34) x (0.0302) + (14.9M + 1.9M + 0.8M – 1.2M) x (1.551) x (0.0302) + (14.9M + 1.9M + 0.8M – 1.2M) x (1.796) x (0.0302) + (14.9M + 1.9M + 0.8M – 1.2M) x (2.079) x (0.0302) + (14.9M + 1.9M + 0.8M – 1.2M) x (2.407) x (0.0302)
+ (1.3M – 1.2M – 25.4M) x (0.0302) = $28.4M/yr

A-16: 5-year VRFB EAC calculation without salvage values

= (Initial Cost + Initial Transportation) x (A/P, 5%, 5) + (PV O&M)
+ (Battery O&M)

(189.4M + 4.8M) x (0.231) + 1.3M + 0.868M = $47.0M/yr

A-17: 5-year Li-Ion EAC calculation without salvage values

= (Initial Cost + Initial Transportation) x (A/P, 5%, 5) + (PV O&M)
+ (Battery O&M)

(181.4M + 4.1M) x (0.231) + 1.3M + 0.294M = $44.5M/yr

A-18: 5-year Lead-Acid EAC calculation without salvage values

= (Initial Cost + Initial Transportation) x (A/P, 5%, 5) + (PV O&M)
+ (Battery O&M) + (Battery Replacement + Transportation Cost) x (F/P, 5%, 3) x
(A/F, 5%, 5)

(179.9M + 4.7M) x (0.231) + 1.3M + 0.158M + (7.9M + 1M) x (1.158) x (0.181)
= $46.0M/yr

A-19: 10-year VRFB EAC calculation without salvage values

= (Initial Cost + Initial Transportation) x (A/P, 5%, 10) + (PV O&M)
+ (Battery O&M)

(225M + 6.2M) x (0.1295) + 1.63M + 1.3M = $32.9M/yr

A-20: 10-year Li-Ion EAC calculation without salvage values

= (Initial Cost + Initial Transportation) x (A/P, 5%, 10) + (PV O&M)
+ (Battery O&M)

(219.8M + 5.2M) x (0.1295) + 1.63M + 0.453M = $31.2M/yr

A-21: 10-year Lead-Acid EAC calculation without salvage values

= (Initial Cost + Initial Transportation) x (A/P, 5%, 10) + (PV O&M)
+ (Battery O&M) + (Battery Replacement + Transportation Cost) x (F/P, 5%, 3) x
(A/F, 5%, 10)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 6) x (A/F, 5%, 10)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 9) x (A/F, 5%, 10)

(216.2 + 6.2M) x (0.1295) + 1.63M + 0.242M + (12.1M + 1.5M) x (1.158) x
(0.0795) + (12.1M + 1.5M) x (1.34) x (0.0795) + (12.1M + 1.5M) x (1.551) x
(0.0795) = $35.1M/yr

A-22: 20-year VRFB EAC calculation without salvage values
= (Initial Cost + Initial Transportation) x (A/P, 5%, 20) + (PV O&M)
+ (Battery O&M)

(268.2M + 7.9M) x (0.0802) + 2.08M + 1.5M = $25.7M/yr

A-23: 20-year Li-Ion EAC calculation without salvage values
= (Initial Cost + Initial Transportation) x (A/P, 5%, 20) + (PV O&M)
+ (Battery O&M)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 12) x (A/F, 5%, 20)

(262.3M + 6.7M) x (0.0802) + 2.09M + 0.504M + (16.8M + 0.66M x (1.796) x (0.0302) = $25.2M/yr

A-24: 20-year Lead-Acid EAC calculation without salvage values
= (Initial Cost + Initial Transportation) x (A/P, 5%, 20) + (PV O&M)
+ (Battery O&M) + (Battery Replacement + Transportation Cost) x (F/P, 5%, 3) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 6) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 9) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 12) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 15) x (A/F, 5%, 20)
+ (Battery Replacement + Transportation Cost) x (F/P, 5%, 18) x (A/F, 5%, 20)

(262.3 + 7.9M) x (0.0802) + 2.09M + 0.298M + (14.9M + 1.9M) x (1.158) x (0.0302) + (14.9M + 1.9M) x (1.34) x (0.0302) + (14.9M + 1.9M) x (1.551) x (0.0302) + (14.9M + 1.9M) x (1.796) x (0.0302) + (14.9M + 1.9M) x (2.079) x (0.0302) + (14.9M + 1.9M) x (2.407) x (0.0302) = $29.3M/yr

A-25: 20-year Diesel Generator and Fuel calculations
= (Initial Cost) + (Fuel Costs) x (A/P, 5%, 20) + Fuel Transportation Cost + (Replacement Generators) x (F/P, 5%, 10) x (A/F. 5%, 20)

9.7M + (1060M) x (0.0802) + 20M + (9.7M) x (1.629) x (0.0302) = $106.2M/yr

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