Green Principles, Parametric Analysis, and Optimization for Guiding Environmental and Economic Performance of Grid-scale Energy Storage Systems

by

Maryam Arbabzadeh

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Doctoral Committee:

Associate Professor Jeremiah X. Johnson, Co-Chair
Professor Gregory A. Keoleian, Co-Chair
Professor of Practice Jose Alfaro
Associate Professor Shelie A. Miller
Professor Levi T. Thompson

Maryam Arbabzadeh

marbab@umich.edu

ORCID iD: 0000-0002-8798-4836

DEDICATION

To Maman

for all her generosity, kindness, and sacrifices

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The development and deployment of grid-scale energy storage technologies have increased recently and are expected to grow due to technology improvements and supporting policies. While energy storage can help increase the penetration of renewables, reduce the consumption of fossil fuels, and increase the grid sustainability, its integration into the electric grid poses unique sustainability challenges that need to be investigated through systematic sustainability assessment frameworks. The main objective of this dissertation is to develop principles and models to assess the environmental and economic impacts of grid-scale energy storage and guide its development and deployment.

The first study of this dissertation is an initial case study of energy storage to examine the role of cost-effective energy storage in supporting high penetration of wind energy and achieving emissions targets in an off-grid configuration. In this study, the micro-grid system includes wind energy integrated with vanadium redox flow battery (VRFB) as energy storage, and natural gas engine. Life cycle greenhouse gas (GHG) emissions and total cost of delivered electricity are evaluated and generation mixes are optimized to meet emissions targets at the minimum cost. The results demonstrate that while incorporating energy storage consistently reduces life cycle GHG emissions in the system by integrating more wind energy, its integration is cost-effective only under very ambitious emission targets.

The insights from this case study and additional literature review led to the development of a set of twelve principles for green energy storage, presented in the second study. These principles are applicable to the wide range of energy storage technologies and grid applications, and are developed to guide the design, maintenance, and operation of energy storage systems for grid applications. The robustness of principles was tested through a comprehensive literature review and also through in-depth quantitative analyses of the VRFB off-grid system.

An in-depth parametric analysis is developed in the third study to evaluate the impacts of six key

parameters (e.g. energy storage service-life) that influence the environmental performance of six energy storage technologies within three specific grid applications (including time-shifting, frequency regulation, and power reliability). This study reveals that round-trip efficiency and heat rate of charging and displaced generation technologies are dominant parameters in time-shifting and regulation applications, whereas energy storage service life and production burden dominate in power reliability.

Finally, an optimization model is developed in the fourth study to examine the real-world application of energy storage in bulk energy time-shifting in California grid under varying renewable penetration levels. The objective was to find the optimal operation and size of energy storage in order to minimize the system total costs (including monetized GHG emissions), while meeting the electricity load and systems constraints. Simulations were run to investigate how the operation of nine distinct storage technologies impacted system cost, given each technology's characteristics. The results show that increasing the renewable capacity and the emissions tax would make it more cost-effective for energy storage deployment. Among storage technologies, pumped-hydro and compressed-air energy storage with lower capital costs, are deployed in more scenarios.

Overall, this research demonstrates how sustainability performance is influenced by storage technology characteristics and the electric grid conditions. The systematic principles, model equations, and optimizations developed in this dissertation provide specific guidance to industry stakeholders on design and deployment choices. The targeted audience ranges from energy storage designers and manufacturers to electric power utilities.

CHAPTER 1
Introduction

There has been a rapid development in grid-scale energy storage systems due to technology improvements and recent policies promoting their deployment such as California's requirement of 1,325 MW of storage by 2020 [1] and the Federal Energy Regulatory Agency Order 755 [2]. Figures 1-1 and 1-2 show how annual energy storage deployment and market size have changed in the U.S. recently and how they are projected to grow within the residential, non-residential, and utility segments [3]. Based on these figures, it is expected that the U.S. energy storage market will grow to roughly 2.5 GW in 2022, 11 times the size of the 2016 market (231 MW). Also, by 2022, the U.S. energy storage market is expected to be worth $3.1 billion, a nine-fold increase from 2016 [3]. However, energy storage integration into the electric grid poses fundamentally unique challenges, and therefore there is a significant need to develop robust methods and frameworks to systematically understand the impacts of energy storage deployment, which is the focus of this dissertation.

Fig. 1-1 U.S. Annual Energy Storage Deployment Forecast, 2012-2022E (MW) [3]

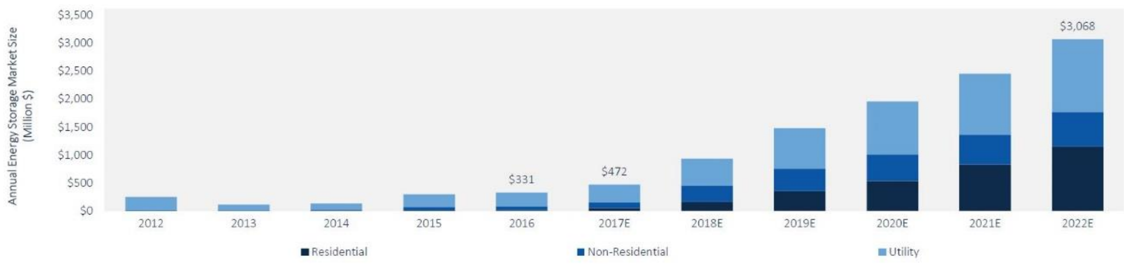

Fig. 1-2 Annual Energy Storage Market Size, 2012-2022E (Million $) [3]

Energy storage can be a potential solution to the integration challenges of intermittent renewable energy such as wind energy and solar energy, reduce greenhouse gas (GHG) emissions, and enhance grid reliability and sustainability [4]. Other grid applications for energy storage systems include energy time-shifting (energy arbitrage), frequency regulation, and transmissions and distribution upgrade deferral, among others [5]. Types of energy storage technologies vary greatly from electrochemical technologies such as batteries; including flow battery and lithium-ion (Li-ion) battery; to compressed air energy storage, flywheels, and pumped-storage technology [6]. Fig.1-3 shows the share of each non-pumped hydro storage technology in the total installed storage capacity of 2016 [7]. Each of these storage technologies has unique characteristics that determine which subset of energy storage technologies is suitable to meet the application's performance requirements.

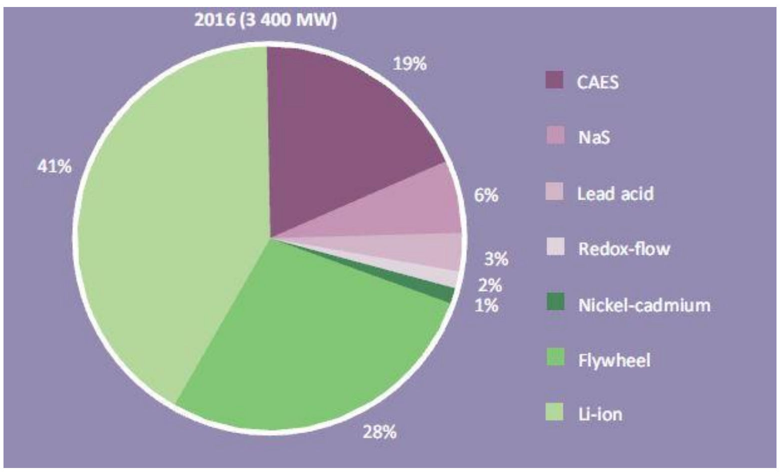

Fig. 1-3 Installed non-pumped hydro storage in 2016 [7]

Several studies have reviewed technical characteristics of energy storage technologies and identified the potential grid applications for each storage technology. These include comprehensive reports by Sandia National Laboratory and the Department of Energy (DOE) [5], [8], [9], [10]. In other reports, Electric Power Research Institute (EPRI) reviewed storage technologies performance characteristics such as service life, efficiency, response time, and compared the suitability of such systems for grid applications including peak shaving, serving in micro-grids, and wind integration [4], [11]. Additionally, Rahman et al. identified potential grid applications for each storage technology based on the technology's main advantages and disadvantages [12]. Their results showed that vanadium redox flow and sodium-sulfur batteries could be a promising technology for renewable energy integration, and flywheels were applicable for frequency regulation. In a comparison of technical characteristics of energy storage systems including power rating, discharge time, storage duration, and lifetime cycle life, Chen et al. identified a suitable application range for each technology [13]. These and other studies [14] - [17] show that deployment of an energy storage system for a specific grid application depends on the storage technology characteristics match with the performance requirements of the desired application.

1.1. Sustainability challenges in deployment of grid-scale energy storage systems

While energy storage supports different grid applications, its extensive adoption in the power grid is limited by high costs. The range for energy storage capital cost differs substantially from one technology to another and also within one storage technology itself. For instance, pumped-hydro storage capital cost (energy component) varies from $5/kWh to $100/kWh and Li-ion battery cost varies between $600/kWh-$2500/kWh [18].

Several studies have identified the economic challenges in deployment of energy storage systems. As discussed by Sardi et al., the cost of energy storage systems; particularly batteries; is the major obstacle to their adoption. In this regard, the current deployment of energy storage is generally uneconomical, as the overall energy storage installment cost is higher than the total benefits obtained from its deployment [19]. Abeygunawardana et al. discuss that at the current market prices of energy storage devices, in most cases, it is not quite cost-effective to utilize energy storage for distribution upgrade deferral application alone [20]. However, combining benefits for one or more complementary storage applications may provide the extra value needed to justify the use of storage for distribution deferral alone. Zheng et al argue that despite the advances in material science and power electronic techniques that have facilitated the effective employment of new storage technologies, the high cost and control issues still limit the wide applications of energy storage systems [21]. Dunn et al. specified varying characteristics across sodium-sulfur (NaS), Li-ion, and redox-flow batteries [22]. They concluded that a successful future for these technologies depended on using low cost materials in order to decrease the installed costs of batteries while improving their performance and durability. A report by DOE identified the cost-competitiveness of energy storage systems as one of the main challenges in the widespread use of energy storage systems [6]. According to Mohd et al., decreasing the capital costs of energy storage systems would lead to dramatic changes in the design and operation of the electric grid [23].

Besides economic issues, both the development and deployment of energy storage systems can lead to different environmental outcomes. Several studies have examined the environmental implications during the production of energy storage systems. In this regard, Tarascon emphasized that, regardless of storage technology, materials with minimum environmental footprint must be developed in an attempt towards green storage systems [24]. Larcher and Tarascon argued that the only feasible path towards greener and more sustainable batteries is rooted in designing electro-active materials that release fewer CO_2 emissions and cost less energy during production, while providing comparable performance to today's electrodes [25]. In another study, McManus examined the environmental impacts of different types of batteries, concluding that Li-ion batteries had the highest contribution to GHG emissions and metal depletion, but nickel metal hybrid had a higher cumulative energy demand [26].

With 29% of total US GHG emissions coming from burning fossil fuels for electricity generation in 2015 [27], renewables are rapidly expanding options to reduce the carbon intensity of power generation and achieve environmental improvements in the power sector. Large-scale integration of intermittent renewables into the electrical grid, however, poses critical challenges. While energy storage utilization can lead to higher penetration of renewable energy, its deployment may not always lead to environmental benefits. Indeed, environmental impacts of energy storage during its operation within the power grid depend on the grid application, the grid profile, and the existing generation mix. For example, Lin et al. showed that depending on the power grid configuration, the integration of energy storage for power systems reserves application may not necessarily lead to environmental improvements [28]. Their results emphasized the need for a more systematic approach in examining the environmental performance of energy storage deployment. In an examination of energy arbitrage application in Texas, Carson and Novan showed that energy storage integration would increase the average daily GHG emissions due to an increase in off-peak fossil fuel generation [29]. In another study, Hiremath et al. emphasized the significance of energy storage operation in the overall environmental performance of these technologies, especially when they had different characteristics parameters [30].

These examples show that the production, operation, and deployment of energy storage systems within a grid application have a significant impact on the environmental and economic outcomes of utilizing such systems. While previous studies have provided valuable insights into the economic and environmental implications of energy storage systems, there remains the need for systematic sustainability assessment tools that provide robust guidance on the development and deployment of these technologies. The central objective of this dissertation is to develop novel tools to evaluate the economic and environmental impacts of integrating energy storage systems within the electric grid and develop principles for guiding deployment of those technologies. A wide range of energy storage systems and their grid applications are studied in this dissertation to investigate how sustainability implications in terms of environmental and economic aspects change across storage technologies within different grid applications.

1.2. Overview of chapters

Table 1-1 provides an overview of chapters, outlining each chapter's research aims and the energy system assumptions including the grid application, energy storage technology studied, and the impacts assessed. In Chapter 2, the role of VRFB energy storage is assessed in integrating wind energy and reaching emissions targets in an off-grid model. Life cycle GHG emissions and total cost of delivered electricity are evaluated and generation mixes are optimized to meet emissions targets at the minimum cost. The results demonstrate that while incorporating energy storage consistently reduces life cycle carbon emissions, it is not cost effective to reduce wind curtailment except under very low emission targets.

A set of twelve principles for green energy storage systems is developed in Chapter 3, which is applicable to the wide range of energy storage technologies and grid applications. In this chapter, potential environmental impacts of energy storage systems development and operation are studied through a comprehensive literature review and through an in-depth quantitative analyses of the off-grid case study from Chapter 2.

In Chapter 4, the impact of six parameters on environmental outcomes of integrating selected energy storage technologies is assessed using model equations, which are applied to time-shifting, frequency regulation, and power reliability applications. This chapter concludes that efficiency and heat rates parameters dominate in time-shifting and regulation applications, whereas energy storage service life and production burden dominate in power reliability.

Chapter 5 examines a real-world case study of energy storage application in time-shifting the peak load of California. An optimization model is developed to find the optimal state of charge and size of energy storage in order to minimize the system total costs (including GHG emissions), while meeting the electricity load and systems constraints. Simulations are run to investigate how the operation of seven distinct battery storage technologies along with pumped-hydro energy storage, adiabatic compressed energy storage, and diabatic compressed energy storage change given their energy storage characteristics. Scenarios with four emission taxes of 0, \$50/ton of CO_2, \$100/ton of CO_2, and \$200/ton of CO_2 are developed to test the operation of each energy storage system under different tax assumptions. The findings show that increasing the installed capacity of wind and solar energy would make it more cost-effective for the energy storage to be deployed and among storage technologies PHES and D-CAES are built in most scenarios due to their lower costs.

Table 1-1 An overview of chapters

	Research Aims	**Grid Application**	**Technology Studied**	**Impacts Assessed**
Chapter 2	An analysis of ESS* operation and its environmental and economic impacts, while emissions targets in an optimization model	Wind integration	VRFB*	Life cycle GHG emissions and cost
Chapter 3	Universal principles for green energy storage- highlighting significant parameters	Across applications	Full range of energy storage technologies	A full range of environmental impacts
Chapter 4	An in-depth analysis to determine the influential parameters on GHG emissions	Time-shifting Frequency regulation Power reliability	Batteries: VRFB, Li-ion*, PbA*, NaS* CAES* PHES* Flywheels	Life cycle GHG emissions

Chapter 5	An in-depth analysis of emissions and costs across technologies with various parameters within an optimization model	Time-shifting in CAISO*	Batteries: VRFB, Li-ion, PSB*, ZBB*, PbA, NaS D-CAES A-CAES PHES	Operational GHG emissions and life cycle costs

* (ESS= energy storage system, VRFB=vanadium redox flow battery, PbA= lead-acid battery, NaS= sodium-sulfur battery, Li-ion= lithium-ion battery, CAES= compressed air energy storage, PHES= pumped-hydro energy storage, CAISO= California Independent System Operator, D-CAES= diabatic compressed air energy storage, A-CAES= adiabatic compressed air energy storage, PSB=polysulfide bromide battery, ZBB= zinc Bromine Battery)

1.2.1. Chapter 2- Vanadium redox flow batteries to reach greenhouse gas emissions targets in an off-grid configuration

1.2.1.1. Research aims

Negative environmental impacts and uncertain prices of fossil fuels are powerful drivers behind new research to understand how to improve technologies supporting renewables. Despite these sustainability opportunities, large-scale integration of variable and non-controllable renewables into the electrical grid poses critical challenges that may be overcome through the use of energy storage systems. In two separate studies of solar energy, Zahedi, and Denholm and Margolis reviewed the challenges in large-scale integration of solar systems and the impact of economically and technically viable energy storage systems in alleviating these challenges [31], [32]. In another study, Denholm and Hand found that storage equal to one day of average demand could enhance the penetration of solar and wind energy up to 80% in the Electric Reliability Council of Texas market [33]. Electric Power Research Institute (EPRI) examined the applications of various energy storage technologies to smooth the integration of grid-connected wind energy [11].

The second chapter of this dissertation investigates the operation of an energy storage system within an off-grid configuration to increase the wind penetration and analyzes the associated environmental and economic impacts. This micro-grid system includes wind energy integrated with energy storage besides natural gas as a back-up generation. The relationship between total system costs and life cycle emissions are used to optimize the generation mixes to achieve emissions targets at the least cost and determine when VRFBs are preferable over wind curtailment.

Several studies have conducted optimization in an isolated system that include renewable energy, energy storage, and other sources of generation to achieve the minimum cost. For example, in an optimization of a stand-alone hybrid system including PV panels, wind energy, and diesel generator, Merei et al. showed that the integration of batteries with renewables was economical and environmentally preferable. They also showed that using redox flow batteries specifically in combination with renewables and diesel was the best option in comparison to lead-acid and lithium-ion batteries integration [34]. In another study, Kaabeche et al. showed that a hybrid system including PV/wind/diesel/battery was more economically viable compared to a PV/wind/battery system and also a diesel generator only system [35]. In addition to batteries, several optimization studies examined hybrid configurations including other storage systems such as compressed air or pumped hydro energy storage [36], [37], [38], [39].

As discussed earlier, while energy storage can help integrate more renewables and potentially increase the grid sustainability, it is critical to evaluate the life cycle environmental impacts associated with the production and operation of such systems. For example, in an analysis of life cycle energy requirements and emissions from large-scale storage systems coupled with renewables, Denholm and Kulcinsi showed that despite the added emissions and energy input, these systems offered lower emissions than fossil fuel based electricity [40]. Other studies also included emissions in their analysis of off-grid systems which included renewables integrated with energy storage [41], [42].

While economic and environmental analyses have been conducted in these previous studies, there remains the need for further examination of the economic and environmental trade-offs between curtailment and energy storage. This chapter examines the trade-offs between environmental and economic metrics when utilizing vanadium redox flow batteries (VRFB) to integrate wind energy and explores the role of energy storage in achieving very low emissions targets. This study contributes to the literature through assessing the full life cycle GHG emissions of all system components and evaluates the total cost of the system. Based on these evaluations, it is determined when the value of large-scale energy storage outweighs the cost of wind curtailment, i.e. when energy storage is preferable over additional wind capacity. The results of this research are published in *Applied Energy* as “Vanadium redox flow batteries to reach greenhouse gas emissions targets in an off-grid configuration” [43].

1.2.1.2. Energy system studies and approach

The case study is intended to represent an island with the same size as "Grosse Ile", Michigan. The island system is an isolated grid and the generation options are assumed to be wind energy integrated with VRFB energy storage and natural gas as a back-up generation. VRFBs offer high round-trip efficiency and different grid applications [44]. By utilizing life cycle analysis, Rydh compared VRFB and PbA batteries, concluding that that former had a lower environmental impact, greater net energy storage efficiency, and longer cycle-life [45]. Joerissen et al. identified load leveling and seasonal energy storage in small grids and stand-alone PV systems applications for VRFB [46]. Stiel and Skyllas-Kazacos assessed the environmental and economic benefits of integrating VRFB with remote wind/diesel power systems, showing that such system had lower carbon emissions and net present cost compared to wind/diesel system [47]. These and other studies focus on economic and environmental aspects of integrating energy storage, without addressing emissions targets, which is a critical criterion especially for decision and policy-makings. In this study, first total environmental GHG emissions of integrating VRFB with wind energy is assessed through a full LCA of all system components. Then the trade-offs between total emissions and total cost of the system are evaluated using an optimization model. In this model, optimal generation mixes comprised of VRFBs, wind turbines, and natural gas reciprocating engines (Fig. 1-4) are determined to minimize the delivered cost of electricity to the isolated load, while meeting progressively more challenging life cycle GHG emissions targets.

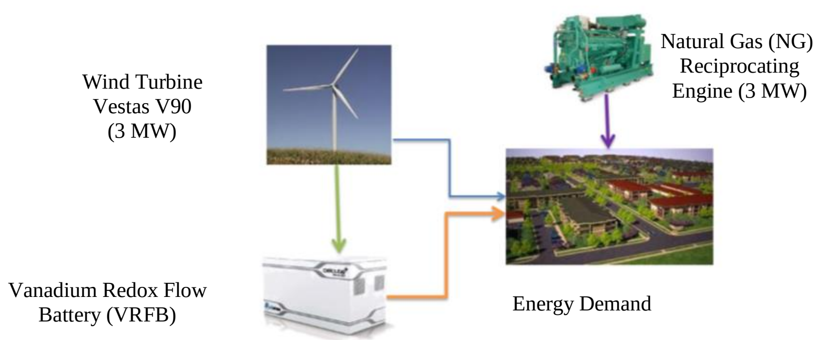

Fig. 1-4 Model components for battery storage integration with wind energy

1.2.2. Chapter 3- Twelve principles for green energy storage in grid applications

1.2.2.1. Research aims

As mentioned earlier, the integration of energy storage systems into the electrical grid can lead to different environmental outcomes based on the grid application, the existing generation assets, and the electrical demand. While studies already cited in the previous sections [24], [25], [26], [28], [29], [30] provide important insights into the environmental impacts of grid-scale energy storage, those who design, maintain, and operate such systems lack a comprehensive and systematic set of principles that can yield improved environmental outcomes. This chapter fills a research gap by providing a transparent set of principles as a novel tool to guide integration, operation and maintenance, design, and material choices that influence environmental outcomes from developing and deploying energy storage systems. The objective is to guide designers, decision makers, and utility operators on design choices and deployment scenarios. These principles for green energy storage build upon the robust body of research that aims to improve environmental outcomes through better design and operation:

Keoleian and Menerey introduced a guidance manual for life cycle design, emphasizing the importance of addressing environmental issues in designing sustainable systems, which led to evolvement of a variety of frameworks to support green design [48]. For example, two sets of twelve principles for green chemistry and twelve green engineering principles made important contributions to guide design of environmentally benign products and processes [49], [50]. In an examination of these principles, Krichhoff demonstrated that combining green chemistry with green engineering would lead to maximum efficiency and minimum waste [51]. In two other studies, McDonough et al. demonstrated the industrial application of green engineering principles [52] while Diwekar used the green engineering principles to develop an integrated computer-aided framework for designing chemical process [53].

While other studies have successfully provided guidance and structure to green design and products, energy storage technologies pose unique assessment challenges that are not fully addressed by those approaches. Inspired by and building off the 12 engineering principles [49], 12 principles for green energy storage are developed in this chapter to provide insights into and improve the environmental outcomes when integrating energy storage systems into power grid.

The principles for green energy storage are published in *Environmental Science & Technology* as "Twelve principles for green energy storage in grid applications" [54].

1.2.2.2. Energy system studied and approach

These principles are broadly applicable to the wide range of energy storage technologies (e.g. batteries, flywheels) and grid applications (e.g. energy time-shifting, frequency regulation) for which they are being used or considered. Principles were developed through comprehensive literature review and were presented to diverse audiences including electrochemists, engineers, industrial ecologists, and sustainability scientists. The principles are grouped into three categories (Fig. 1-5): (1) system integration for grid applications, (2) the maintenance and operation of energy storage, and (3) the design of energy storage technologies. The first category of principles addresses the specific nature of the grid applications for which energy storage is considered. Existing grid infrastructure and electricity demand profiles influence environmental outcomes from the integration of energy storage systems. The second category addresses impacts associated with the operation phase and also the importance of efficient maintenance of energy storage system to provide the desired outcomes. The third category highlights the importance of performance characteristics of storage system such as efficiency and service life and addresses the impacts from materials and production phase.

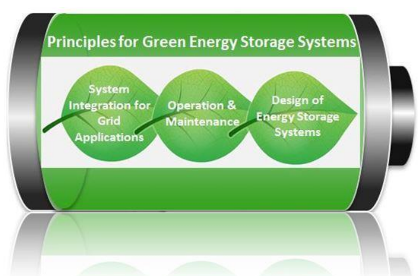

Fig. 1-5 Categories of principles for green energy storage systems [38]

1.2.3. Chapter 4- Parameters driving environmental performance of energy storage systems across grid applications

1.2.3.1. Research aims

The principles address the importance of the operational parameters of energy storage such as service life, round-trip efficiency, and degradation but do not address how their influence would vary across grid applications. Motivated and guided by this need, a universal set of equations is developed in this chapter to investigate the influence of selected parameters on the environmental outcomes of integrating energy storage for specific applications. Existing environmental assessments of energy storage systems have not systematically evaluated the influence of various parameters on environmental performance of these technologies. This chapter aims to fill this research gap by illustrating that across the full range of parameters, environmental outcomes could be positive or negative. The main focus is to understand the interaction between energy storage parameters (e.g., round-trip efficiency, degradation, service life, and production burden) and grid application parameters (e.g., generators' heat rates). This parametric analysis indicates the relative importance of each parameter in determining the environmental performance of utilizing energy storage, and provides guidance to determine, systematically, when and how to choose storage systems to achieve positive environmental outcomes.

In 2012, Hittinger et al. evaluated the impact of energy storage parameters on the economic cost of providing energy service across grid applications [55]. The study presented here is novel because it presents a parametric analysis tool to identify how selected parameters drive environmental outcomes in grid applications, providing new insights for the design and deployment of new technologies and the modification and improvement of existing ones.

1.2.3.2. Energy system studied and approach

Three case studies of energy storage applications—energy time-shifting, frequency regulation, and power reliability applications—are selected to demonstrate the impact of parameters on the environmental performance of energy storage. These grid applications were chosen to illustrate a wide range of performance requirements such as required energy storage power rating, capacity, and number of cycles. Suitable technologies were selected for each grid application through a comprehensive literature review. To illustrate the range of outcomes for net emissions during the operation of energy storage, a range of energy storage parameters and grid application parameters are assumed. A full literature review was conducted to find a feasible range for parameters of potential energy storage systems that were suitable for each application.

The impacts of selected parameters on net emissions are summarized in Table 1-2 and published as “Parameters driving environmental performance of energy storage systems across grid applications” in *Journal of Energy Storage*. This table shows the relative differences of the parameters’ influence across time-shifting, frequency regulation, and power reliability applications based on our baseline assumptions [56]. The assumptions include energy storage sizing, discharge duration, and number of cycles per year, and are defined for each of the three applications. Given these assumptions, each application represents a generalized case study rather a specific grid example.

Table 1-2 Influence of parameters on net CO_{2eq} emissions in time-shifting, frequency regulation, and reliability applications [56]

	Time-shifting	Frequency Regulation	Power Reliability
Round-trip efficiency	◆	◆	●
Annual degradation	●	●	■
Heat rate charge	◆	◆	●
Heat rate displace	◆	◆	●
Service life	■	■	◆
Energy storage production burden	■	■	◆

Strong influence ◆ Moderate influence ● Weak influence ■

1.2.4. Chapter 5- Energy storage for time-shifting and greenhouse gas reductions under varying renewable penetrations- A CAISO case study

1.2.4.1. Research aims

The environmental and economic impacts of energy storage integration depend on the energy system characteristics such as the generation mix, energy storage sizing, and energy storage operation within the power grid. Many studies have optimized the operation and size of an energy storage system for a given grid application from an economic point of view. For example, Ho et al. optimized the scheduling and capacity of an energy storage system to achieve minimum investment cost using integer linear programming in a distributed energy generation system [57]. Their results indicated that for renewable integration application, energy storage with high capital costs was advised to operate in daily cycles (vs. weekly cycles) due to intermittency of renewables. In another study, Parra et al. optimized the size of lead-acid (PbA) and Li-ion batteries for time-shifting application in a 100-home community in cases of time-of-use or real-time-pricing tariffs [58]. Their results showed that the time-of-use tariff is much more attractive for demand-shifting in that community. In addition to economic analysis, few studies have included environmental emissions accounting in their optimizations. For example, Hemmati et al. developed a multistage generation expansion plan for a test system to minimize the total costs including the emissions cost [59]. Their results showed that adding energy storage into the test system would decrease the planning costs as well as environmental pollutions due to the reduced need for installing peak demand capacity. de Sidternes et al. modeled an electricity system with demand and renewable generation data from the Electricity Reliability Council of Texas to determine the optimal portfolio of generation capacities to meet the demand in 2035 at minimum cost, subject to system requirements, operational limits, and a mass-based CO_2 limit [60]. In their analysis, energy storage capacity was defined exogenously, therefore, they did not consider the capital cost of the energy storage system. Also, they assumed two generic energy storage systems rather than a specific technology for the analysis.

An optimization model is developed in Chapter 5 to evaluate the role of cost-effective energy storage in time-shifting the peak load of California Independent System Operator (CAISO), while accounting for the GHG emissions. The objective function in this optimization is to minimize the total costs of the system, which include natural gas operating fuel costs, energy storage capital costs, and a GHG emissions cost as a tax imposed on the system. The goal is to find the optimal natural gas generator production level, optimal size, optimal operation of energy storage, and optimal level of wind and solar energy delivered to demand. This novel approach contributes to literature through investigating which of the studied storage technologies is cost-effective for integration into CAISO, when the renewable energy generation and the emissions tax are increased exogenously.

1.2.4.2. Energy system studied and approach

The case study examined is the application of energy storage for bulk energy time-shifting in CAISO. Due to the great development of renewable energy and also the state recent actions towards advancing energy storage [1], [61], California has become an interesting case study to analyze the impact of energy storage integration. In this regard, Solomon et al. evaluated the opportunities for the higher utilization of renewable energy in California in scenarios with and without energy storage integration [62]. In another two comprehensive studies by National Renewable Energy Laboratory, value of energy storage was estimated in California with high penetration of renewable energy [63], [64].

The load data as well as all the generation data including natural gas generator marginal cost and marginal emissions, nuclear, imports, hydro, and all renewable except for wind and solar resources are collected from EPA Clean Air Markets Program Data, U.S. Energy Information Administration (EIA), and CAISO online resources [65]- [68]. Wind and solar generations are assumed to change exogenously based on pre-defined hourly capacity factors and assumed installed capacities of 0, 10, 20 GW for wind energy and 0, 20, 40 GW of solar energy. The wind and solar capacity factors across the state are estimated using NREL WIND Toolkit and NSRDB resources [69], [70]. In this optimization, natural gas generator production level, size and operation of energy storage, and the level of delivered wind and solar energy are optimized to minimize the total system costs. Total costs include the natural gas operating marginal costs, energy storage capital costs, and monetized GHG emissions cost. Total emissions of the system are calculated using the generators' marginal emissions and monetizing them through an emissions tax rate. For the electric energy time-shifting application, several energy storage technologies offer the most suitable characteristics: pumped-hydro storage, flow batteries, PbA batteries, Li-ion batteries, sodium-sulfur batteries, and compressed-air energy storage [5], [56]. In this analysis, simulations are run for each of those particular technologies in various scenarios to investigate how the optimal results would change across technologies.

Fig. 1-6 shows the relative size of the selected technologies that are deployed in different combinations of installed wind and solar capacity, assuming 0, \$50/ton of CO_2, \$100/ton of CO_2, and \$200/ton of CO_2 emissions tax. This figure shows that an expensive technology such as Li-ion battery is deployed only in scenarios with high installed capacity of wind energy and high emissions tax of \$200/ton of CO_2. On the other hand, less costly technology such as PHES is deployed in more scenarios.

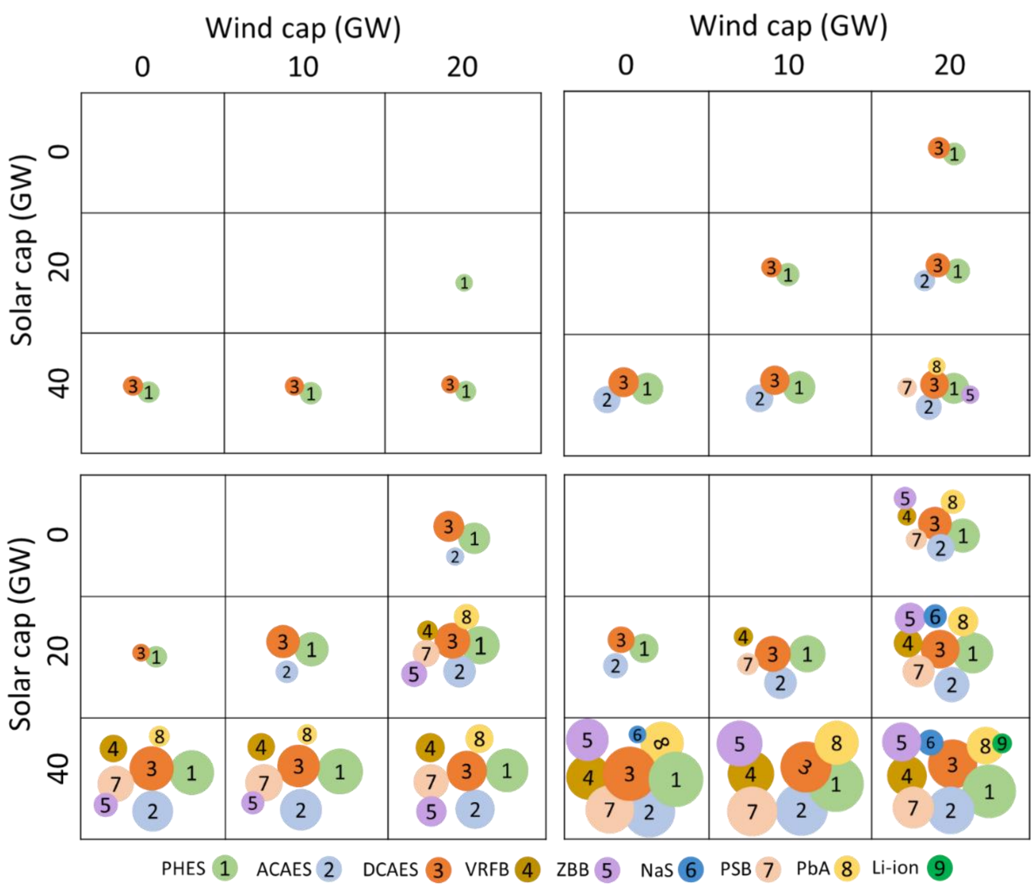

Fig. 1-6 Optimal size of nine energy storage technologies in different combinations of installed wind and solar capacity in CAISO, assuming 0, \$50/ton, \$100/ton, and \$200/ton of CO_2 emissions taxes

A summary of key findings of this dissertation and recommendations for future research are presented in Chapter 6. Areas for future research include examining other sustainability impacts (beyond GHG emissions) associated with the production and deployment of grid-scale energy storage technologies, a comprehensive investigation of end-of-life strategies for energy storage technologies, and examining the robustness of twelve principles developed in Chapter 3 by applying them to other grid examples. Also, the optimization model developed in Chapter 5 can be applied to other electric grids with different characteristics from CAISO, which is assumed to have no coal generation. Many other opportunities for future exploration are also highlighted throughout this dissertation.

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CHAPTER 2

Vanadium redox flow batteries to reach greenhouse gas emissions in an off-grid configuration

Abstract

Energy storage may serve as a solution to the integration challenges of high penetrations of wind, helping to reduce curtailment, provide system balancing services, and reduce emissions. This study determines the minimum cost configuration of vanadium redox flow batteries (VRFB), wind turbines, and natural gas reciprocating engines in an off-grid model. A life cycle assessment (LCA) model is developed to determine the system configuration needed to achieve a variety of $CO_{2\text{-eq}}$ emissions targets. The relationship between total system costs and life cycle emissions are used to optimize the generation mixes to achieve emissions targets at the least cost and determine when VRFBs are preferable over wind curtailment. Different GHG emissions targets are defined for the off-grid system and the minimum cost resource configuration is determined to meet those targets. This approach determines when the use of VRFBs is more cost effective than wind curtailment in reaching GHG emissions targets. The research demonstrates that while incorporating energy storage consistently reduces life cycle carbon emissions, it is not cost effective to reduce curtailment except under very low emission targets (190 g of $CO_{2\text{-eq}}$/kWh and less for the examined system). This suggests that "overbuilding" wind is a more viable option to reduce life cycle emissions for all but the most ambitious carbon mitigation targets. The findings show that adding VRFB as energy storage could be economically preferable only when wind curtailment exceeds 66% for the examined system. The results were most sensitive to VRFB costs, natural gas upstream emissions (e.g. methane leakage), and wind capital cost.

2.1. Introduction

The development of renewable energy sources, such as wind and solar, is considered an important strategy to decrease both environmental impacts and energy price volatility. With 38% of US carbon dioxide emissions coming from burning fossil fuels for electricity generation in 2012 [1], wind power is an appealing option to decrease the carbon intensity of power generation. Despite these sustainability opportunities, large-scale integration of variable renewables into the electrical grid poses critical challenges that may be overcome through the use of energy storage systems. When the objective is to integrate variable renewables such as wind and solar, energy storage must compete with other solutions such as increased flexibility of firm generation or simply allowing some wind or solar curtailment. Understanding the total environmental impacts of using grid-scale energy storage requires the integration of LCA and energy systems analysis, as is done in this study.

Many studies have assessed the role of energy storage in increasing the penetration of renewable energy. A major study by Electric Power Research Institute (EPRI) examined the applications of different energy storage systems for grid connected wind generation [2]. Denholm and Margolis considered energy storage to alleviate the challenges of introducing variable solar energy [3]. Denholm and Hand examined Electric Reliability Council of Texas (ERCOT) market and found that storage equal to one day of average demand could increase the wind and solar penetration up to 80% [4]. Zahedi reviewed the challenges in large-scale integration of solar photovoltaic (PV) systems and the utilization of economically and technically viable energy storage systems to solve these challenges [5].

While energy storage holds the promise of integrating high penetrations of variable renewables, its adoption is limited by high costs. Several studies have optimized an isolated hybrid system consisting of renewable energy, energy storage, and other sources of electricity generation to achieve the minimum cost. For example, Merei et al. optimized a stand-alone hybrid system comprising of PV panels and wind turbines as renewable sources of energy, diesel generator as back-up generation and batteries as energy storage to minimize the overall costs. Their results showed that the integration of batteries with renewables was economical and environmentally preferable. Also their optimization results showed that using redox flow batteries in combination with renewables and diesel was the best option in comparison to lead-acid and lithium-ion batteries integration [6]. Ma et al. also evaluated the techno-economic feasibility of a stand-alone hybrid solar wind energy system integrated with battery storage system as an electricity supplier for a remote island to achieve an optimal cost-effective configuration [7]. On the other hand, Kaabeche et al. showed that a stand-alone hybrid configuration consisting of PV/wind/diesel/battery was more economically viable compared to a PV/wind/battery system and also a diesel generator (DG) only system [8]. Besides batteries, other studies optimized hybrid configurations integrated with other energy storage systems such as compressed air or pumped storage systems [9], [10], [11], [12].

In addition to economic issues, the lifecycle environmental impacts of energy storage systems from cradle-to-grave will influence their overall sustainability performance. Denholm and Kulcinski analyzed the life cycle energy requirements and emissions from large-scale energy storage systems coupled with renewables. Their results showed that despite the added emissions and energy input, these systems offered lower emissions than fossil fuel based electricity [13]. Sioshansi evaluated the impact of adding wind and energy storage to a market based electric power system [14]. In an examination of environmental impacts of different batteries, McManus concluded that lithium ion batteries had the most significant contribution to greenhouse gases and metal depletion, but nickel metal hydride batteries had a more significant cumulative energy demand [15]. Galvez et al. optimized an autonomous hybrid system consisting wind turbines, solar panels and hydrogen storage with the objective of minimizing net present cost and net avoided emissions in the system life cycle [16]. Bondesson introduced a comparative LCA model on renewable solutions integrated with batteries for off-grid base stations [17].

Among various energy storage systems, vanadium redox flow batteries (VRFBs) offer high energy density and efficiency [18], suggesting the potential for cost competiveness in applications for variable renewable energy integration. Rydh compared VRFB and lead-acid batteries utilizing life cycle analysis and found that former had a lower environmental impact, greater net energy storage efficiency, and longer cycle-life [19]. Stiel and Skyllas-Kazacos also assessed the environmental and economic benefits of integrating vanadium redox battery with remote wind/diesel power systems using the HOMER model. Their results showed that the system comprised of wind, diesel and vanadium flow batteries had lower carbon emissions and net present cost compared to wind/diesel system [20]. Our current study differs from this work by examining natural gas generation (at a far lower cost), including all life cycle impacts of the system components, and optimizing to meet life cycle emissions targets. Joerissen et al. showed the ability of VRFBs for load leveling and seasonal energy storage in small grids and stand-alone PV systems [21]. Zhang et al. showed the importance of the vanadium to the overall capital costs of all-vanadium redox flow batteries in a sensitivity analysis [22]. While those studies have done economic and environmental analyses, there remains the need for further examination of the economic and environmental trade-offs between curtailment and energy storage.

2.1.1. Objectives and Energy System Assumptions

This chapter examines the trade-offs between environmental and economic metrics when using energy storage to integrate wind energy and explores the role of energy storage in achieving very low emissions targets. In this study, optimal generation mixes comprised of VRFBs, wind turbines, and natural gas reciprocating engines are determined to minimize the delivered cost of electricity to an isolated load, while meeting progressively more challenging life cycle GHG emissions targets. This study is novel because it assesses the environmental emissions of integrating VRFB with wind energy through a full LCA of all system components and evaluates the total cost of the system. LCA methods are utilized to compare the GHG emissions associated with the system components, including upstream effects of fuel and material production and equipment manufacturing. The total cost of the off-grid system is calculated to determine when the value of large-scale energy storage outweighs the cost of wind curtailment, i.e. when energy storage is preferable over additional wind capacity. There are emissions associated with the production of batteries; this study examines if such emissions are compensated by the reduction in environmental impact due to less natural gas combustion.

The case study is intended to represent an island with the same size as “Grosse Ile”, the largest island in the Detroit River, which has population of 10,894 [23]. Using MISO-wide per capita data, it is estimated that this system has annual demand of 10.6 MWh per capita, and annual peak and minimum demand of 22 MW and 8.7 MW respectively. The annual electrical load profile of State of Michigan is scaled down to create a load profile of the island. The distribution losses are assumed to be 3 percent and the load factor is 60%. The island system is an isolated grid and the generation options are assumed to be wind energy integrated with energy storage and natural gas. Planning for reliability is achieved by maintaining a reserve margin of 20 percent [24], assuming that the system does not have any grid connection.

In this model wind is treated as a must-take resource. Excess wind is stored in the battery (if available), and it is discharged when needed. If battery storage is not available, the excess wind is curtailed. Natural gas reciprocating engines are used to provide firm capacity, to meet the annual peak plus the reserve margin, and to meet all energy demand unmet by the wind and battery. Three scenarios are developed to assess the optimal system configurations to meet emission targets at minimum cost. The scenarios are described as follows:

- *Natural gas generation without any wind generation and energy storage*
- *Wind energy, natural gas generation*
- *Wind energy, energy storage, and natural gas generation*

2.2. Methods

2.2.1. Life Cycle Assessment

In this analysis, a full LCA is developed for the off-grid system to evaluate total GHG emissions. Fig. 2-1 shows the system boundary diagram for the LCA. The LCA is conducted using SimaPro© software, based on the material inventories for the wind turbine, VRFB, and natural gas engine and energy requirements for each stage during products lifespan from cradle-to-grave. IPCC 2007 GWP 100a was selected as LCA method in SimaPro© for all components. The functional unit for the LCA study is one kilowatt-hour of delivered electrical energy. The study horizon matches the 20-year lifetime of the system components. The system boundary for life cycle assessment is shown in Fig. 2-1.

Regarding the recycling methodology, the recycled-content approach is used in this LCA. In this method, environmental credits are received for the incoming raw-materials used to manufacture the wind turbine, VRFB and natural gas reciprocating engine based upon the actual recycled material content of these components. Incoming raw material impacts are distinguished between recycled and primary materials.

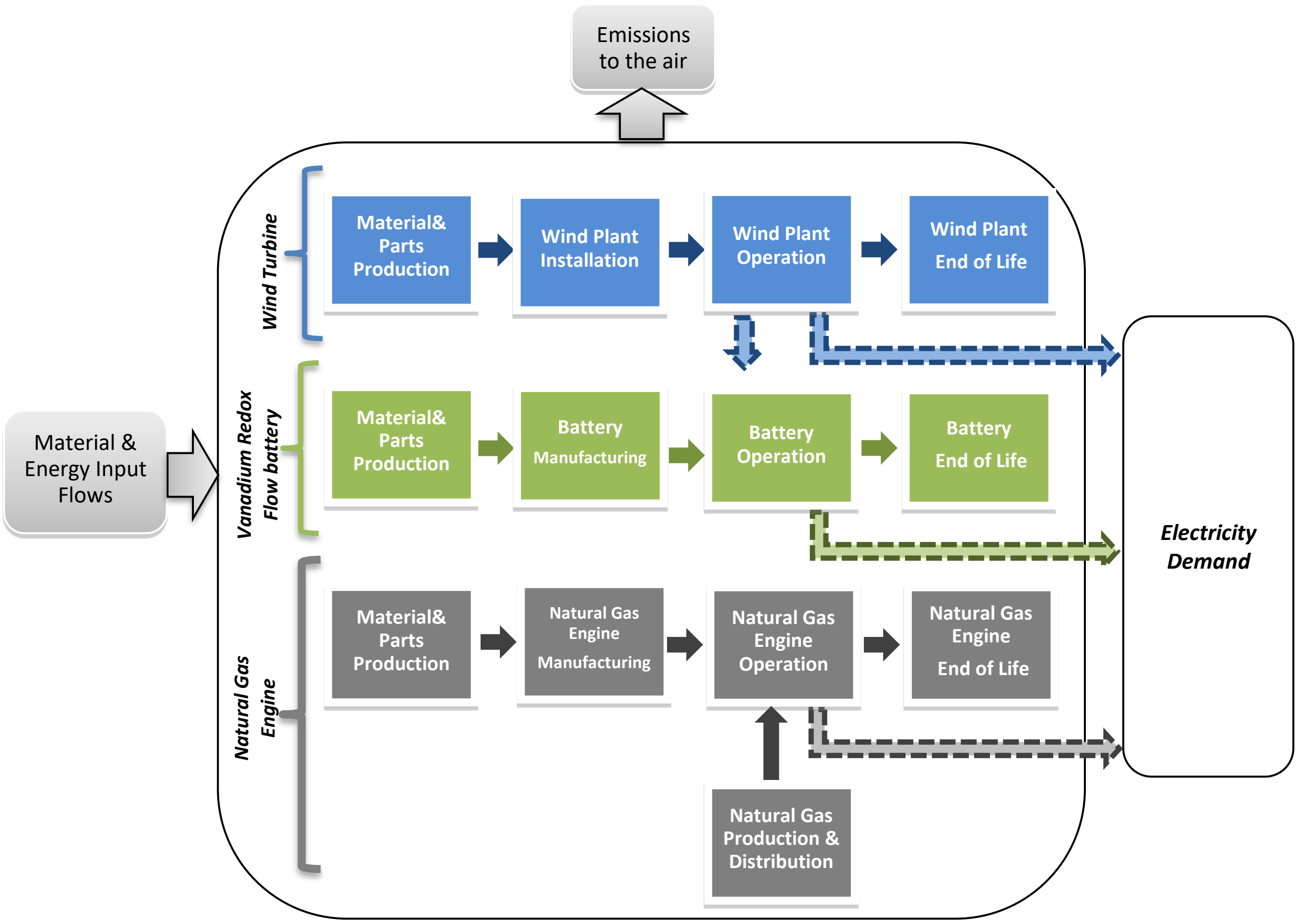

Fig. 2-1 LCA boundary for the off-grid system (The dashed lines show the electrical energy flow.)

2.2.2. Life Cycle Emissions Data

2.2.2.1. Natural Gas Reciprocating Engine and Fuel

Due to the small size of the island system, natural gas reciprocating engines (representative of Caterpillar G3616 LE, 3 MW) were selected to provide the natural gas generation when needed. The life cycle inventory for the engine includes the material requirements for the engine life cycle stages [25]. It is calculated that nine natural gas engines are required to provide firm capacity necessary to meet the annual peak plus the reserve margin and to meet all energy demand unmet by the wind and battery. The natural gas upstream and combustion emissions are calculated based on the engine performance parameters shown in Table 2-1. There are uncertainties associated with CH_4 leakages during natural gas production and transmission [28], [29], [30], therefore an analysis is done to test the sensitivity of the emissions targets to different upstream emission factors and the results are presented in the sensitivity analysis section.

Table 2-1 NG Reciprocating Engine Typical Performance Parameters

	Variable	**Unit**	**Value**
Nameplate Capacity [26]	P_{eng}	kW	3000
Electric Heat Rate [27]	HR	MMBtu/MWh	9.5
Natural Gas Upstream $CO_{2\text{-}eq}$ Emissions Factor [30]	EF_U	lb/MMBtu	35
Exhaust CO_2 Emissions Factor [27]	EF_O	lb/MWh	1,110
Total Installed Cost [27]	C_{eng}	$/kW	1,130
NG Variable Fuel Cost [31]	C_f	$/MMBtu	5.08
Non-Fuel NG Engine O&M Variable Cost [27]	VOM	$/MWh	10
Engine Weight [26]	M	kg	29,891
Lifetime	Y	years	20
Engine Manufacturing Emissions Factor [25]	$EF_{mfc,eng}$	kg of $CO_{2\text{-}eq}$/kg of engine	2

The total upstream emissions (E_u) are a function of the annual natural gas generation (NG) required in MWh, the engine heat rate (HR) in MMBtu/MWh, and the upstream emissions factor (EF_u) in lb/MMBtu. It is calculated during the life span of the project (Y), which is 20 years and is shown in Eq. 1. Also, the engine operating emissions ($E_{o,eng}$) during the same lifetime are dependent on annual fuel consumption (NG) in MWh and the exhaust emissions factor (EF_O) in lb/MWh, as shown in Eq. 2. β is the conversion factor to convert E_U and E_O units from pounds to grams of $CO_{2\text{-}eq}$ and is equal to 453.5.

$$E_u = Y * NG * HR * EF_u * \beta \qquad (Eq. 1)$$

$$E_{o,eng} = Y * NG * EF_o * \beta \qquad (Eq. 2)$$

The engine is constructed mainly from cast iron, steel and aluminum [25]. The recycled content (RC) of these metals and their primary and secondary GHG emissions factors are provided in Appendix B. The amount of primary (P) and secondary (S) materials for each component is calculated based on their RCs as shown in Eq.3 and Eq.4, where T is the metals' total masses (T, S and P are all in kg).

$$S = RC * T \qquad (Eq. 3)$$

$$P = T - S \qquad (Eq. 4)$$

Total GHG emissions associated with the production for each of these materials (E_t), using the recycled content approach, are calculated in Eq. 5 [32].

$$E_t = P * GHG_p + S * GHG_s \qquad (Eq. 5)$$

where GHG_p and GHG_s are the primary and secondary emissions factors for each metal respectively, both in kg of $CO_{2\text{-}eq}$ per kg of metal. Natural gas engine life cycle inventory includes other materials requirement such as rubber, bronze, polypropylene [25]. This inventory is implemented in Simapro©, choosing EcoInvent database version 2.2 and IPCC 2007 GWP 100a methodology. Therefore, the total engine's material production emissions are calculated in Eq.6.

$$E_{mtrl,eng} = E_t + E_{other,eng} \qquad (Eq. 6)$$

where $E_{other,eng}$ is the emissions results from Simparo© in kg of $CO_{2\text{-}eq}$. The manufacturing emissions are calculated per kg of engine, based on the life cycle inventory, therefore the total emissions associated with the manufacturing of the engine in terms of $CO_{2\text{-}eq}$ is calculated in Eq.7.

$$E_{mfc,eng} = M * EF_{mcf,eng} \qquad (Eq. 7)$$

where M is the engine's total mass in kg and $EF_{mcf,eng}$ is the engine manufacturing emissions factor in kg of $CO_{2\text{-}eq}$ per kg of engine.

2.2.2.2. Wind Turbine

The wind turbine selected for this study is represented as a Vestas V90-3MW wind turbine. The wind speed data throughout the year 2013 is obtained from West Shore Estates weather station, which has the weather forecast and also historical data for Grosse Ile Township, MI for the past two decades [33]. The year 2013 is chosen as it represented the most recent year for which complete wind speed data was available at the time of the analysis. The wind speeds are calculated at the wind turbine hub height, which is 80 meters and it is assumed that Hellman coefficient for neutral air above human inhabited areas is 0.34 [34]. The annual wind generation of one turbine in the location is calculated using the wind turbine power curve [35] and is equal to 8585 MWh, yielding a capacity factor of approximately 33%.

The wind turbine life cycle inventory includes the material breakdown of Vestas V90-3 MW, foundation, cables, switch gears and transformers and energy requirement for manufacturing, transportation and end of life stages [36]. The life cycle inventory is utilized in SimaPro© (utilizing EcoInvent database version 2.2 and IPCC 2007 GWP 100a method) to quantify the total life cycle emissions of the wind turbine. The total life cycle emissions include the wind turbine and site parts material production ($E_{mtrl,w}$), ($E_{mtrl,site}$), wind power plant installment (E_{inst}) and operation phase (E_o) emissions all in kg of $CO_{2\text{-}eq}$. The environmental crediting for recycling is given at the material production stage based on the metals recycled contents and primary and secondary GHG emissions factors provided in Appendix B.

2.2.2.3. Vanadium Redox Flow Battery

In a flow battery, the electrolyte contains one or more dissolved electroactive species flowing through a power cell in which the chemical energy is converted to electricity. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cell of the reactor. The power rating is independent of the storage capacity and is determined by the quantity of electrolyte used [19]. VRFB stores energy by employing vanadium redox couples V2+/V3+ in the negative and V4+/V5+ in the positive half-cells.

In this study, it is assumed that the battery has a round-trip efficiency (η) of 75% [19] and the battery's ramp rate is sufficient enough to respond the changes in load and wind generation. The safe operating window for the battery is assumed to be 10 to 90 percent state of charge. The life cycle inventories include the material and energy requirements during different life cycle stages of VRFB [19], [37]. There are two groups of materials in the structure of a VRFB. The first group includes those materials that are used for the production of cell components such as electrodes, ion-exchange membrane and pumps. The amounts of these materials are dependent on the battery power rating (P_B) in MW. On the other hand, the second group includes the materials that are used for the production of storage components such as electrolyte and storage tanks and are dependent on the storage capacity of the battery (S) in MWh. Therefore the material production emissions comprise two parts; storage-dependent materials emissions in grams of $CO_{2\text{-}eq}$ per kWh ($E_{mtrl,S}$) and power-dependent materials emissions in kg of $CO_{2\text{-}eq}$ per kW ($E_{mtrl,P}$). All materials are assumed to be primary material without any recycled content. The battery operation phase is modeled as the amounts of materials required to be replaced during the 20-year lifetime of the battery and is included in the material inventory [19]. Other emissions include the battery production emissions ($E_{P,B}$) and are dependent on the battery storage capacity based on the inventory and their units are in grams of $CO_{2\text{-}eq}$ per kWh of storage capacity. The inventory is implemented in SimParo© utilizing EcoInvent database version 2.2 and IPCC 2007 GWP 100a method.

2.2.2.4. System of Equations

The total environmental impact (E) of the off-grid system during 20-year lifetime (Y) is compromised of the life cycle emissions of the system components; wind turbine environmental impact (I_W), VRFB environmental impact (I_B), and natural gas reciprocating engine environmental impact (I_{eng}). All impacts are defined in grams of $CO_{2\text{-}eq}$ per kWh electricity delivered to the electrical demand (g $CO_{2\text{-}eq}$ /kWh). Eq. 8 shows that I_{eng} is a function of the annual required natural gas (NG) in MWh. I_w is also a function of number of wind turbines (T) and the annual delivered megawatt-hours of wind energy (W) (Eq. 9) and I_B is dependent on storage capacity (S) in MWh (Eq. 10). The total GHG emissions of the integrated system (E) is calculated in Eq. 11 based on each components' impact and the fraction of delivered electricity that is provided by wind (Dw), VRFB (D_B) and the NG engine (D_{NG}).

$$I_{eng}(\frac{g\ CO_{2eq}}{kWh_e}) = \frac{E_u + E_{mtrl,eng} + E_{mfc,eng} + E_{o,eng}}{NG * Y} \qquad (Eq. 8)$$

$$I_w(\frac{g\ CO_{2eq}}{kWh_e}) = \frac{E_{mtrl,site} + T * (E_{mtrl,w} + E_{inst,w} + E_{o,w})}{W * T * Y} \qquad (Eq. 9)$$

$$I_B(\frac{g\ CO_{2eq}}{kWh_e}) = \frac{E_{mtrl,S} * S + E_{mtrl,P} * P_B + E_{P,B} * S}{S * Y} \qquad (Eq. 10)$$

$$E\left(\frac{g\ CO_{2eq}}{kWh_e}\right) = I_w * D_w + I_{eng} * D_{NG} + I_B * D_B \qquad (Eq. 11)$$

The total cost of the off-grid system in terms of $/MWh delivered electricity is quantified based on each component costs. D is the total electrical demand that is supplied annually and is defined in megawatt-hours. The fixed cost ($C_{fixed,eng}$) and the annual variable costs ($C_{var,eng}$) of natural gas are calculated in Eq. 12 and Eq. 13 assuming 16% carrying cost (CC_{eng}) to cover return on equity, debt, payments, fixed O&M, taxes, insurances and the values of any subsidies. The fixed cost is a function of the reciprocating engine installed cost (C_{eng}) in \$/kW and its nameplate capacity (P_{eng}) in kW, which is assumed to be 3 MW for each of the nine reciprocating engines. While, the variable cost is a function of natural gas fuel cost (C_f) in \$/MMBtu, annual required natural gas generation (NG) in MWh, heat rate (HR) in MMBtu/MWh and variable operation and maintenance costs (VOM) in \$/MWh.

$$C_{fixed,eng}(\$) = C_{eng} * P_{eng} * CC_{eng} \qquad (Eq. 12)$$

$$C_{var,eng}(\$) = NG * (C_f * HR + VOM) \quad (Eq. 13)$$

To calculate the cost of wind energy, the total installed cost (C_w) of 2000 \$/kW and 12% carrying cost (CC_w) are assumed for the wind turbine [38], [43]. The Allowance for Funds During Construction (AFUDC) is equal to 3% of overnight costs [39]. The wind capacity is 3 MW for each wind turbine (P_w). Therefore, the annual total cost of the system is calculated as shown in Eq. 14.

$$C_{wind}(\$) = T * C_w * P_w * CC_w \qquad (Eq. 14)$$

Total cost of energy storage is calculated based on the battery components' cost, segmented into costs driven by storage capacity (MWh) and costs driven by rated power (MW), both in \$. The stack cell components' costs ($C_{battery/power}$) are dependent on the rated power of the battery and the storage components costs ($C_{battery/storage}$) are based on the storage capacity of the battery. There are different values presented in the literature for the capital costs of VRFB [40], [41], [42], therefore a sensitivity analysis is done for different battery costs (section 3.4). It is assumed that the power-related capital costs are \$1,111/kW and energy-related costs are \$215/kWh [41] and carrying cost (CC_B) is 16% as shown in Eq. 15

$$C_B(\$) = CC_B(C_{battery/power} + C_{battery/storage}) \qquad (Eq. 15)$$

Finally, the total cost of the off-grid system (C) in \$/MWh comprises of the share of each component in the delivered cost as shown in Eq.16:

$$C(\frac{\$}{MWh}) = \frac{(C_B + C_{wind} + C_{fixed,eng} + C_{var,eng})}{D} \qquad (Eq. 16)$$

In the first scenario, the total electricity demand of the island grid is met by natural gas without any renewable energy generation or any stored energy in the battery. As mentioned earlier, the island's annual total electricity demand is 115,523 MWh and in this scenario the only generation is natural gas. The environmental emissions are calculated based on the $CO_{2\text{-eq}}$ emitted in each stage utilizing the data provided in Table 2-1 and the life cycle inventory [25].

In the second scenario, wind generation is a must-take resource and natural gas reciprocating engines are used to meet all electrical demand unmet by wind. Eq.17 and Eq. 18 show how hourly electrical demand, D (i) is met in this scenario and Eq.19 defines wind curtailment i.e. wind generation that cannot be delivered or stored.

$$W(i) = \begin{cases} W_G(i), & W_G(i) < D(i) \\ D(i), & W_G(i) \geq D(i) \end{cases} \quad (Eq. 17)$$

$$NG(i) = \begin{cases} D(i) - W_G(i), & W_G(i) < D(i) \\ 0, & W_G(i) \geq D(i) \end{cases} \quad (Eq. 18)$$

$$W_{curt}(i) = \begin{cases} W_G(i) - D(i), & W_G(i) > D(i) \\ 0, & W_G(i) \leq D(i) \end{cases} \quad (Eq. 19)$$

where W(i) is the delivered wind energy at hour i, W_G (i) is the amount of wind generation at hour i and NG(i) is the amount of required natural gas at hour i, and finally W_{curt}(i) is wind curtailment at hour i; all in MW. In this scenario two components of natural gas engine and wind turbine are included in the system; therefore, the total environmental impact of the system (E) is estimated by adding the two components' environmental impact based on their share in providing electricity to the demand (D_{NG} and D_w).

The last scenario includes all three components of wind generation and energy storage and natural gas reciprocating engine. In this case, wind is treated as a must-take resource as well. Excess wind is stored in the battery, and it is discharged (assuming 75% round-trip efficiency) when there is not enough wind generation. Natural gas generation is used to meet all energy demand unmet by the wind and battery, as shown in Eq. 20 to Eq. 23.

$$W(i) = \begin{cases} W_G(i), & W_G(i) < D(i) \\ D(i), & W_G(i) \geq D(i) \end{cases} \quad (Eq. 20)$$

$$B_R(i) = \begin{cases} W_G(i) - D(i), & W_G(i) > D(i) \\ \left(\frac{1}{0.75}\right) * (W_G(i) - D(i)), & W_G(i) < D(i) \end{cases} \qquad (Eq.21)$$

$$NG(i) = \begin{cases} D(i) - W_G(i), & W_G(i) < D(i), SOC(i) = 10\% \\ 0, & W_G(i) \geq D(i)\ or\ SOC(i) > 10\% \end{cases} \qquad (Eq.22)$$

$$W_{curt}(i) = \begin{cases} W_G(i) - D(i), & W_G(i) > D(i), SOC(i) = 10\% \\ 0, & W_G(i) \leq D(i) \end{cases} \qquad (Eq.23)$$

where $B_R(i)$ is the battery power rating at hour i in MW, and SOC(i) is battery's state of charge as a percentage of the total storage capacity.

Finally, different emissions targets are defined for the off-grid system to determine the combination of components at which adding energy storage to the system is more cost-effective than adding another wind turbine, considering the wind curtailment. Eq.24 shows how the design variables i.e. number of turbines (T) and battery capacity (B) in MWh are defined to meet the required target (in g of $CO_{2\text{-eq}}$/kWh) at the least cost:

$$Define\ (T, B) \rightarrow\ so\ as\ to\ minimize\ C(T, B) \qquad (Eq.24)$$

$$subject\ to\ E(T, B) < target$$

2.3. Results

2.3.1. Life Cycle Assessment Results

The results of the LCA analysis over the 20-year lifetime of the system components are shown in Table 2-2 as GHG emissions by life cycle stage for the natural gas reciprocating engine, wind turbine, and VRFB. These values are used to determine the environmental impact of the system in each scenario.

Table 2-2 Life Cycle GHG Emissions Results

Life Cycle Stage			Variables	Emissions
Engine	Material & Parts Production		$E_{mtrl,eng}$	78*10^3 (kg of $CO_{2\text{-}eq}$ per engine)
	Manufacturing		E_{mfc}	59*10^3 (kg of $CO_{2\text{-}eq}$ per engine)
Wind Turbine	Material & Parts Production	Wind Turbine, Foundation and Switch Gear	$E_{mtrl,w}$	7.3*10^5 (kg $CO_{2\text{-}eq}$ per turbine)
		Other Site parts	$E_{mtrl,\ site}$	23*10^5 (kg $CO_{2\text{-}eq}$)
	Wind Plant Installment		E_{inst}	34,172 (kg $CO_{2\text{-}eq}$ per turbine)
	Wind Plant Operation		Eo	68,300 (kg $CO_{2\text{-}eq}$ per turbine)
VRFB	Material & Parts Production	Storage dependent	$E_{mtrl,s}$	34,800 (g of $CO_{2\text{-}eq}$/kWh)
		Power rating dependent	$E_{mtrl,p}$	160,600 (g of $CO_{2\text{-}eq}$/kW)
	Battery Production		E_P	55,000 (g of $CO_{2\text{-}eq}$/kWh)

2.3.2. Scenarios Analysis Results

In the pure natural gas scenario, the total life cycle emissions of $CO_{2\text{-}eq}$ into the air are 650 g of $CO_{2\text{-}eq}$/kWh. The total cost of the delivered electricity is $105/MWh, which includes fixed costs and variable fuel and maintenance costs. The results of other scenarios are shown in Fig. 2-2(a) and Fig. 2-2(b). In each case, the number of wind turbines is selected to be 0, 5, 10, 15, 20 and 25 turbines. A full table of results, including number of turbines, storage capacity and wind curtailment in each scenario is provided in Appendix C. The results show that in the second scenario with combination of natural gas and wind generation, increasing wind penetration reduces the total emissions, while the environmental impact of the renewable energy is less than 2% of the whole impact of the off-grid system. On other hand, the cost of wind energy is the significant component in the total cost compared to fossil fuel. (Each component's share in total emissions and total costs are presented in Appendix C).

The results of the last scenario, which includes all three components of renewable energy, fossil fuel combustion and energy storage are shown in Fig. 2-2(b). In this case, the size of the storage is held constant at 400 MWh to determine the effect of increasing wind penetration in total emissions and cost. The amount of wind curtailment is less than the scenario without energy storage (Appendix C).

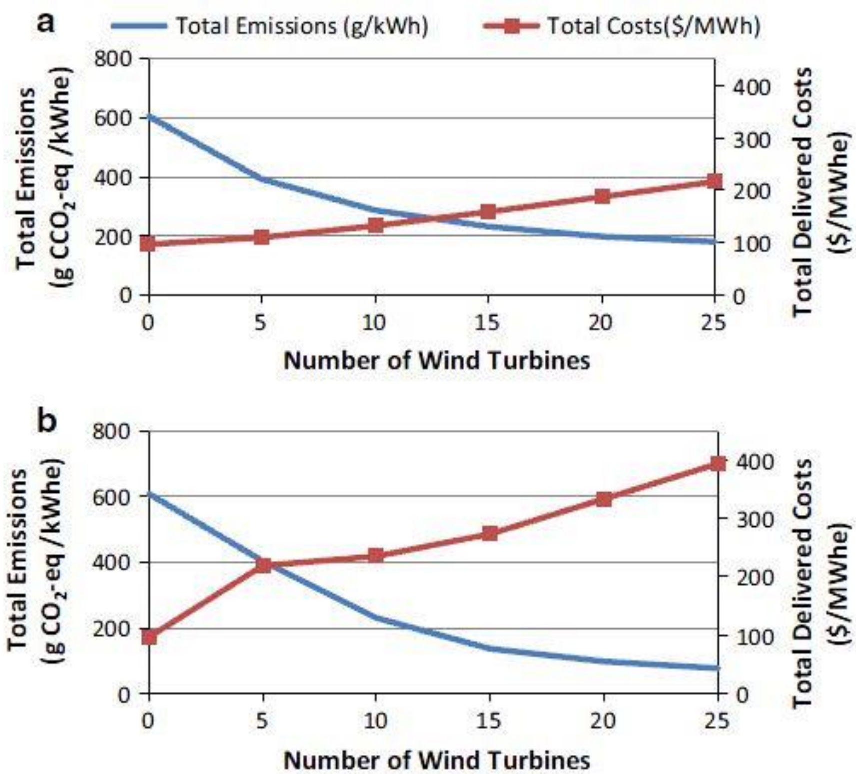

Fig. 2-2 (a) Total emissions and total costs of the system in scenario 2 with natural gas combustion and wind energy. (b) Total emissions and total costs of the system in scenario 3 with natural gas combustion and wind energy integrated with VRFB as energy storage. (The storage capacity is held constant at 400MWh.)

2.3.3. Optimization Results

This section details the total environmental impact and total cost of the off-grid system for a range of wind turbines and VRFB storage capacity. Fig. 2-3 shows the total emissions and total costs of the off-grid system for different combinations of system components: wind generation, energy storage and natural gas. Under the cases where wind and/or VRFBs are added, life cycle $CO_{2\text{-eq}}$ emissions decrease, as compared to natural gas only case, which yielded 650 g of $CO_{2\text{-eq}}$/ kWh. It also shows that, while there are emissions associated with different life cycle stages of VRFBs, their integration promises decreasing total system life cycle emissions.

Fig. 2-4 shows the total costs of the off-grid system also for different combinations of wind turbines, storage capacity and natural gas. All scenarios show an increase in cost over the pure natural gas case, which yielded delivered cost of $105/MWh. It is noticeable that adding renewable energy integrated with energy storage can reduce the environmental impact of the system significantly but at the same this adds more cost to the system. Fig. 2-5 shows this trade-off in the concept of cost of carbon mitigation. The costs and emissions in each combination of wind turbines and battery capacities are compared to the pure natural gas scenario to evaluate the cost of carbon mitigation, as calculated in Eq. 25.

$$C_{carbon}\left(\frac{\$}{tons\ of\ CO_{2eq}}\right) = \frac{C(T,B) - C_{NG}}{\left(E_{NG} - E(T,B)\right) * \delta} \qquad (Eq. 25)$$

where C_{NG} is the total delivered costs in pure natural gas case in $/MWh and E_{NG} is the total emissions in that case in g of $CO_{2\text{-}eq}$/kWh, and δ is the conversion factor to convert grams into tons and is equal to $1.1 * 10^{-6}$.

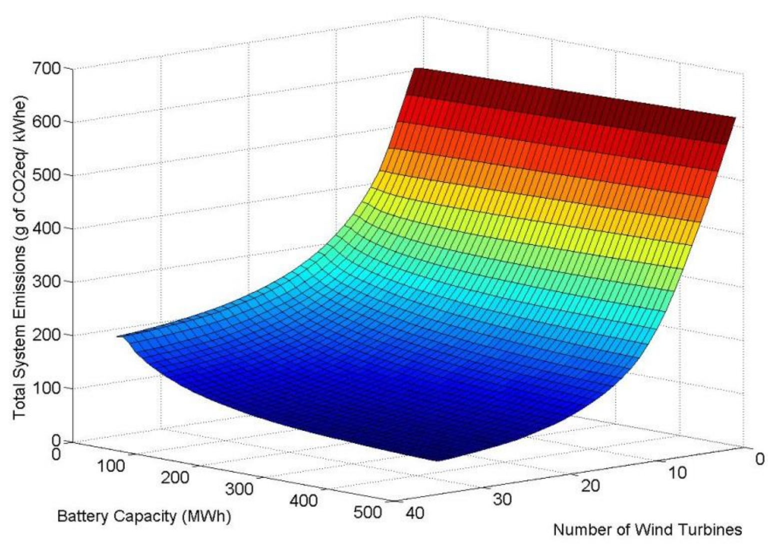

Fig. 2-3 Total emissions of the system (in g of $CO_{2\text{-}eq}$/kWh) in different system configuration

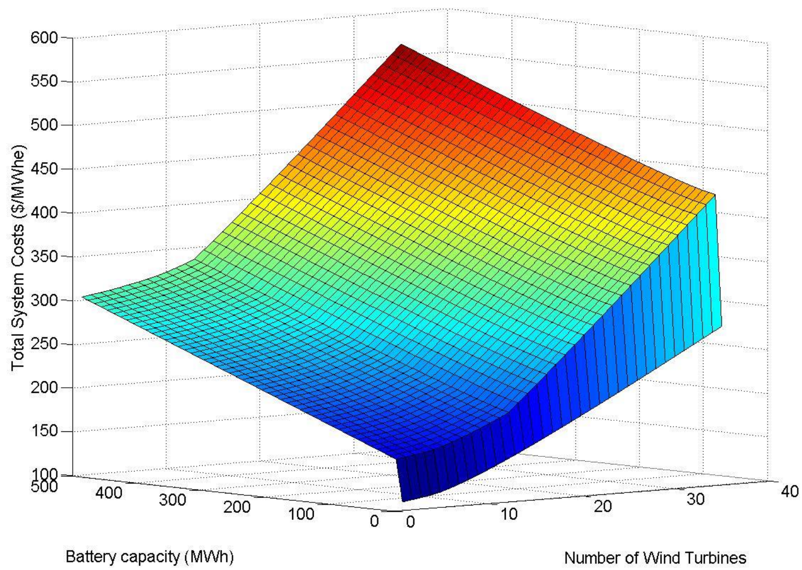

Fig. 2-4 Total costs of the system (in $/MWh) in different system configuration

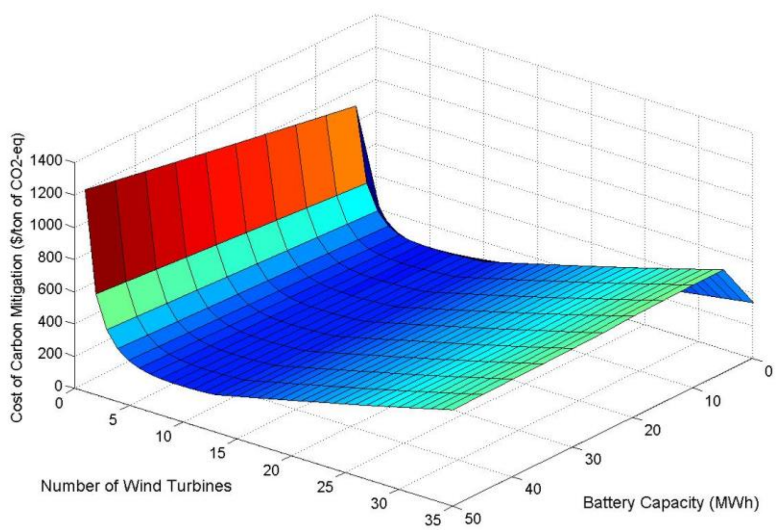

Fig. 2-5 Cost of carbon mitigation in different system configuration (minimum at T=1, B=0)

Fig. 2-6. shows the wind curtailment in different combination of system components. The maximum wind curtailement occurs when the maxiumum number of wind turbines are available without any energy storage integration.

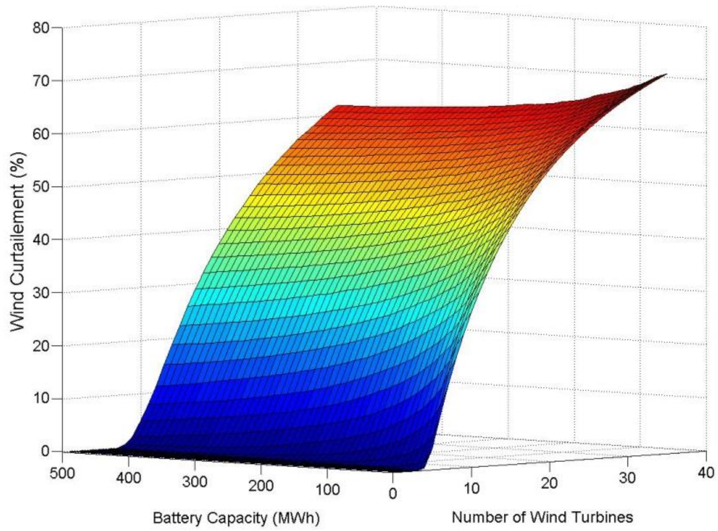

Fig. 2-6 Wind curtailment in different system configurations

Next, emissions targets are defined in the range of 100 to 650 g of $CO_{2\text{-eq}}$/kWh with increment of 10 g/kWh to determine the combination of components at which adding energy storage to the system is more cost-effective than additional wind capacity. For each life cycle emissions target, the number of wind turbines and the amount of battery storage capacity are determined to meet the minimum cost configuration. The optimization results show that with emission targets equal to and less than 190 g/kWh, adding energy storage to the system is a more cost-effective solution than adding more wind energy.

Table 2-3 Life cycle emissions target optimization results

Emission Target (g of $CO_{2\text{-eq}}$/kWh)	Number of Wind Turbines	Battery Capacity (MWh)	Wind Curtailment (%)	Delivered Energy Cost ($/MWh)
100	25	300	50.2	394.5
110	23	290	46.6	370.9
120	22	250	45.4	349.2
130	21	220	44.1	330.4
140	20	200	42.5	314.6
150	19	180	40.9	298.9
160	18	170	38.9	286
170	17	160	36.8	273.1
180	16	150	34.4	260.4
190	15	150	31.2	250.5
200	28	0	65.6	233.3
210	24	0	61	208.1
220	22	0	58.2	197.8
230	20	0	55.1	186.3

240	18	0	51.5	174.8
250	17	0	49.4	169.2

Based on the results in Table 2-3, integrating energy storage is not cost-effective to achieve the emissions targets of 200 g of $CO_{2\text{-eq}}$/kWh and higher. Also, the energy storage becomes economically viable when the wind curtailment reaches approximately 66%.

2.3.4. Sensitivity Analysis

A sensitivity analysis was conducted to test the results of the breakeven emissions target where VRFB are used against several assumptions. Results are most sensitive to battery cost, natural gas upstream emissions, wind price, and battery round-trip efficiency (η). The assumptions for the base case are provided in Appendix D. The tornado chart in Fig. 2-7 represents the results of the analyses. The breakeven emissions target for the viability of energy changed in a range of 160-260 g/kWh in different scenarios.

It is clear that the natural gas upstream emissions and battery costs have the highest contributions to the uncertainty of the results. There are large uncertainties associated with the natural upstream emissions indicated by the wide range of values presented in the literature; and in addition to this uncertainty, there is also variability based on natural gas sources [28], [29], [30]. The main difference is in the amount of methane leakage during natural gas production. For instance, a range of 0.97% to 5.47% of NG produced is estimated for conventional NG and a range of 0.71% to 5.23% is estimated for shale gas, while a range of 0.972 to 1.629 grams of CO_2 per MJ of NG is estimated for both gases [30]. In this study, the global warming potential (100-year) of 21 is used for methane [44]. Therefore, a range of 10 to 60 lbs/MMBtu is assumed for the natural gas upstream emissions factor, and the mean value (35 lbs/MMBtu) is considered to be the base case value.

To find the sensitivity of the result to the battery component costs, two cases were defined for the VRFB; the low cost battery and the high cost one. It is assumed that the most expensive battery costs $1,143/kW and $356/kWh, while the cheapest (optimistic) battery costs $382/kW and $78/kWh [40]. If the low cost battery becomes available, the energy storage outweighs the cost of wind curtailment at higher emissions target of 250 g/kWh.

The onshore wind overnight capital cost has fluctuated in the range of 1200 to 2600 $/kW in the past five years [43] and the results were tested for this range of wind price. For the round-trip efficiency of the VRFB, a range of 65% to 90% is assumed. The results show that emissions target does not change by decreasing the round-trip efficiency from 75% (base case) to 65%.

The Michigan natural gas price sold to electric power consumers has changed between $3.37/MMBtu to $12.09/MMBtu from April 2013 to April 2014 [31]. The emissions target was tested to this range of fuel price. However, the result was not sensitive to the natural gas fuel cost, due to the high cost of the battery and the wind energy price compared to the fuel; and also wind and battery power exceeded natural gas cost.

	Low value	Base case	High value
wind price ($/kW)	1200	2000	2600
battery cost	$382/kW+ $78/kWh	$1,111/kW +$215/kWh	$1,143/kW +$356/kWh
NG upstream emission factor (lb/MMBtu)	10	35	60
round-trip efficiency (%)	65	75	90

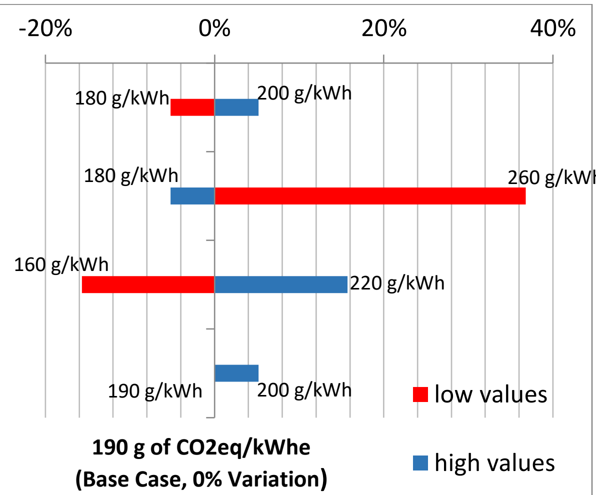

Fig. 2-7 Results of sensitivity analysis to wind price, battery cost, NG upstream emissions factor and round-trip efficiency

2.4. Conclusions and Discussion

Environmental and economic metrics of an off-grid electrical system are evaluated in different configurations to determine the effect of energy storage on total emissions and total system costs. Life cycle assessment is utilized to analyze the emissions associated with different life cycle stages of the system components: wind plant, vanadium redox flow battery, and natural gas reciprocating engine. The relationship between system life cycle emissions and total costs are utilized to determine emissions targets, for which VRFBs are lower cost option. The optimization results show that energy storage reduces the wind curtailment and life cycle emissions significantly, and at greenhouse gas emissions target of 190 g of $CO_{2\text{-}eq}$/kWh and lower, energy storage can be a lower cost alternative. The cost of the battery is still high and potentially volatile, and can change the results significantly. The results are also sensitive to natural gas upstream emissions and wind energy capital cost and battery round-trip efficiency.

This research combines both environmental and economic sustainability metrics of large-scale integration of energy storage to define different GHG emissions targets in a cost-effective configuration comprising renewable energy, energy storage, and natural gas generation. Other studies focus on economic and environmental aspects of integrating energy storage, without addressing emissions targets which is a critical criterion especially for decision and policy makings.

EPA has proposed CO_2 emissions targets to cut carbon pollution from existing power plants under Clean Power Plan [45]. At the time this research was conducted, this plan aimed to help cut carbon emissions from the power sector across the country by 30 percent from 2005 levels by 2030[46]. For example, the final GHG emissions goal (2030 and thereafter) for the state of Michigan was proposed 526.6 g of $CO_{2\text{-eq}}$/kWh at this time [47]. The state emissions goal reflects a composite emissions rate including fossil and zero emitting non-fossil technologies and vary in different states based on their pre-existing technologies and generations. Integration of variable renewable energies such as wind or solar into existing electrical grid can help reduce the carbon emissions from electricity generation and therefore help states achieve these emissions targets. This research suggests that energy storage integration shows promise for lowering the total life cycle emissions, for systems with high levels of wind curtailment.

The case study is an isolated electrical load without any grid connection. Therefore, it is assumed that the isolated electrical demand can be supplied entirely by the off-grid system and the adjacent electrical grid infrastructure is not considered. However, the life cycle emissions associated with several life cycle stages of the system's components will not change even if the system is connected to the electrical grid. The full LCA presented in this study could be extended to examine grid-connected systems as well, with life cycle modeling of the battery storage systems and utility scale applications informing the optimal solution to reach low GHG targets sets depending on grid profiles (fuel mix, renewables and demand) and dispatch models for a specific region.

The demand for battery energy storage has increased in line with growing attempts to integrate renewable energies into the grid. From a policy perspective, California in 2010 passed legislation, requiring 1,325 MW of electricity storage by 2024 (excluding large-scale pumped storage) [48]. In practice, one of the largest utility-scale operational electricity storage is a 4 MW sodium-sulfur (NaS) battery system in Presidio, Texas. This energy storage facility was started in 2010 to provide rapid back up to voltage fluctuations and momentary fluctuations in the ERCOT grid due to its quick response [48]. Among battery storage technologies, VRFBs have potential applications such as renewables integration, ramping, electric supply capacity, renewables capacity firming, micro-grid capability and load leveling [48]. VRFB technology can be a possible match to the needs of utility-scale wind farms. Wind energy charges the batteries and then storage system discharges to regulate the wind farm output to the grid requirements. When wind speed changes over the course of a few seconds, the storage system flattens the frequency fluctuations that would happen, maintaining the quality of power delivered to the consumers [42], [49].

This study helps to develop a set of guidelines for improving the early stage battery chemistry research and development that addresses the battery storage systems and their requirements for utility scale applications. Vanadium is the significant element in VRFB construction; future studies could consider whether the availability of vanadium is a constraint to large scale deployment of VRFB. Accordingly, a future study can be developed based on the results of this research to investigate how economic and environmental sustainability metrics shape the battery design process with the goal of reducing the components costs, so that energy storage integration becomes cost-effective at higher emissions targets. Finally, this research will advance the application of life cycle analysis methods to energy storage systems and provide a better understanding of the role of energy storage in achieving emissions goals.

Appendices

Appendix A.

Table 2-4 Definition of variables

Total demand	MWh	D
Annual natural gas generation	kWh	NG
Heat rate	Btu/kWh	HR
Upstream air emissions factor	lb/MMBtu	EF_U
Upstream emissions	g/kWh	E_U
Engine operating emissions factor	lb/MWh	EF_O
Engine manufacturing emissions factor	kg of $CO_{2\text{-eq}}$/kg of engine	$EF_{mfc,engine}$
Operating emissions	grams of $CO_{2\text{-eq}}$	E_O
Material production emissions	grams of $CO_{2\text{-eq}}$	E_{Mtl}
Manufacturing emissions	grams of $CO_{2\text{-eq}}$	E_M
Installment emissions	grams of $CO_{2\text{-eq}}$	E_{Ins}
End of life emissions	grams of $CO_{2\text{-eq}}$	E_{EOL}
Natural gas engine fixed installed cost	$/kW	C_{eng}
Natural gas engine fixed cost	$	$C_{fixed,eng}$
Natural gas engine variable cost	$	$C_{var,eng}$
Natural gas engine rated power	MW	P_{eng}
Natural gas fuel cost	$/MMBtu	C_f
Variable operations and maintenance costs	$/MWh	VOM
Number of turbines	-	T
Wind turbine installed cost	$/MW	C_w
Installed wind capacity	MW	P_w
Annual wind cost	$/MWh	C_{wind}
Battery installed cost	$/kW $/MW-h	$C_{battery,power}$ $C_{battery,storage}$
Carrying cost	%	CC
Natural gas engine environmental impact	g $CO_{2\text{-eq}}$/kWh	I_{eng}
Wind plant environmental impact	g $CO_{2\text{-eq}}$/kWh	I_w
Battery environmental impact	g $CO_{2\text{-eq}}$/kWh	I_B
Total emissions of the system	g $CO_{2\text{-eq}}$/kWh	E
Total cost of the system	$/MWh	C
Total wind delivered to demand	kWh	W
Storage capacity	kWh	S
Battery power rating	kW	P_B
Total cost of battery	$	C_B
Total electricity generation of the battery	kWh	B
Percentage of demand met by NG	%	D_{NG}
Percentage of demand met by battery	%	D_B
Percentage of demand met by wind	%	D_W
Cost of carbon mitigation	$/g of CO_2	C_{carbon}

Appendix B. The assumption for recycled content methodology

Table 2-5 The assumption for recycled content methodology

Material	Recycled Content (%)	Reference	Emissions Factor of Primary Material	Reference	Emissions Factor of Secondary Material	Reference
Steel & Iron	41	[50]	1.5	[52]	0.1	[52]
Cast Iron	90	[51]	2.08	[53]	1.4	[53]
Aluminum	36	[50]	11.9	[53]	1.6	[53]
Copper	30	[50]	1.9	[53]	0.9	[53]

Appendix C. Scenario Analysis Details

Appendix C.1.

Table 2-6 Life cycle emissions in different scenarios

Scenario	Number of Turbines	Battery Energy Storage (MWh)	Battery rating (MW)	Wind Emissions (g/kWh)	Battery Emissions (g/kWh)	NG Engine Emissions (g/kWh)	Total Emissions (g/kWh)
2	5	0	0	2.8	0	417.9	420.7
	10	0	0	4.6	0	308.1	312.7
	15	0	0	6.4	0	250.4	256.8
	20	0	0	8.2	0	216.8	225
	25	0	0	10	0	194.8	204.8
3	5	400	29.2	2.8	18	416.5	437.3
	10	400	29.2	4.6	18.1	228.7	251.4
	15	400	35.3	6.4	14.5	135.2	156.1
	20	400	50.3	8.2	19.5	89.9	117.6
	25	400	65.3	10	20.6	61	91.6

Appendix C.2.

Table 2-7 Contribution to total cost of delivered electricity in different scenarios

Scenario	Number of Turbines	Battery Energy Storage (MWh)	Battery rating (MW)	Wind Cost[a] ($/MWh)	Battery Cost[a] ($/MWh)	NG Engine Cost[a] ($/MWh)	Total Delivered Cost[a] ($/MWh)
2	5	0	0	31.1	0	79.6	110.7
	10	0	0	62.3	0	69.8	132.1
	15	0	0	93.4	0	64.6	158
	20	0	0	124.6	0	61.6	186.2
	25	0	0	155.8	0	59.6	215.4
3	5	400	29.2	31.1	164.1	79.3	274.5
	10	400	29.2	62.3	164.1	62.7	289.1
	15	400	35.3	93.4	173.5	54.3	321.2
	20	400	50.3	124.6	196.6	50.2	371.4
	25	400	65.3	155.8	219.7	47.7	423.2

Note: a) per MWh of total delivered electricity.

Appendix C.3.

Table 2-8 Electricity storage/generation cost by technology type

Scenario	Number of Turbines	Battery Energy Storage (MWh)	Battery rating (MW)	Wind Cost [b] ($/MWh)	Battery Cost [c] ($/MWh)	NG Engine Cost [d] ($/MWh)
2	5	0	0	87.3	0	123.9
	10	0	0	118.4	0	147.3
	15	0	0	152	0	167.9
	20	0	0	186.9	0	184.9
	25	0	0	222.4	0	199.2
3	5	400	29.2	87.3	2.4*10^4	124.6
	10	400	29.2	118.4	1.3*10^3	178.3
	15	400	35.3	152	978.8	261.5
	20	400	50.3	186.9	1000	364.2
	25	400	65.3	222.4	1060	509.8

Note: b) per MWh of Wind electricity delivered. Excludes wind electricity stored in battery.
Note: c) per MWh of stored electricity delivered.
Note: d) per MWh of NG electricity delivered.

Appendix D.

Table 2-9 Base case assumptions

NG variable fuel cost [31]	C_f	5.08 ($/MMBtu)
Natural gas upstream CO_2 emissions [30]	EF_U	35 (lb/MMBtu)
wind overnight capital cost [43]	C_w	2,000 ($/kW)
Battery cost [41]	$C_{battery/power}+C_{battery/storage}$	$1,111/kW+$215/kWh
Round-trip efficiency [19]	η	75%

Appendix E.

Table 2-10 Life cycle inventory sources

Technology	Life Cycle Inventory Source
Natural Gas Reciprocating Engine	• V.M. Smith, G.A. Keoleian, "The value of remanufactured engines," *Industrial Ecology*, vol. 8, issue 1-2, p. 193-221, 2004. • Energy and Environmental Analysis, "Technology Characterization: Reciprocating Engines," EPA: Washington, DC, 2008. • Burnham, J. Han, C. E. Clark, et al., "Life-cycle greenhouse gas emissions of shale gas, natural gas, coal and petroleum," *Environmental Science & Technology*, vol. 46, p. 619-627, 2012.
Wind Turbine	• P. Garret, K. Ronde, "Life cycle assessment of electricity production from an onshore V90-3MW wind plant," Vestas Wind Systems, Denmark, 2012.

VRFB	• C. Rydh, “Environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage,” *Journal of Power Sources*, vol. 80, p. 21-29, 1999. • N. Jungbluth, R. Frischknecht, “Life cycle assessment for vanadium pentoxide from secondary resources,” ESU-Services (fair conducting in sustainability), Uster, 2001.

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CHAPTER 3
Twelve principles for green energy storage in grid applications

Abstract

Energy storage technologies represent a potential solution for several grid applications such as integration of renewables and deferring investments in transmission and distribution infrastructure. The integration of energy storage systems into the electrical grid can lead to different environmental outcomes based on the grid application, the existing generation mix, and the demand. Given this complexity, a framework is needed to systematically inform design and technology selection about the environmental impacts that emerge when considering energy storage options to improve sustainability performance of the grid. To achieve this, 12 fundamental principles specific to the design and grid application of green energy storage systems are developed to inform policy makers, designers, and operators. The principles are grouped into three categories: (1) system integration for grid applications, (2) the maintenance and operation of energy storage, and (3) the design of energy storage systems. We illustrate the application of each principle through examples published in academic literature, illustrative calculations, and a case study with an off-grid application of vanadium redox flow batteries (VRFBs). In addition, trade-offs that can emerge between principles are highlighted.

Abstract Art

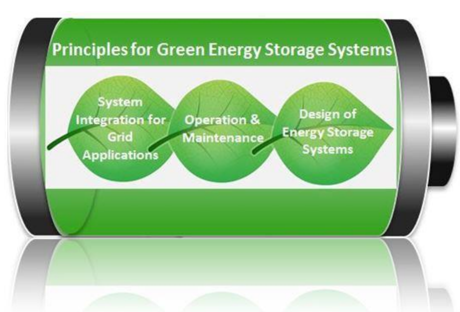

Fig. 3-1 Categories of principles for green energy storage systems.

3.1. Introduction

Energy storage is expected to play an important role in the future of a sustainable electrical grid [1]. Energy storage may serve as a solution to the integration challenges of variable renewable energy, reduce greenhouse gas (GHG) emissions, and increase grid reliability [2]. Options for grid-connected energy storage vary greatly, including flow batteries, Li-ion batteries, compressed air energy storage (CAES), flywsheels, and pumped-storage hydroelectricity. Each storage technology has specific operating characteristics such as response time, ramp rate, round-trip efficiency, service life, and discharge duration, which make it suitable for a particular grid application. Eyer and Corey reviewed energy storage technologies' technical characteristics and identified their potential grid-scale applications and benefits [3]. Another study by Department of Energy examined the state of energy storage in the U.S. and abroad, describing grid applications for each storage system [4]. Recent policies have mandated the integration of energy storage (e.g., California's requirement of 1,325 MW of storage by 2020 [5]) or created more favorable conditions for their integration (e.g., the Federal Energy Regulatory Agency Order 755 [6]). These developments suggest the potential for greater use of energy storage on the grid in coming years.

Not only do the grid benefits vary greatly across technologies, the design, manufacturing, deployment, and operation of energy storage systems may lead to significantly different environmental impacts. Other researchers have considered and analyzed the environmental performance of energy storage systems. Larcher and Tarascon argued that the only viable path towards greener and more sustainable batteries is rooted in designing electroactive materials that cost less energy and release less CO_2 emissions during production, while providing comparable performance to today's electrodes [7]. In another study, Tarascon emphasized that, regardless of energy storage technology, materials with minimum environmental footprint must be integrated in new research towards greener storage systems [8]. Poizot and Dolhem highlighted that to improve the environmental footprint of rechargeable batteries and to sustain the benefits of using them, it is necessary to decrease the consumption of non-renewable resources, energy, and waste produced [9]. They also emphasized that "greenness" of a battery does not depend solely on the type of materials used in the battery, but also on how the battery is managed throughout its life. Indeed, the environmental outcomes of integrating energy storage within the power grid depend on the grid application, the existing generators, and the demand profile. Carson and Novan examined the social benefits of integrating bulk energy storage in Texas electricity market, which has a large amount of renewable capacity [10]. Their results showed that energy storage for arbitrage would increase the average daily GHG emissions in Texas due to an increase in off-peak fossil fuels generation.

Trends suggest that energy storage is poised to play an increasingly important role in power system operations, with the potential to greatly influence emissions. Denholm analyzed the environmental benefits of a biomass-based CAES integrated with wind energy in Midwestern US [11]. In this system, the natural gas fuel of the CAES is replaced by biomass fuel, leading to reduction in net CO_2 emissions and the need for transmission expansion. In an overview of energy storage technologies for mitigating the fluctuations of renewable energy generations, both Beaudin et al. and Evans et al. examined the environmental benefits and challenges of such systems [12], [13]. In another study, Denholm and Kulcinski showed that the energy systems including renewables integrated with large-scale energy storage offer lower life cycle emissions [14].

These and other studies [15], [16], [17], show how design, development, and application of energy storage systems within the power grid influence environmental sustainability outcomes. They all provide valuable insights into the complexity associated with the environmental outcomes of integrating energy storage systems. However, those who design, maintain, and operate such systems lack a comprehensive and systematic set of principles that can yield improved environmental outcomes.

This chapter provides a comprehensive set of principles specific to the design and grid applications of green energy storage systems to guide their research, development, and deployment. These principles for green energy storage build upon previous research that aims to improve environmental outcomes through better design and operation.

In a guidance manual for life cycle design, Keoleian and Menerey emphasized the importance of addressing environmental issues in design in order to achieve a more sustainable system [18] and a variety of tools to support green design have evolved. Anastas and Zimmerman made an important contribution through their development of 12 engineering principles to guide design of environmentally benign products and processes [19]. McDonough et al. illustrated the industrial application of these principles [20] while Diwekar used the green engineering principles to develop an integrated computer-aided framework for chemical process design [21]. Before the development of the green engineering principles, Anastas and Warner developed 12 principles for green chemistry [22]. Kirchhoff highlighted the impact of decisions made by chemists on the options available to engineers, as she defined green chemistry as a foundation on which to design the green engineering technologies needed to produce sustainable products, processes, and systems [23]. Krichhoff demonstrated that combining green chemistry with green engineering would lead to maximum efficiency and minimum waste.

While these studies have successfully provided guidance and structure to green design and products, energy storage technologies pose unique assessment challenges that are not fully addressed by those approaches. Given the complexity of the grid, this study fills a research gap by providing a transparent set of principles to guide integration, operation and maintenance, design, and material choices that influence environmental impacts from integrating energy storage systems. The objective is to guide designers, decision makers, and utility operators on design options and deployment scenarios. Through analysis of expected outcomes based on application of these principles, one can assess the trade-offs that may emerge when faced with competing responses.

Principles and frameworks are valuable as a guideline to develop sustainable solutions for environmental problems that continue to become more complex [24]. 12 green chemistry [22], 12 green engineering [19], and EPA's green engineering principles [25] have been used by industry and adopted in curricula, guiding effectively academic research and training future practitioners [26]. Inspired by and building off the 12 engineering principles [19], we propose 12 principles for green energy storage to provide insights into and improve the environmental outcomes when integrating energy storage systems into power grid.

Interactive, participatory, and multi-disciplinary research is key in sustainability science to integrate the best available knowledge [27]. Therefore, to create the broad set of principles, we first convened a multi-disciplinary group of scholars including chemical engineers, industrial ecologists, chemists, and electrical engineers. Drawing on existing academic literature and conducting novel research, the group created an extensive list of potential principles. We recognized that for the principles to be widely deployed, the final list would need to be sufficiently succinct and broadly applicable across energy storage technologies. Wide and effective application of green engineering and green chemistry principles has demonstrated that twelve principles have proven to be both sufficiently comprehensive, while still being manageable [19], [22]. This was a motivation for authors to consolidate similar concepts, resulting in a robust set of twelve principles specific to green energy storage systems. To solicit feedback, we presented these principles at several conferences with diverse audiences including electrochemists, engineers, industrial ecologists, and sustainability scientists [28], [29], [30], [31], [32]. Throughout this two-year process, we refined and finalized this set of principles presented in this chapter.

3.1.1. Elements of Principles for Green Energy Storage

The principles for green energy storage are grouped into three categories, which address impacts related to: (1) system integration for grid applications, (2) the maintenance and operation of energy storage, and (3) the design of energy storage systems including materials and production.

The first category of principles addresses the impact of energy storage due to system integration for a variety of grid applications. The environmental impacts of integration of energy storage are greatly influenced by power system characteristics such as the existing grid infrastructure and electricity demand profiles. Also, the balance of rated power and the hours of storage capacity, as influenced by the application, have significant impact on the net environmental impact.

There is a distinction between energy storage systems classified as those best suited for capacity applications and those best suited for energy applications [3]. For capacity applications, energy storage is used to displace or defer the need for installing new infrastructure such as transmission and distribution (T&D) lines or substations [3]. In such applications, a limited amount of energy storage discharge capacity may be needed for such applications. However, in energy-driven applications such as renewable curtailment reduction, the storage technology may require multiple hours of energy storage to achieve the desired results. The environmental impacts of integrating energy storage for each of these applications should be analyzed in the context of the application for which it serves.

For example, applications of energy storage to reduce wind curtailment (which would nearly universally lead to improved environmental outcomes) must be evaluated in a manner different than applications to defer T&D projects. In the first application, energy storage environmental burdens are compared with the displaced fossil fuel generation emissions. In the second application, energy storage provides the capacity needed to defer the construction of new T&D infrastructure. In this case, the energy storage burdens are compared with the displaced T&D infrastructure's environmental footprint.

The second category of principles addresses impacts associated with operation and the importance of effective maintenance of energy storage systems to achieve the desired outcomes. The principles included in the third category relate to the impacts associated with materials and production, which are also among the foci of the 12 engineering principles developed by Anastas and Zimmerman [19]. Targeting improvements in materials, device production, and also their end of life is critical in advancing clean and sustainable energy storage systems for grid applications. This category details the interventions that can occur during the design of the energy storage technology, highlighting the importance of performance characteristics such as efficiency and service life, while addressing the impacts from materials and manufacturing.

We provide supporting examples for each principle to illustrate their application to a range of energy storage technologies such as, batteries, flywheels, pumped hydro, and compressed air energy storage (CAES). Examples are drawn from existing literature, as well as novel analysis of a case study. In this case study, we analyze a micro-grid to demonstrate the utility of several principles (Principles # 4, 6, and 11).

Principles for Green Energy Storage in Grid Applications

The three categories of principles are shown in Fig. 3-2 and they are explained in the next section.

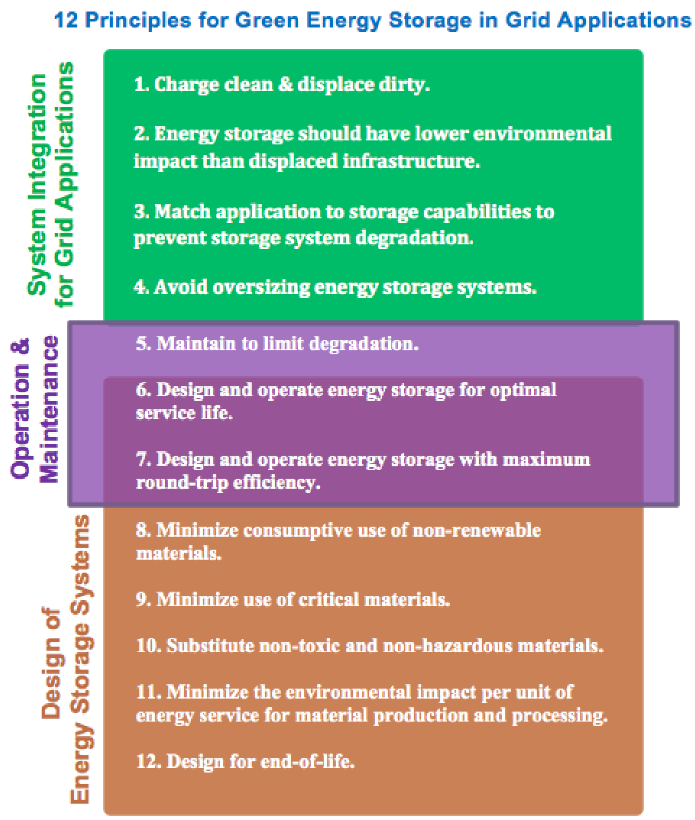

Fig. 3-2 List of principles for green energy storage systems.

3.2. The Principles

Principle #1: Charge clean & displace dirty.

This principle addresses use-phase emissions from generators on the grid. The net emissions during the operation of energy storage depend on three main factors: the emissions associated with the electricity that charges the energy storage system, the round-trip efficiency of the storage technology, and the emissions associated with the displaced generation resource. The generators that can be attributed with charging the energy storage system, as well as those determined to be displaced by the discharge of the energy storage system, are typically the marginal generators during the hours of charging and discharging. This means that, for many power systems, the generation that is increased or displaced will often vary by the time of day and season of the year. This also suggests that variable renewables such as wind and solar, which may be considered to have no dispatch costs, would typically not change their generation upon the introduction of an energy storage system. A notable exception to this would be the reduction of curtailment of these resources.

For many power systems, determination of the generators impacted by energy storage would require extensive modeling (e.g., deployment of unit commitment and economic dispatch models). However, a basic understanding of the system's operations can inform one about the type of generator that is typically the marginal unit during off-peak and on-peak hours throughout the year. Using such information, we provide the following approach to estimate the net use-phase emissions.

The emissions associated with fossil fuel based electricity generation technology are defined by the generator's heat rate (HR) and its fuel's upstream and combustion emissions factors (EF_U, EF_C). To illustrate the range of outcomes for net emissions, we examine several common plant and fuel types and a range of plant efficiencies. A range of annual heat rates for each technology is obtained from the annual electric utility data provided by the U.S. Energy Information Administration, and the net use-phase emissions are calculated for multiple combinations of charge-displace patterns using the 10%, 30%, 50%, 70%, and 90% percentiles for heat rates for each technology, excluding low-used generators and outliers [33].

Net emissions (NE) during the operation of energy storage system in tons of CO_{2eq} per MWh are calculated using Eq. 1, where EF_C and EF_U are the combustion and upstream emissions factors of coal and natural gas fuels. Their assumptions are provided in Supporting Information. In this example, the system boundary includes the use-phase emissions during operation of energy storage system, and also the upstream emissions of natural gas and coal fuels, excluding emissions associated with the power plants construction and energy storage production burden.

$$NE = \left\{ \left(\frac{EF_C * HR + EF_U}{\eta}\right)_{Charge} - (EF_C * HR + EF_U)_{Displace} \right\} / 1000 \qquad (Eq. 1)$$

The net emissions in different charge-displace scenarios of an energy storage system are shown in Fig. 3-3, assuming 75% round-trip efficiency (η) [1]. As shown in Fig. 3-3, the green areas represent charge-displace combinations for which energy storage reduces net emissions from grid generation, while the energy storage increases net emissions for the red combinations. This figure shows the importance of fuel type and generator efficiency on emissions for both the charging and displaced technologies.

Therefore, it is very crucial to consider the marginal units that are dispatched to charge the energy storage system and the marginal units that are displaced by energy storage within an interconnected grid. For example, if a pumped-hydro storage facility is charged by coal during off-peak hours at night and its stored electricity is used to displace natural gas during the day, the net emissions would increase. On the other hand, when the battery is charged with CO_2 free technology such as wind that would have otherwise been curtailed due to transmission constraint, the environmental benefits (green area) increase as the discharged electricity is used to displace more polluting fossil fuels, up to 1.2 t of CO_2/MWh when used to displace an inefficient coal plant.

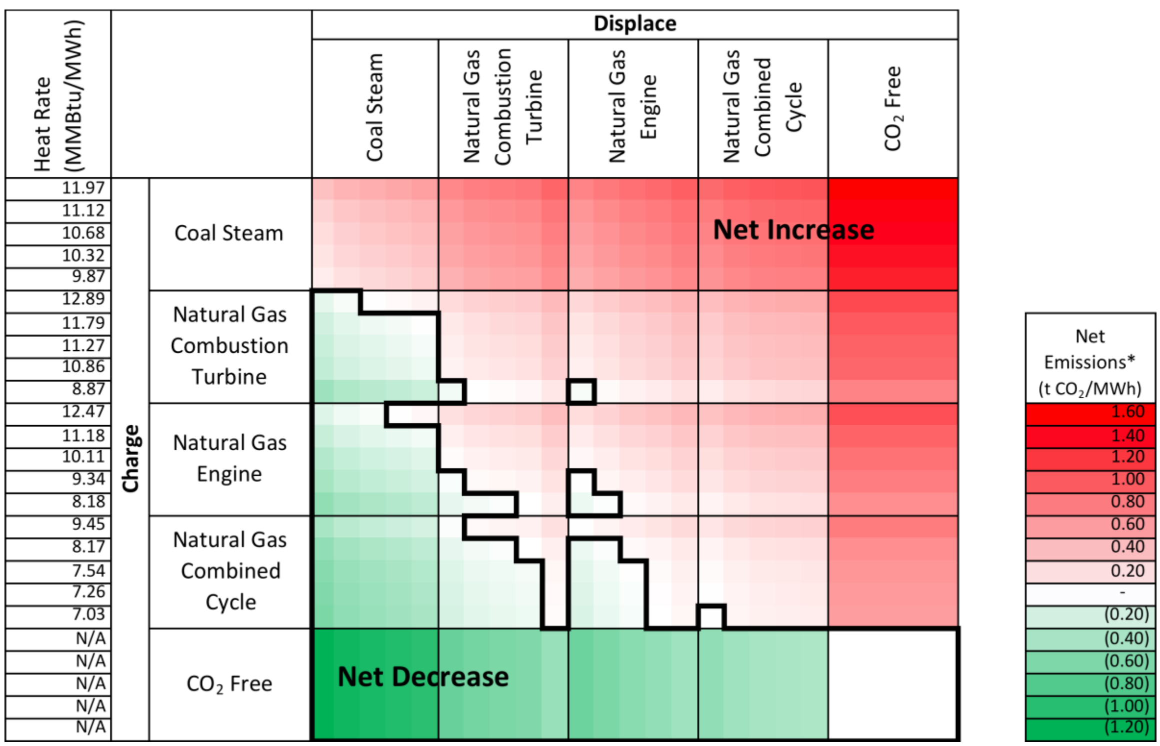

Fig. 3-3 Net GHG emissions in different charge-displace scenarios for an energy storage system with 75% round-trip efficiency. (*Net Emissions include fuels' combustion and upstream emissions for the fuel. Negative amounts are shown in parentheses.)

Principle #2: Energy storage should have lower environmental impact than displaced infrastructure.

In capacity applications, energy storage can be used to displace or defer the need for other equipment and lead to both financial and environmental benefits [3]. For example, energy storage can be utilized to defer the need to buy new generation capacity (e.g. a simple cycle combustion turbine) to meet peak demand [3]. Energy storage systems can also be utilized to defer the need to build new T&D infrastructure [34], [35]. Growing electricity demand can strain T&D infrastructure as the peak power pushes the equipment's limits and causes congestion. At locations where T&D resources are stretched, installing a small amount of energy storage capacity can defer upgrades of transmission systems, cables, or substations for several years depending on growth in demand [36]. The energy storage systems for grid applications typically have a service lifetime of at least five years [37], and when installed for infrastructure deferral, they are typically only used for that purpose a small percentage of the year, when the demand exceeds the infrastructure capacity at maximum peak times [36].

When assessing the environmental benefits of using energy storage for T&D upgrade deferral, it is essential to consider both the lifetime of the energy storage and the expected length of time the T&D can be deferred. Eyer et al. developed a method to calculate two key storage system parameters to defer T&D upgrade for one year: the power output and discharge duration (or the amount of energy that must be stored) [35]. They define the amount of power required from the storage system at a given T&D node as the portion of the peak electric demand, which exceeds the load carrying capacity at that node. Discharge duration is estimated based on the shape of the load profile expected when peak demand occurs and the amount of energy needed if the storage systems is to serve load. Deferral for additional years must consider impacts of load growth [35].

There are environmental impacts associated with both the displaced equipment and the energy storage system life cycle. For example, Jorge et al., developed a life cycle environmental assessment of electricity T&D systems including power lines, cables, transformers, and substation equipment [38]. For such applications, energy storage life cycle environmental impact should be lower than the environmental impacts associated with the displaced infrastructure in order to improve the sustainability performance of the grid.

As an illustrative example, we compare a 375 kW energy storage system with 3.5 hours discharge duration to a substation upgrade. The energy storage defers the need for upgrading a 15 MW substation, for one year. The upgrade requires a 5 MVA additional capacity to meet 2% load growth per year [3], [36]. Using life cycle GHG emissions of a VRFB and a 10 MVA substation and matching their sizes with this example results in 9 tons of $CO_{2\text{-eq}}$, per year for the scenario with energy storage, which is far less than 76.6 tons of $CO_{2\text{-eq}}$ per year for the additional capacity scenario [38], [39].

Principle #3: Match application to storage capabilities to prevent degradation.

In general, all energy storage technologies experience fatigue and wear over their service lifetime [40]. For example, the degradation of batteries occurs gradually over time as manifested by declining capacity, increasing internal resistance, and elevated self-discharge [41], [42]. Different studies have evaluated the degradation of energy storage systems and the factors that affect it. A study by National Renewable Energy Laboratory reviewed models for predicting battery chemical degradation and mechanical stresses [43]. Chawla et al. presented a method to evaluate a batteries' cycle degradation under dynamic cycle duty. They showed that selection of energy storage for a specific grid application depends on its size, power to energy ratio, discharge duration, ramp rates, and life cycle cost [42]. The degradation of energy storage systems over time, specifically batteries, depends on how they are used in the application. In general, every charge-discharge cycle results in some degradation [42].

There are a variety of energy storage systems for grid applications. The features of each technology such as power rating, response time, or spacing requirements make it suitable for each application [44]. For example, flywheels have high charge/discharge rates for many cycles. However, their self-discharge rates are high, which leads to energy efficiency degradation when cycling is not continuous and energy is stored in the flywheel system for a period of time [45]. Therefore, these systems should not be a good match for grid applications that require long-term energy storage. Regarding their capabilities, one of the main applications of flywheels is to provide reliable standby power [45]. On the other hand, deep charges can shorten the cycle life of Li-ion batteries, because their capacity loss is dependent on temperature, rate, and depth of discharge [46]. Thus, they may not be utilized for back-up generation where they need to be discharged completely [45].

Therefore, matching the grid application to storage capabilities such as discharge duration, and charge/discharge characteristics can reduce the storage system degradation.

Principle #4: Avoid oversizing energy storage systems.

Energy sizing in terms of rated power and the hours of storage capacity, as influenced by the application, is a significant driver for the net environmental impacts. Oversizing the storage system can lead to an unnecessary environmental impacts through increased material and manufacturing burdens, if the storage sizing does not appropriately match application requirements.

A micro-grid model is analyzed in two scenarios to test the impact of VRFB sizing on total emissions of the system. In this micro-grid, electricity is provided for an off-grid system comprised of a VRFB for energy storage, wind energy, and natural gas generation. This system has an assumed annual demand of 10.6 MWh per capita and annual peak demand of 22 MW. The life cycle model developed by the authors for the case study is presented in greater detail in Arbabzadeh et al. [39]. In this off-grid system, wind energy is treated as a must-take resource; wind in excess of demand is stored in the battery. Natural gas reciprocating engines provide back-up generation when there is not enough wind energy or stored electricity.

In the first scenario, the off-grid system is comprised of five 3-MW wind turbines and in the second scenario it is comprised of 25 turbines. Total emissions include life cycle emissions associated with system components: wind turbines, VRFB, and natural gas engines [39]. As shown in Fig 3-4, in case of five wind turbines, there is not enough wind energy that needs to be stored in the battery. Therefore, for higher than 50 MWh of battery capacity, there is no change in the amount of stored electricity delivered to demand and this oversizing of the battery results in increasing the total emissions of the system associated with the production burdens of the battery. However, in the other scenario with 25 wind turbines, there is enough wind energy to be stored in the battery that would have otherwise been curtailed. Therefore, a bigger battery leads to reducing more $CO_{2\text{-}eq}$ emissions by reducing wind curtailment and offsetting more natural gas combustion. This demonstrates that the generator mix and load profile affect the environmental outcomes of integrating energy storage systems.

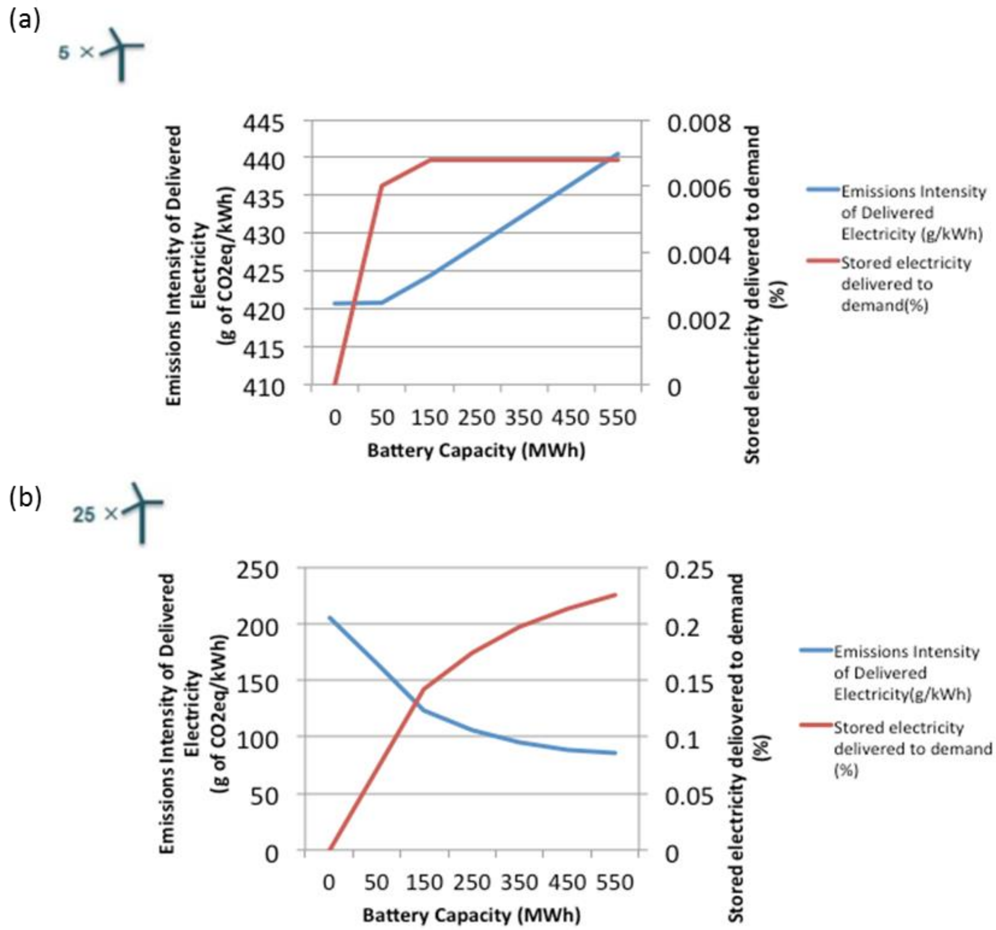

Fig. 3-4 The impact of battery sizing on emissions intensity of delivered electricity and stored electricity utilization in two scenarios with (a) 5 wind turbines and (b) 25 wind turbines.

Principle #5: Maintain to limit degradation.

In Principle #3, we discussed the importance of appropriate technology selection for a given application to mitigate energy storage degradation and ensure favorable environmental outcomes. A similar logic applies to the maintenance of energy storage systems to limit degradation. The regular preventative maintenance of energy storage systems lessens the likelihood of their degradation and failing and maximizes their performance and life expectancy [47], [48]. Some energy storage systems require routine and proper maintenance based on their characteristics. For example, a study by the U.S. Department of Bureau of Reclamation outlined the proper maintenance processed of batteries. The processes include readings of temperature, voltage, specific gravity and connection resistance, visual inspection, cleanliness, and neutralizing spilled electrolyte, among others [48]. EPRI has identified the operation and maintenance requirements for pumped-storage hydro plants, which can limit the wear and tear imposed to mechanical and electrical equipment due to frequent operational mode changes and vibration during pumping [49]. As mentioned in Principle #3, maintaining the appropriate temperature for Li-ion batteries is necessary to avoid capacity fade, which can be increased by 14% when the temperature is increased from 10 °C to 46 °C [46]. In addition, a protection circuit is required to maintain safe operation for these fragile batteries to limit the battery overcharge and lithium plating [45]. Thus, it is necessary to maintain the energy storage systems effectively based on their requirements and specifications, to help limit system degradation and forced outages.

Principle #6: Design and operate energy storage for optimal service life.

Service life affects the materials and energy requirements for energy storage systems production and operation. Therefore, this principle is also relevant to design, since service life should be considered in both stages of energy storage design and also operation.

From a life cycle perspective, replacing products causes additional environmental impacts associated with material production and processing [50]. To demonstrate this trade-off, two scenarios are considered for the micro-grid case study presented in Principle #4. In the first scenario, a 60% efficient VRFB is utilized for 20 years (only the necessary materials are replaced over this period of time). However, in the second scenario, a far more efficient (round-trip efficiency=95%) battery becomes available in Year 10, and the operators have the option to switch the old battery with the new one. It is assumed that the micro-grid model is comprised of 25 wind turbines, a 150 MWh (65 MW) VRFB, and natural gas reciprocating engines as back up generation. As shown in Fig. 3-5, if the battery is exchanged at Year 10, there is an increase in total GHG emissions of the system in that year associated with the production burden of the battery. However, there will be fewer emissions after 20 years if the battery is replaced with the more efficient one (the blue line). In this example, we assume an improvement to the technology offers the potential for markedly better round-trip efficiency in Year 10. For the given technology, we assume that the round-trip efficiency is optimized (and fixed) over the lifetime of the energy storage system for simplicity.

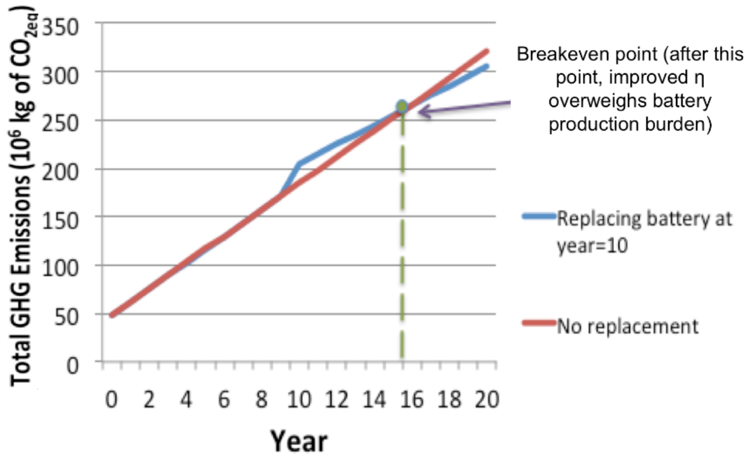

Fig. 3-5 Total GHG emissions of the off-grid configuration after 20 years in 2 scenarios: Replacing the battery (η=60%) with a more efficient one (η =95%) at Year 10 and no replacement scenario.

Principle #7: Design and operate energy storage with maximum round-trip efficiency.

Round-trip efficiency is one of the most important parameters for energy applications of energy storage systems, and needs to be considered in both the design and operation phases. It defines the ratio of energy input to energy retrieved from the storage system [37]. Higher round-trip efficiency means that less energy is lost during charge and discharge cycles.

As discussed in Principle #1 and shown in Eq. 2, round-trip efficiency is one of the main three factors that affects the net use-phase emissions during the operation of energy storage systems. To demonstrate the impact of round-trip cycle efficiency, Fig. 3-3 is modified to assume three values for round-trip efficiency of the energy storage system to test the use-phase emissions results: 65%, 75%, and 85%. Fig. 3-6 shows the impact of increasing battery round-trip efficiency on net use-phase emissions during the operation of energy storage in different charge-displace scenarios. It is clear that increasing efficiency yields greater environmental benefits (green area) for a greater number of charge-displace combinations. The round-trip efficiency of an energy storage device is determined by intrinsic properties of the technology, as well as operational strategies once deployed. In the latter category, thermal management strategies can mitigate the heat produced during rapid charge and discharge cycles of Li-ion batteries, yielding improved efficiency [51], [52]. In this example, it is assumed that round-trip efficiency is fixed over the lifetime of the energy storage system for simplicity.

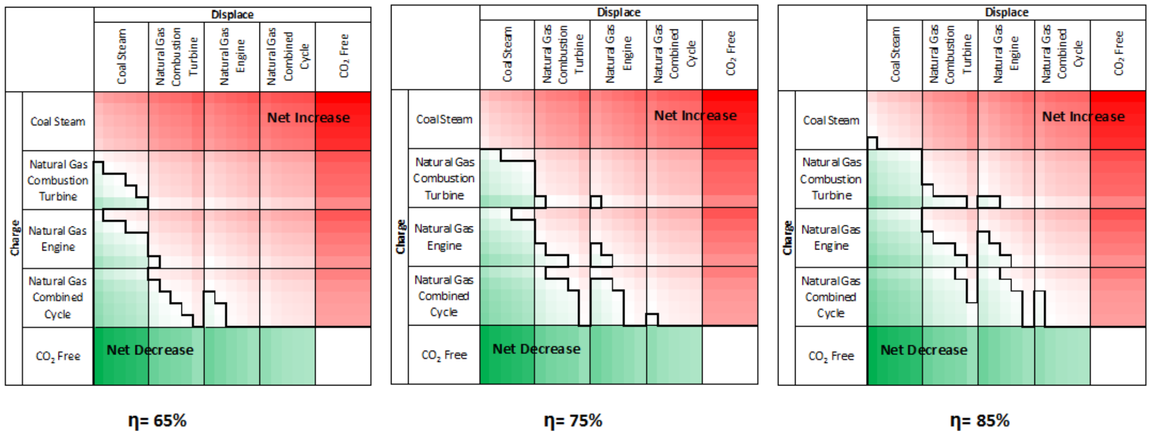

Fig. 3-6 Net use-phase GHG emissions in different charge-displace scenarios, assuming 3 values for the energy storage round-trip efficiency. (Net use-phase emissions include fuels' combustion and upstream emissions for the fuel. Negative amounts are shown in pare

Principle #8: Minimize consumptive use of non-renewable materials.

The growing demand for energy storage systems requires the need for advanced materials research and development to address many challenges associated with storage systems economics, technical performance, and design. Consumptive use of non-renewable materials and resources changes their forms and contents in such a way that they are no longer available for their original use, reducing their availability and limiting the future generations' access to these resources [53]. While energy storage systems can offer different grid applications, their design and production should minimize the consumptive use of non-renewable materials; otherwise depletion of materials can pose constraints on the continued deployment of these systems.

Materials selection will also play an important role in making energy storage technologies affordable, efficient, and reliable [54]. Consumptive use of materials can be reduced either through end-of-life recovery or by substitution using renewable materials. There is considerable research interest in the latter category, with the aim of developing suitable material substitutes. For example, renewable and organic biomass-derived materials are introduced for developing sustainable energy storage technologies such as battery's electrodes [54], [55]. In another study, renewable synfuel derived from biomass gasification replaces non-renewable natural gas in CAES [11]. Huskinson et al. also indicated that wide-scale utilization of flow batteries is limited by the abundance and the cost of their materials [56]. They described a class of energy storage materials utilized in a metal-free flow battery. The research on investigating materials with lower environmental implications is not limited to energy storage and includes other energy systems such as thin-film photovoltaic technologies [57].

Principle #9: Minimize use of critical materials.

Energy storage systems can be material intensive and if they are to be widely deployed, their feedstock elements will be needed in large quantities [58]. A report by Sandia National Laboratory and Pacific Northwest National Laboratory presents a strategic material selection for energy storage systems [59]. This strategy emphasizes that while cost reduction of storage technologies is highly important and material costs have the biggest share in the cost of these technologies, it is critical that both abundant and low cost materials are used in storage devices. Another study identifies a class of chemical elements that are critical to energy sector and their shortage would significantly limit and transform the way energy is produced, transmitted, stored and conserved [59]. Risks to a material's availability, whether that is absolute scarcity, vulnerable supply chains, or monopolistic suppliers, can be a potential constraint for rapid deployment of energy storage systems. For example, near criticality of tellurium [57], [60], [61], [62] may present a potential risk to its widespread use in batteries [63], [64]. On the other hand, magnesium is not typically considered a critical material [62], [65] and has promising performance for battery storage systems' electrode [65], making it potentially more desirable than its more critical counterparts.

The method adopted by the U.S. Department of Energy to assess the criticality of materials in energy sector, is framed in two dimensions: importance to clean energy and supply risk [60]. In another study, Graedel et al. characterized the criticality of metals and metalloids in three dimensions: supply risk, environmental implications, and vulnerability [62]. Considering these criticality dimensions in materials selection for energy storage systems that are used for grid applications can enhance sustainability performance.

Principle #10: Substitute non-toxic and non-hazardous materials.

Safety must be emphasized within energy storage systems at every level to enable the success of these technologies in increasing grid environmental performance. As described in a safety strategic plan by U.S. Department of Energy, detailed hazard analysis must be conducted for entire systems to identify failure points caused by abuse conditions [66]. The possibility of cascading events should also be determined to prevent large-scale damage. There are different levels of toxicity or hazard associated with each energy storage system that needs to be understood to manage the trade-offs between safety and system performance. For example, in case of a CAES in depleted natural gas reservoirs, the risk of ignition and explosion exists [67]. In batteries, there are risks associated with their basic electrochemistry [66]. For example, the utilization of large-scale nickel-cadmium batteries has been reduced due to cadmium toxicity and associated recycling complexity [68], [69]. Although Li-ion batteries are used widely in devices such as cell phones or laptops, their grid-scale usage needs to be examined from a safety point of view, since these grid applications require higher energy and power capacities [70]. When batteries are misused or facing abnormal environments, their inherent hazards cause accidental scenarios. In this case, if the active materials are highly energetic, their contact with flammable organic solvent-based electrolyte may cause dangerous situations, such as combustion of the electrolyte [70].

The EPA describes the toxic effects of chemicals as adverse health effects they may cause and how the extent of these effects depends on dose, route and duration of exposure. The toxicity assessment is divided into two parts: (1) characterizing and quantifying the non-carcinogenic effects of a chemical, and (2) addressing the carcinogenic effects of a chemical [71].

The EPA also describes hazard identification in two steps. The first step determines whether exposure to an agent can cause adverse health effect and whether this effect is likely to occur in human beings. The second step is called dose-response evaluation, which evaluates quantitatively the toxicity information and characterizes the relationship between the dose of received contaminant and the incidence of adverse health effects in the exposed population. From this quantitative analysis, toxicity values are determined and are used in the risk assessment to estimate the potential for adverse health occurring in humans at different exposure levels [72].

Principle #11: Minimize the environmental impact per unit of energy service for material production and processing.

Materials production and manufacturing phases have significant environmental burden among energy storage systems' life cycle stages. To demonstrate this principle, the total emissions of the micro-grid system, first presented in Principle #4, are tested using three values for representing

VRFB production burden. The VRFB material production emissions comprise two parts: energy-dependent materials emissions in grams of $CO_{2\text{-eq}}$ per kWh ($E_{mtrl,S}$) and capacity-dependent materials emissions in kg of $CO_{2\text{-eq}}$ per kW ($E_{mtrl,P}$) [39]. The detailed GHG emissions assumptions for VRFB materials production and manufacturing are provided in Supporting Information.

Fig. 3-7 shows the total emissions of the micro-grid system, which is comprised of the system components' greenhouse gas emissions. As shown in in this diagram, the total emissions of the micro-grid system decrease, as more battery capacity is available to offset more natural gas combustion. However, this reduction is steeper when the battery production burden is decreased.

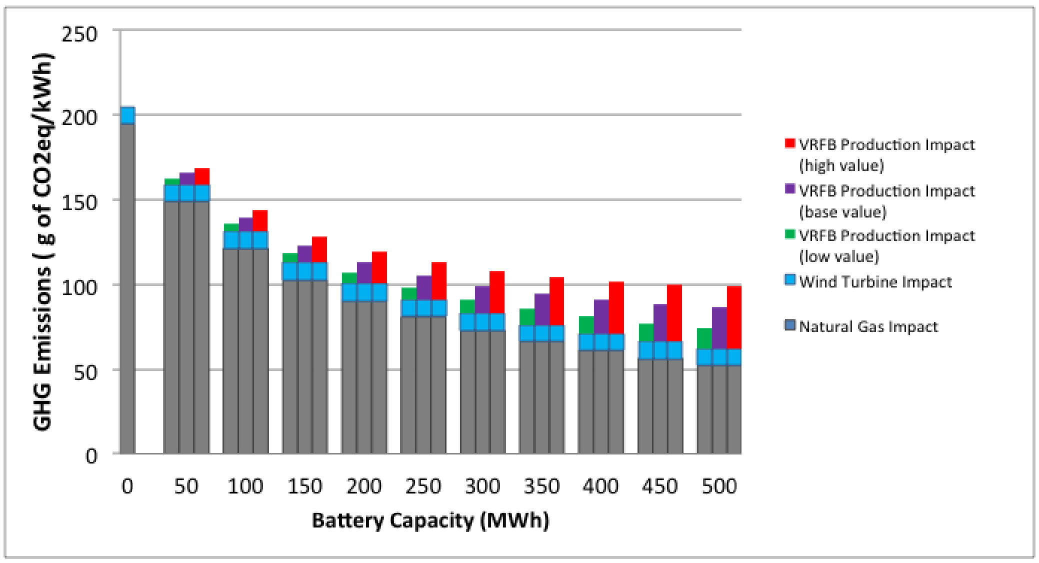

Fig. 3-7 The impact of decreasing battery production burden on total emissions in the micro-grid case study, which includes 25 wind turbines, natural gas, and VRFB.

Principle #12: Design for end-of-life.

Recently, increased attention has been paid toward environmental impacts of energy storage systems' end of life [73]. Careful analysis of environmental burdens associated with disposal of storage systems is necessary to determine the best disassembly, recycling, remanufacturing, and reuse approaches.

Herman et al. argues that due to the increasing demand for Li-ion batteries, economically beneficial and technically mature disassembly systems are necessary for the end-of-life of these systems [74]. End-of-life approaches such as, recycling and reuse can significantly reduce global demand for extracted materials [60]. Designing energy storage systems such as batteries with recyclable materials leads to environmental improvements and cost reduction [75]. Wang et al. argues that eliminating landfilling as a result of recent disposal bans on rechargeable batteries increases the need for development of alternative end-of-life management strategies such as recycling valuable metals contained within the battery [76]. As opposed to traditional recycling of batteries, refunctionalization of cathodes is the remanufacturing of active materials to regain electrochemical performance at end-of-life, offering economic and environmental savings [77].

One example of battery reuse is the emerging trend of utilizing used batteries that first served in automotive applications, in grid-scale stationary applications [78]. Reuse of electric vehicle (EV) Li-ion batteries can offset the production burden of new batteries by extending battery service life [79]. One of the promising applications of second use batteries is to replace combustion turbine peak plant and provide peak-shaving grid application [80]. However, one of the critical methodological challenges is the allocation of environmental impacts of batteries across their mobile and stationary applications [79], [81]. The challenge is to take into account the allocated environmental impacts associated with the production of EV battery's cells and module, end of life management, refurbishment, and efficiency losses into the overall environmental burden of the refurbished EV battery that will have a stationary application [79].

3.3. Discussion

There has been a rapid development in energy storage technologies and the demand for energy storage is expected to grow due to recent policies such as California's requirement of 1,325 MW of storage by 2020 [5] and the Federal Energy Regulatory Agency Order 755 [6]. Energy storage systems can be utilized for different grid applications such as renewable integration, load leveling, and T&D upgrade deferral. However, the deployment of energy storage systems within the electrical grid creates unique challenges for integration and can yield different environmental outcomes. These challenges and outcomes depend on grid characteristics, electricity demand, and existing generation assets; therefore, a framework is needed to systematically assess the environmental outcomes of energy storage systems integration. The primary objective of this chapter is to provide a robust set of principles specific to energy storage systems to inform decision makers, utility operators, and energy storage designers about these challenges and environmental outcomes.

This new set of principles for the design and application of green energy storage systems builds upon the 12 engineering principles developed by Anastas and Zimmerman [19], but departs from them in two key aspects. First, these principles are designed to directly address challenges and issues of integration that relate to unique aspects of the deployment of these technologies. Secondly, the principles are grouped into three categories that target different audiences: namely system operators, load serving entities, and energy storage systems designers.

For each principle, we provided examples of improved environmental outcomes, using published studies, illustrative calculations, and a case study with an off-grid application of VRFB. These principles are designed to be universally applicable to all energy storage technologies such as various types of batteries, flywheels, pumped-storage hydroelectricity, and CAES. The grid applications for these energy storage systems can also span a broad range including reserve capacity, T&D upgrade deferral, and renewable integration, among others. Different environmental impact categories including GHG emissions, resource depletion, criticality, and toxicity were considered in these examples.

These principles provide broad guidance for design considerations, operations, and grid integration that can yield sustainability improvements. When viewed in isolation, each of them achieves this stated goal. However, in real applications, the principles may conflict with each other and create the need to evaluate trade-offs. For example, Principle #7 seeks to increase round-trip efficiency. On the other hand, enhancing the efficiency may require additional materials or energy inputs, such as adding sulfuric acid to activate the graphite felt surface of VRFB and decrease its internal resistance and consequently increase the round-trip efficiency [82], [83]. This can increase the environmental impacts associated with the material production and conflict with Principle #11, which focuses on decreasing an energy storage system’s material production burden. Another example of such trade-offs relates to Principle #4, in which avoiding oversizing energy storage systems, yield to environmental benefits. However, the use-phase may dominate and displacing additional coal generation (Principle #1) may be well worth any material burdens associated with oversizing. Limiting energy storage system's size may also lead to degradation. This conflicts with Principle #5, which focuses on limiting degradation.

In such instances when the principles conflict, a robust sustainability assessment is required to evaluate different options to find the most sustainable approach in energy storage systems' design, deployment, and operation scenarios. The goal of this chapter is to present a robust framework to guide initial decisions, as well as identify such areas of conflict where further analysis is needed. In future work, we will apply the principles in a sustainability assessment algorithm based on LCA methods to evaluate the sustainability performance of different energy storage systems to meet specific grid applications, particularly for cases where the principles conflict.

Appendices

Appendix A. Principle #1: Charge clean, displace dirty

Table 3-1 Natural gas and coal emissions factors

	Upstream Emissions (kg of CO_{2eq}/MWh) [84]	Combustion Emissions (kg of CO_2/MMBtu) [85]
Natural Gas	15.8	53
Coal	5.6	97

Appendix B. Principle #11: Minimize the environmental impact per unit of energy service for material production and processing.

Table 3-2 The detailed GHG emissions assumptions for VRFB materials production and manufacturing of the battery in the model

				Low value [a]	Base case [a]	High value [a]
VRFB Life Cycle GHG Emissions	Materials & Parts Production	Energy dependent	$E_{mtrl,s}$ (kg of CO_2-eq/kWh)	30	34.8	76
		Capacity dependent	$E_{mtrl,p}$ (kg of CO_2-eq/kW)	103.3	160.6	228.5
	Battery Production		E_p (kg of CO_2-eq/kWh)	10	55	65

[a] Rydh compared the environmental impacts of VRFB to lead-acid battery [86]. Rydh's GHG results for VRFB are considered as the minimum value, the results provided by Arbabzadeh et al. [39] as base case and Rydh's GHG results of a lead-acid battery as high value [86].

Clarifications:

The case study and life cycle assessment results presented in Arbabzadeh et al. [39] are used in this study to develop new demonstrating examples for selected principles.

The principles are designed to inform early decision-making and help steer choices to environmental improvements. The evaluation of full impacts will use a life cycle framework, in turn evaluating tradeoffs.

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CHAPTER 4
Parameters driving environmental performance of energy storage systems across grid applications

Abstract

Large-scale energy storage may effectively meet the needs of several grid applications. However, understanding the environmental impact of energy storage for these grid applications is challenging due to diversity in loads, grid mixes, and energy storage systems. Comprehensive sustainability assessments are necessary to yield the best environmental outcomes for grid-scale energy storage systems. To achieve this, we first developed fundamental principles for green energy storage, addressing key issues such as material sustainability, round-trip efficiency, service life, and degradation. In the current study, we couple the principles with a sustainability assessment model to investigate the impact of design and operational parameters on environmental outcomes of utilizing energy storage for grid applications. This model takes into account the service that the energy storage would provide (e.g., bulk energy time-shifting) as well as the energy storage parameters and grid application parameters that influence environmental outcomes. Parameters examined include energy storage round-trip efficiency, degradation, service life, upstream production burden, and heat rates of charging and displaced generation technologies. Environmental sustainability performance is evaluated using a universal set of equations that incorporates all the mentioned parameters. The relationships between these parameters are investigated to determine their influence on environmental performance of energy storage for three grid applications: energy time-shifting, frequency regulation, and power reliability. This model guides the design and operation of new and existing technologies, targeting audiences from energy storage designers to energy storage operators and power utilities.

Table 4-1 Nomenclature

Nomenclature	
η	energy storage round-trip efficiency
n	energy storage service life
deg	annual degradation in energy storage round-trip efficiency and capacity
$ESBurden_s$	energy storage production burden (storage dependent)
$ESBurden_p$	energy storage production burden (power rating dependent)
E_{uch}	charging technology upstream emissions factor
E_{Cch}	charging technology combustion emissions factor
E_{udis}	displaced technology upstream emissions factor
E_{Cdis}	displaced technology combustion emissions factor
HR_{ch}	charging technology heat rate
HR_{dis}	displaced technology heat rate
P	energy storage power rating (MW)
S	energy storage size (MWh)
$cycle$	number of cycles
T	study lifetime

4.1. Introduction

The integration of energy storage systems into the power grid may lead to a wide range of environmental impacts [1], [2]. Environmental sustainability assessments can guide both development and deployment of energy storage technologies to achieve better environmental outcomes. Many existing environmental assessments, however, have not systematically evaluated the influence of various parameters on these environmental impacts across grid applications. In this study, we address this gap by developing model equations to explore the key parameters that influence environmental outcomes of integrating energy storage systems. This parametric model shows how environmental impact of energy storage integration may be influenced by energy storage parameters and grid application parameters. Across the full range of parameters, environmental outcomes could be positive or negative. It can be used as a guideline to determine, systematically, when and how to choose storage systems to achieve positive environmental outcomes.

Several studies have analyzed the environmental implications of energy storage systems [3], [4]. Argonne National Laboratory conducted life cycle assessments of different battery technologies, examining emissions, energy requirements, water, and solid waste indicators [5]. Their results indicated that lead-acid batteries had the lowest production burden compared to other battery technologies. Chul et al. conducted life cycle analysis of lithium-ion battery electric vehicles from cradle-to-gate [6]. Their results demonstrated that cell manufacturing had the main contribution in upstream greenhouse gas emissions. In a life cycle analysis of batteries, Bossche et al. concluded that the environmental impacts of assembly and production stages could be offset significantly when the collection and recycling of batteries was efficient and performed on a large scale [7]. Hou et al. and Larcher and Tarascon emphasized that the advancements for sustainable energy storage systems depended on the discovery of less expensive and environmentally benign materials [8], [9]. In a life cycle assessment of compressed air energy storage (CAES), Bouman et al. concluded that the design and processing of underground air storage had a large contribution in environmental impacts [10].

Other studies have explored the integration of storage systems and the associated environmental outcomes. Arbabzadeh et al. showed that in an off-grid system, increasing vanadium redox flow battery capacity would have environmental benefits when reducing high wind curtailment [11]. Hiremath et al. showed that it would be misleading to exclude the use stage impacts and neglect the stationary application of battery technologies in an evaluation of their environmental performance, especially when they had different characteristic parameters [12]. They also demonstrated that increasing round-trip efficiency of batteries reduced their life cycle greenhouse gas (GHG) emissions significantly. Poizet and Dolhem emphasized that, besides reducing the consumption of non-renewable materials in rechargeable batteries, managing the batteries during their lifetime would influence their sustainability performance [13].

Other studies have demonstrated the importance of the grid mix [1], [14], [15], presence of renewables [16], [17], [18], and off-peak marginal generation [19] on environmental outcomes from integrating energy storage. Across all of these examples, we see that production, operation, and deployment of energy storage systems within a grid application can impact the environmental outcomes. Although these studies provide valuable insights into the environmental impacts of integrating energy storage systems, they do not systematically examine the role of energy storage parameters and grid application parameters in affecting these impacts. Our parametric analysis allows us to provide concrete recommendations which can be tailored to different grid applications and storage technologies, to influence the environmental impacts of integrating energy storage systems.

Each energy storage technology differs in operational parameters, longevity, and materials requirements. Several studies have identified and compared the characteristics of various energy storage systems that need to be evaluated when considering energy storage on the utility scale. These studies demonstrated that key energy storage parameters such as service life, efficiency, capacity, and number of cycles, among others, differed greatly across technologies [8], [20], [21], [22], [23], [24].

Energy storage systems can be utilized for several distinct grid applications such as ancillary services and bulk storage for renewable integration [25] [26]. Each grid application has specific performance requirements that determine which energy storage technologies are suitable to meet the application's performance requirements. Several studies have reviewed technical characteristics of energy storage technologies and identified their potential grid applications, including reports by the Department of Energy and the Sandia National Laboratory [27] [28] [29] [30] [31], and the Electric Power Research Institute [25] [32]. These and other studies [33] - [38] show that the fit of an energy storage system to a specific grid application depends on its match with the performance requirements of the desired application.

Understanding the interaction between energy storage parameters (e.g., round-trip efficiency, degradation, service life, and production burden) and grid application parameters (e.g., generators' heat rates) can inform the relative importance of each parameter in determining the environmental performance of utilizing energy storage, which is the focus of this study. In 2012, Hittinger et al. evaluated the impact of energy storage parameters on the economic cost of providing energy service across grid applications [39]. The study presented here is novel, however, because it identifies how these parameters drive environmental outcomes in grid applications, providing new insights for energy storage designers, operators, and utilities.

This analysis is informed by the twelve principles for green energy storage systems, which detail key drivers for improving environmental performance when integrating energy storage systems in grid applications [2]. The principles address the importance of the operational parameters of energy storage such as service life, round-trip efficiency, and degradation but do not address how to deal with trade-offs and competing objectives. Motivated and guided by this framework, we have developed universal equations to address the conflicts among the principles. In this model, the viable energy storage technologies for the given application are determined based on the required performance characteristics. The influence of parameters on the environmental outcomes is investigated using the universal equations, providing insights into the design and deployment of new technologies and the modification and improvement of existing ones. Three examples of energy storage applications—energy time-shifting, frequency regulation, and power reliability applications—are selected to demonstrate the impact of parameters on the results. These grid applications were chosen to illustrate a wide range of performance requirements such as required energy storage power rating, capacity, and number of cycles.

4.2. Case studies: Energy Time-shifting, Frequency Regulation, and Power Reliability

The first case study examined is the application of energy storage for bulk energy time-shifting. The minimum and maximum size range studied for energy storage in this application is 1 MW to 3 GW, with discharge duration between 2 to 10 hours, operated at 300 to 400 cycles per year [25], [28], [40]. For the electric energy time-shifting application, several energy storage technologies offer the most suitable characteristics: pumped-hydro storage, flow batteries, lead-acid batteries, sodium-sulfur batteries, and compressed-air energy storage [25].

In the second application, energy storage provides frequency regulation services. Frequency regulation involves managing the momentary variations between demand and supply in order to maintain grid frequency [41]. Frequency regulation has been typically provided by generation resources, which are online and are able to change their power output quickly. However, generators that are used for this application may not operate at partial/variable load efficiently, incurring more air emissions and wear and tear when not operating at constant load [28]. Several energy storage systems can be suitable alternatives for this application, due to their ability to change output rapidly (i.e., fast ramp rate) and efficiently. These technologies include flywheels, capacitors, Li-ion batteries, and advanced lead-acid batteries [28]. The size range studied for this application is 1 MW to 100 MW with a short discharge duration of 15 minutes and 8,000 cycles per year [25], [28].

The third application considered in this study is energy storage used for commercial and industrial power reliability. In case of a complete power failure that lasts more than a few seconds, the storage technology provides enough energy to compensate for outages of extended duration, to complete an orderly shutdown of processes, and/or to transfer to on-site generation resources [28]. In this application, we explore minimum and maximum of 0.05 to 1 MW energy storage sizing with 4 to 10 hours of discharge duration. Also, it is assumed that energy storage used for this application experiences 50 cycles per year, which are far fewer compared to the other two applications [25]. Advanced lead-acid, sodium-sulfur, Li-ion, and flow batteries have shown promising applicability for power reliability [25], [27].

Table 4-2 summarizes the potential energy storage technologies for each grid application.

Table 4-2 Selected Energy Storage System for Each Grid Application

	Time-Shifting	Frequency Regulation	Power Reliability
vanadium redox flow battery (VRFB)	✓		✓
lead-acid batteries (PbA)	✓	✓	✓
sodium-sulfur batteries (NaS)	✓		✓
compressed-air energy storage (CAES)	✓		
pumped-hydro storage (PHES)	✓		
Li-ion batteries (Li-ion)		✓	✓
flywheels		✓	
capacitors		✓	

4.3. Methods

A set of universal equations is developed to investigate the influence of various parameters on the environmental impact of using energy storage systems, which will be applied to time-shifting, frequency regulation, and power reliability applications. Although these equations can be applied to other grid applications, these three were selected to highlight a diverse set of applications that offer distinct differences in their charging patterns and technical requirements. Later, analysis is conducted to illustrate the interaction of parameters within the universal equations and highlight the importance of each parameter on environmental benefits.

4.3.1. Universal Model Equations

Motivated by the twelve principles for green energy storage systems in grid applications [2], we developed a set of universal equations to evaluate the net emissions (NET) including upstream and use-phase emissions during the operation of an energy storage system. For example, one of the principles (Principle#1: *Charge clean and displace dirty*.) emphasizes charging energy storage with low emissions sources and using the stored electricity to displace higher emitting generation. The aim is to decrease the emissions during the use-phase of an energy storage system [2]. In other words, this principle considers the marginal units that are dispatched to charge the energy storage system as well as the marginal units that are displaced by energy storage within an interconnected grid [2]. Another principle (Principle#11: *Minimize the environmental impact per unit of energy service for material production and processing*.) highlights the necessity to minimize the production burden (upstream emissions) of energy storage systems.

The net emissions (NET) during the development and deployment of an energy storage system are comprised of use-phase emissions ($E_{usephase}$) and energy storage upstream emissions ($E_{upstream}$) (Eq.1c). All emissions are defined in terms of kg of CO_{2eq}/MWh. In this study, we investigate CO_{2eq} impact factor; however, this model can be applied to other impact factors as well. Eq. 1a shows that $E_{usephase}$ is a function of the following parameters:

- round-trip efficiency of energy storage system (η)
- service life of energy storage system in years (n)
- degradation as a yearly decrease in energy storage round-trip efficiency and capacity (*deg*)
- energy required to achieve a full state of charge given the storage system operating constraints in MWh (S_{ch})
- grid energy displaced by a fully discharged storage system given the storage system operating constraints in MWh (S_{dis})
- fuel upstream emissions (E_{uch}, E_{udis}), and combustion emissions (E_{Cch}, E_{Cdis}) associated with the electricity that charges the energy storage system and the displaced generation resource in kg of CO_{2eq}/MMBtu
- the heat rates of charging and displaced generation in MMBtu/MWh (HR_{ch}, HR_{dis})

- number of annual full cycles that energy storage experiences during its operation within the application (*cycle*)
- study lifetime in years (*T*)

Eq. 1b shows that $E_{upstream}$ is a function of the following parameters:

- production burden of the energy storage system, storage dependent burden in kg of CO_{2eq}/MWh ($ESBurden_s$)
- production burden of the energy storage system, power rating dependent in kg of CO_{2eq}/MW ($ESBurden_p$)
- sizing of energy storage in terms of power rating (*P*) and storage capacity (*S*) in MW and MWh
- service life of energy storage system in years (*n*)
- study lifetime in years (*T*)

$$E_{usephase} = \left\lfloor \frac{T}{n} \right\rfloor * \sum_{i=1}^{i=n} \left\{ \frac{HR_{ch} * (E_{Cch} + E_{uch}) * (S_{ch(i-1)} - deg * S_{ch(i-1)})}{\eta_{i-1} - deg * \eta_{i-1}} - HR_{dis} * (E_{Cdis} + E_{udis}) * (S_{dis(i-1)} - deg * S_{dis(i-1)}) \right\} * cycle + \sum_{i=1}^{i=T-\left\lfloor \frac{T}{n} \right\rfloor * n} \left\{ \frac{HR_{ch} * (E_{Cch} + E_{uch}) * (S_{ch(i-1)} - deg * S_{ch(i-1)})}{\eta_{i-1} - deg * \eta_{i-1}} - HR_{dis} * (E_{Cdis} + E_{udis}) * (S_{dis(i-1)} - deg * S_{dis(i-1)}) \right\} * cycle \qquad (Eq. 1a)$$

$$E_{upstream} = \left(ESBurden_s * S + ESBurden_p * P\right) * \left(\left\lfloor \frac{T}{n} \right\rfloor + \frac{T - \left\lfloor \frac{T}{n} \right\rfloor * n}{n}\right) \qquad (Eq. 1b)$$

$$NET = E_{usephase} + E_{upstream} \qquad (Eq. 1c)$$

As shown in Equations 1a through 1c, NET in kg of CO_{2eq} depends on two sets of parameters. The first group is related to the characteristics of energy storage technology, which are also addressed in principles for green energy storage systems (Principles# 3, 4, 5, 6, 7, and 11) [2]. The second group of parameters is determined based on the grid application performance criteria. To illustrate the range of outcomes for net emissions during the operation of energy storage, a range of energy storage parameters and grid application parameters are assumed and provided in Tables 4-3 and 4-4. A full literature review was conducted to find a feasible range for parameters of potential energy storage systems that were suitable for each application.

In this model, the system boundary includes the use-phase emissions during operation of energy storage system, its production burden, and also the fuel upstream emissions of charging and displaced generation. It excludes emissions associated with the power plants construction. The replacement strategy of energy storage systems is also based on its service life (*n*) and study lifetime (*T*). For example, if an energy storage system is designed to have a service life of 6 years and the desired study lifetime is 20 years, then in this case three new storage systems are used for eighteen years, and the fourth system will be used for the remaining two years. The full production burden of the fourth system is allocated based on the ratio between the remaining project lifetime and the total service life of the energy storage system. Study lifetime (*T*) is assumed to be 20 years for all three applications and the index (*i*) is used to trace the drop in round-trip efficiency and storage capacity per year due to degradation. Two scenarios are assumed: 1) energy storage is charged with natural gas (NG) fuel and is used to displace coal based electricity generation to test the impact of parameters on net emissions through the lens of increasing the environmental performance, 2) energy storage is charged with coal based electricity generation and displaces NG to test the impact of parameters in a scenario that is closer to some real world applications. We assume that a safe operating window for the energy storage is 10-90 percent state of charge (i.e. S_{ch}=0.9*S, S_{dis}=0.8*S).

Table 4-3 Possible Ranges for Energy Storage Systems Parameters*

Parameter	**Variable**	**VRFB**	**PbA**	**NaS**	**CAES**	**PHES**	**Li-ion**
Round-trip efficiency (%) [3] [33], [34] [40] [42] [43] [44] [45] [46] [47] [48] [49]	η_0	70-95	70-90	71-90	45-89	75-85	70-90
Service life (years) [42][43], [47], [50]	n	5-15	3-15	5-15	20-60	40-60	5-20

Annual Degradation (%/year) [51] [52] [53] [54] [55] [56]		deg	0-3	0-3	0-3	0-3	0-3	0-3
Energy Storage Production Burdens [3] [6] [7] [9] [11] [17] [57] [58] [59] [60] [61] [62]	Storage dependent (kg of CO_{2eq}/MWh)	$ESBurden_s$	47,400-161,400	18,000-211,866	7,200-128,440	19,400	35,700	61,000-487,000
	Power Rating dependent** (kg of CO_{2eq} /MW)	$ESBurden_p$	160,000	160,000	160,000	160,000	160,000	160,000

* Flywheel and capacitors are not included in the analysis due to the lack of availability of data for their production burden. A range could not be found for CAES and PHES production burdens in the literature.

** This component of energy storage production burden is held constant due to the lack of availability of data.

Table 4-4 Grid Application Assumptions

Parameter		**Variable**	**Value**
Natural Gas Emissions Factor	Upstream (kg of CO_{2eq}/MMBtu) [63]	E_{uch}	13.63
	Combustion (kg of CO_{2eq}/MMBtu) [64]	E_{Cch}	53
Coal Emissions Factor	Upstream (kg of CO_{2eq}/MMBtu) [63]	E_{udis}	5.6
	Combustion (kg of CO_{2eq}/MMBtu) [64]	E_{Cdis}	97
Heat Rates (MMBtu/MWh) [65]	Natural Gas Generator	HR_{ch}	7-13
	Coal Generator	HR_{dis}	9-12
Power Rating (MW)	Time-Shifting	P	1-3,000
	Frequency Regulation		1-100
	Power Reliability		0.05-1
Size (MWh)	Time-Shifting	S_0	2-30,000
	Frequency Regulation		0.25-25
	Power Reliability		0.2-10
Number of Full Cycles ($year^{-1}$) [25]	Time-Shifting	$cycle$	350
	Frequency Regulation		8,000
	Power Reliability		50

Study lifetime (year)	T	20

A set of two analyses, namely extreme parameter testing and Latin Hypercube Sampling, are conducted to investigate the impact of parameters on net emissions during operation of energy storage in each of the three applications, using model Equations 1a through 1c.

4.3.2. Extreme Parameter Testing

In this approach, net emissions are calculated using Equations 1a through 1c by holding all parameters constant at their average values (shown in Table 4-5) except for one parameter that is varied between minimum and maximum ranges. These calculations are repeated for the six parameters of each storage technology that is suitable for each of time-shifting, frequency regulation, and power reliability grid applications (Table 4-2). These parameters are round-trip efficiency, service life, annual degradation, production burdens, and heat rates of charging and displaced generations. The objective is to compare the dominance of each parameter over net, use-phase, and upstream emissions. To illustrate the results, the net emissions results for lead-acid (PbA) battery technology are shown in Fig. 4-1 as spider diagrams.

Table 4-5 Default Values for Spider Diagrams

Energy Storage Parameter		**Variable**	**VRFB**	**PbA**	**NaS**	**CAES**	**PHES**	**Li-ion**
Round-trip efficiency (%)		η	82.5	80	80.5	67	80	80
Service life (years)		n	10	9	10	40	50	13
Annual Degradation (%/year)		deg	1.5	1.5	1.5	1.5	1.5	1.5
Energy Storage Production Burdens	Storage dependent (kg of CO_{2eq} /MWh)	$ESBurden_s$	104,400	114,933	67,820	19,400	35,700	274,000
	Power Rating dependent (kg of CO_{2eq} /MW)	$ESBurden_p$	160,000	160,000	160,000	160,000	160,000	160,000
Grid Application Parameter		**Variable**	**Time-shifting**		**Frequency Regulation**		**Power Reliability**	

Heat Rates (MMBtu/MWh)	Natural Gas Generator	HR_{ch}	10	10	10
	Coal Generator	HR_{dis}	10.5	10.5	10.5
Power Rating (MW)		P	1,500	50	0.5
Size (MWh)		S	15,000	12.5	5
Number of Cycles		Cycle	350	8,000	50

4.3.3. Latin Hypercube Sampling

Latin Hypercube Sampling (LHS) is a statistical modeling technique to generate controlled random samples [66]. In this study, LHS is used to generate sample values for energy storage parameters and grid application parameters (round-trip efficiency, service life, annual degradation, production burdens, and heat rates) within their ranges provided in Table 4-3 and Table 4-4. Parameter sets were generated from 70,000 samples. Therefore, in each round, random values are created for each parameter within its lower and higher bound. The ranges are defined for each feasible storage system for each of time-shifting, frequency regulation, and power reliability applications. Based on the generated samples, the net emissions during the operation of energy storage are calculated using Equations 1a through 1c. This calculation is repeated 70,000 times with different sample parameter sets to provide an inclusive range of possibilities. The goal is to demonstrate the impact of each parameter on net emissions, for scenarios that span plausible outcomes for the other parameters.

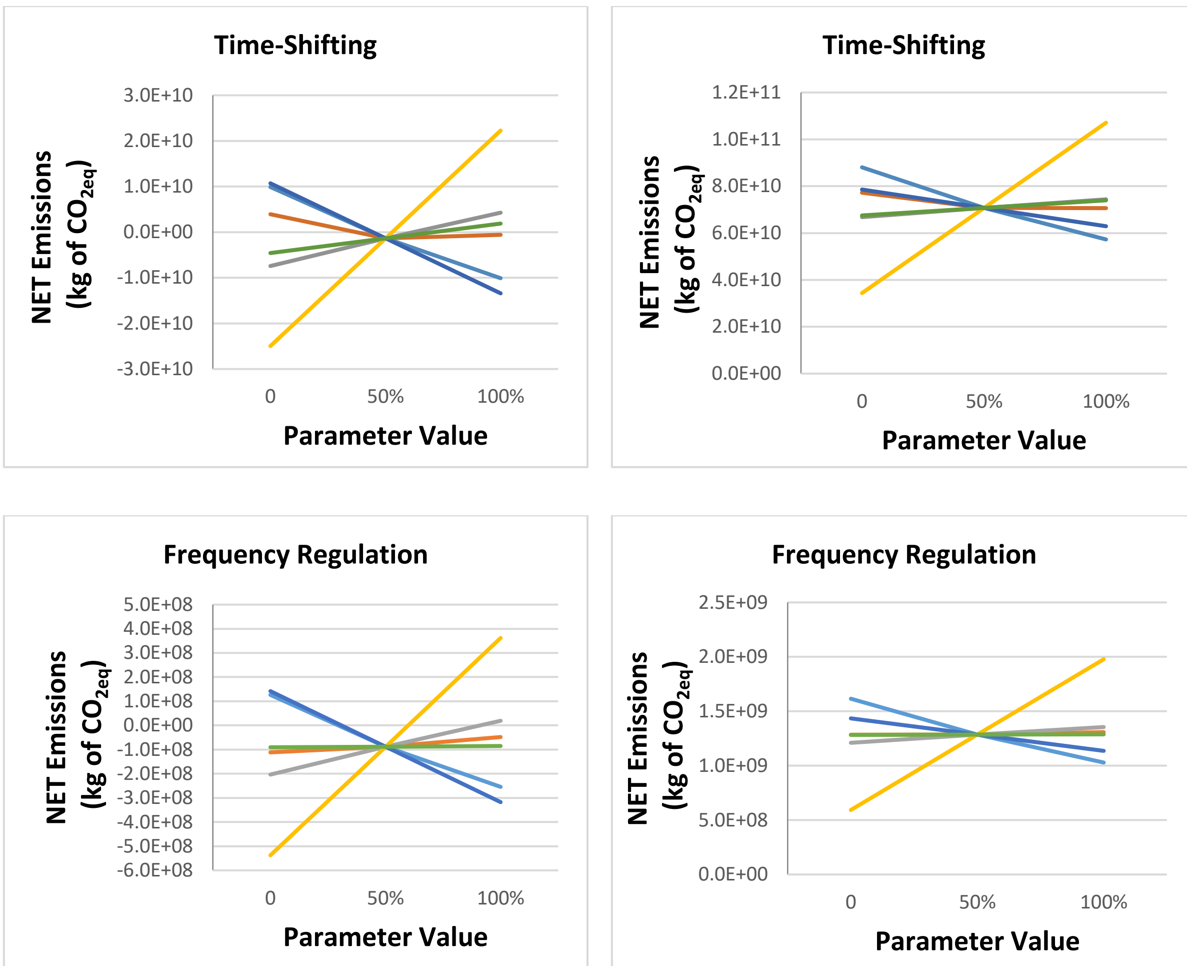
Since a range of storage sizing is assumed for each grid application, two scenarios are created—minimum size scenario and maximum size scenario—and parameter sets are created in each scenario. The ranges studied for energy storage sizing are provided earlier for each application. The results of the minimum size scenario are presented in the Results section, and the results of the maximum size scenario are provided in Appendix A.

4.4. Results

Fig. 4-1 shows the comparison among the impact of each parameter on net emissions in case of lead acid (PbA) battery technology. The results of other technologies are provided in Appendix B. For each parameter, minimum, maximum, and average values are provided in Tables 4-3 through

4-5. In this figure, the influence of round-trip efficiency, energy storage service life, annual degradation, heat rates of charging and displacing technologies, and production burden of energy storage are demonstrated. For example, increasing round-trip efficiency leads to environmental improvement across all three applications. On the other hand, among the three applications, power reliability is the only one in which production burden dominates over the net emissions. Increasing energy storage service life reduces the net emissions in the reliability application significantly.

Charge with NG-Displace Coal (tech=PbA) **Charge with Coal-Displace NG (tech=PbA)**



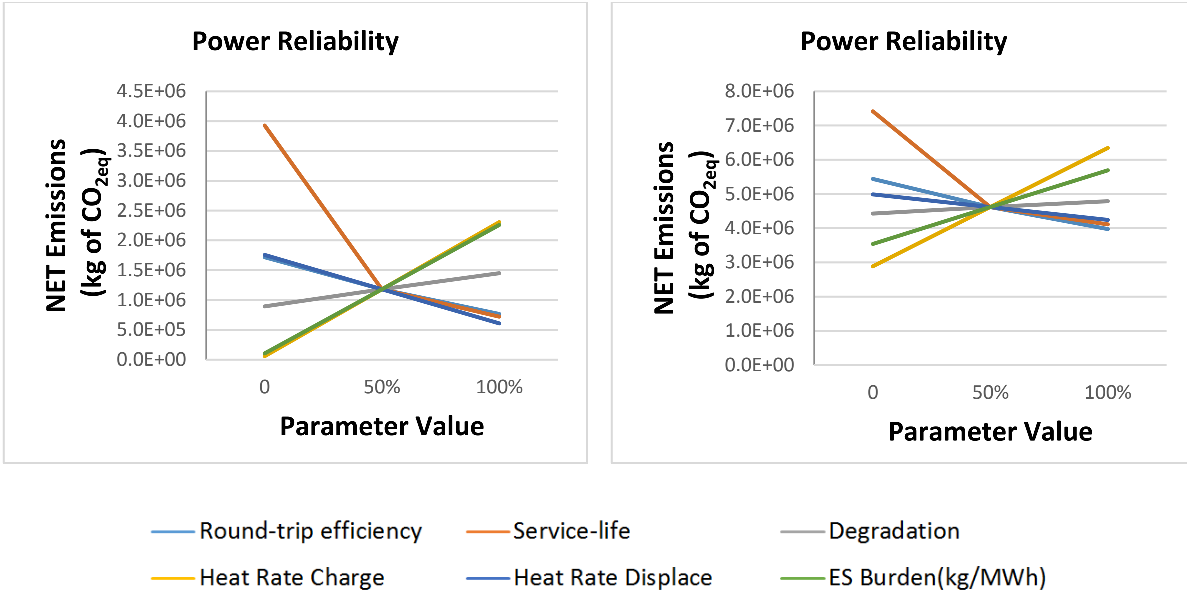


Fig. 4-1 Impacts of each parameter on CO_{2eq} net emissions in three applications: time-shifting application, frequency regulation, and power reliability in case of PbA technology. Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation, 2) energy storage is charged with coal, and displaces natural gas generation. "ES Burden" stands for energy storage production burden. X-axis represents the minimum, average, and maximum values for each parameter.

The results from the spider diagrams (Fig. 4-1) are elaborated in Fig. 4-2, which shows net, use-phase, and upstream emissions in three values of minimum, average, and maximum for each parameter. As shown in this figure, use-phase and net emissions have similar patterns in time-shifting and frequency regulation applications. They are influenced by round-trip efficiency and heat rates greatly due to the higher number of cycles in these applications.

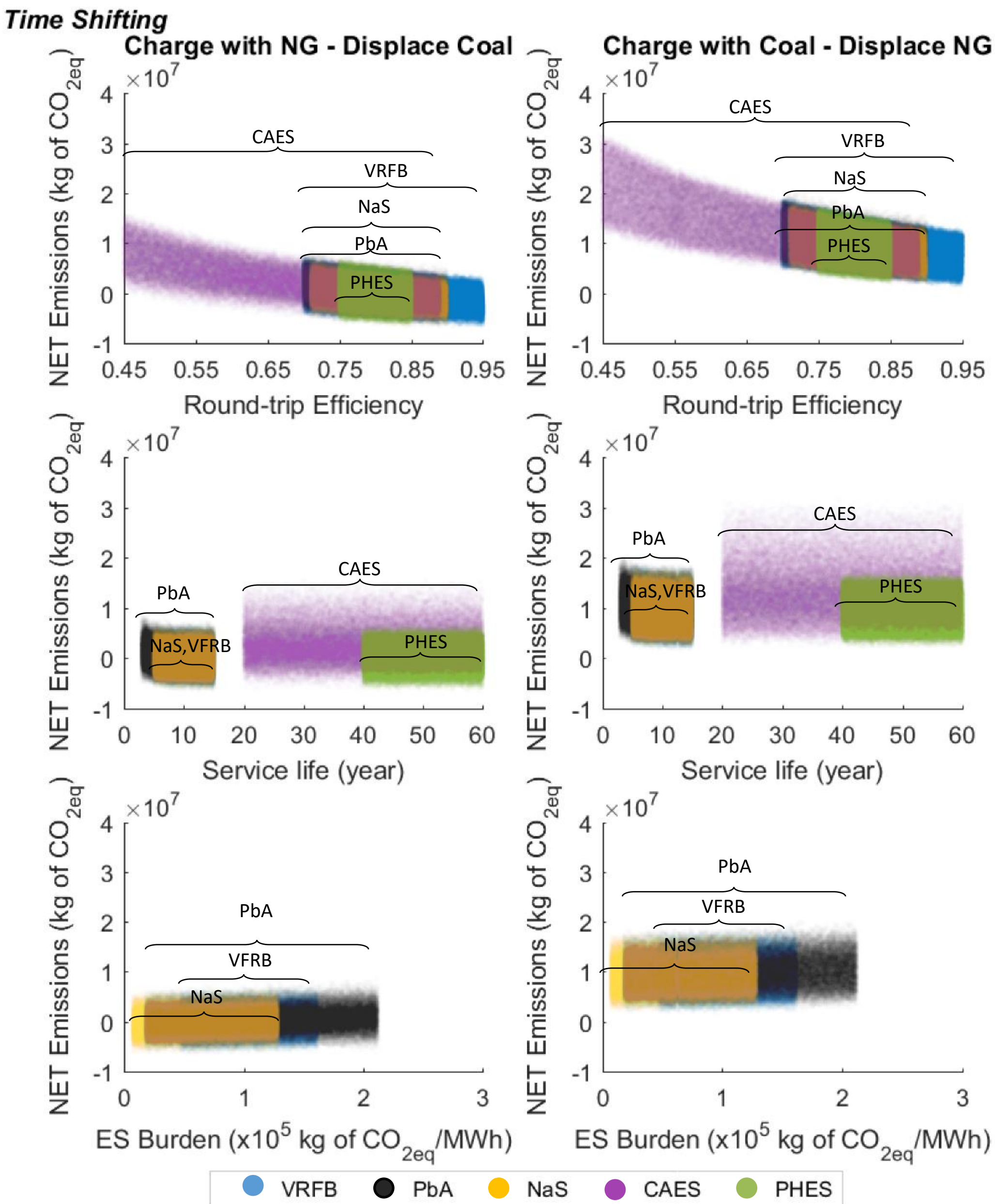
In power reliability, increasing service life would have major environmental benefits. The reason is that energy storage is not utilized frequently in this application and it does not experience severe degradation. In this application, energy storage production burden (kg of CO_{2eq} /MWh) has a large impact on upstream and net emissions. Overall, upstream emissions have a larger contribution in net emissions in the power reliability application.

Fig. 4-2 Dominance of parameters over upstream, use-phase, and net emissions in time-shifting, frequency regulation, and reliability applications in case of PbA technology. Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation, 2) energy storage is charged with coal, and displaces natural gas generation. “ES Burden” stands for energy storage production burden. The color scales vary by application and charging pattern.

Figures 4-3 to 4-5 show the results of LHS modeling for each parameter in the minimum energy storage size scenario in three applications: energy time-shifting, frequency regulation, and power reliability. The results of maximum size scenario are provided in Appendix A. As shown in these figures, round-trip efficiency has a significant impact on net emissions in time-shifting and frequency regulation applications, in which energy storage is used more frequently (higher number of cycles). Higher utilization of energy storage results in the dominance of use-phase emissions, which are greatly influenced by round-trip efficiency (as shown in Eq.1a). This is also applicable to generator heat rates, and related diagrams show a higher slope in energy time-shifting and frequency regulation applications.

Increasing energy storage service life would reduce the emissions due to a lower energy storage utilization rate in the power reliability application (Fig. 4-5). One of the twelve principles for green energy storage is to operate such systems with optimal service life (Principle# 6) [2]. This comparison across applications gives insights to energy storage operators on substituting strategies.

As shown in Fig. 4-5, the energy storage production burden (kg of CO_{2eq}/MWh) has a significant impact in the power reliability application due to a low number of cycles (i.e., low utilization of energy storage during its lifetime). Therefore, in this application upstream emissions associated with the production of the energy storage system dominate. For a higher production burden of $2.5*10^5$ kg of CO_{2eq} /MWh, integrating energy storage in this application would yield positive net emissions. Therefore, minimizing the environmental impact per unit of energy service for material production and processing, as listed in Principle#11, has a more significant influence on environmental performance in specific grid applications.


Time Shifting
Charge with NG - Displace Coal
Charge with Coal - Displace NG
NET Emissions (kg of CO2eq)
Round-trip Efficiency
Service life (year)
ES Burden (x10^5 kg of CO2eq/MWh)
CAES
VRFB
NaS
PbA
PHES
NaS,VFRB
VFRB
VRFB PbA NaS CAES PHES

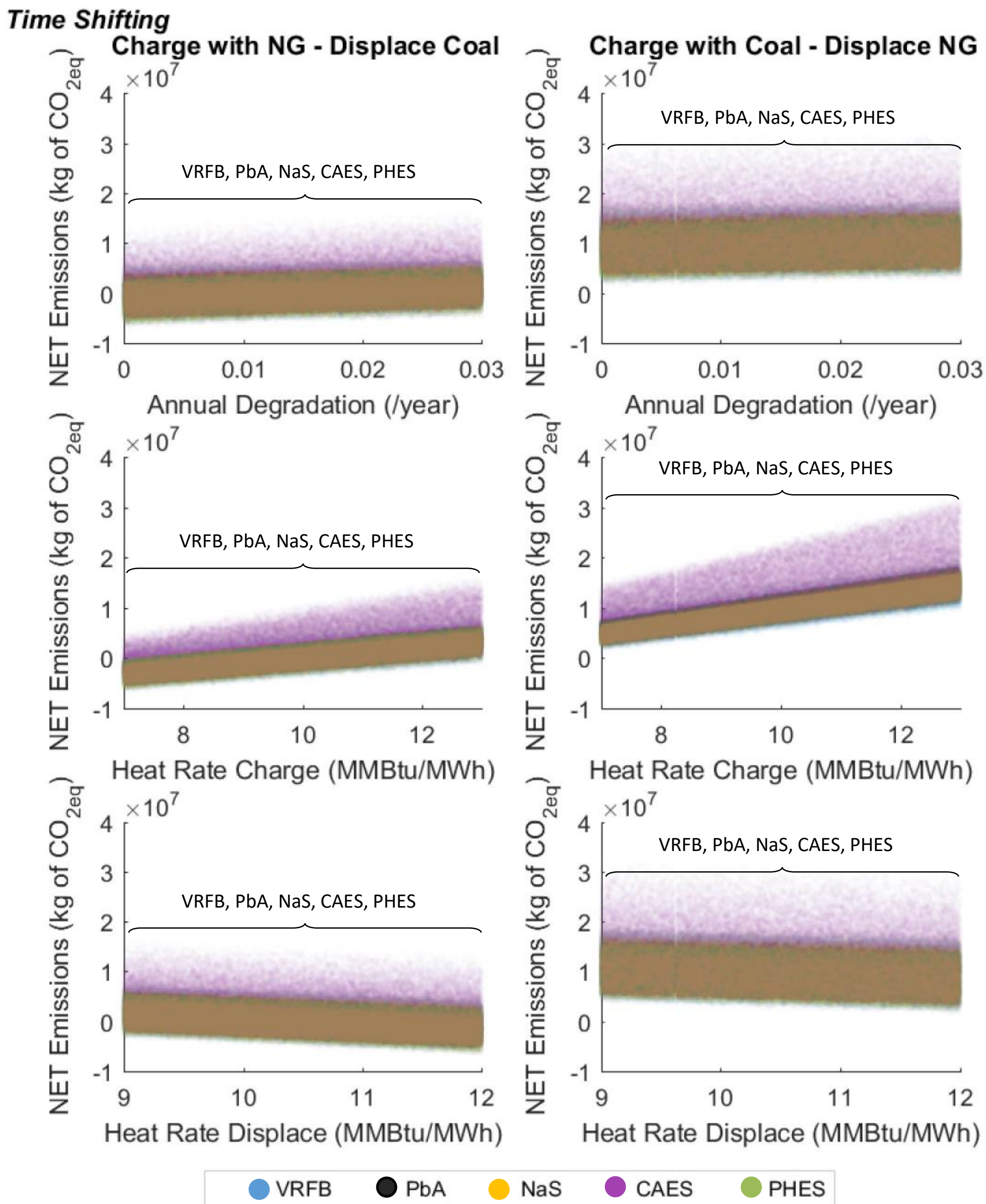
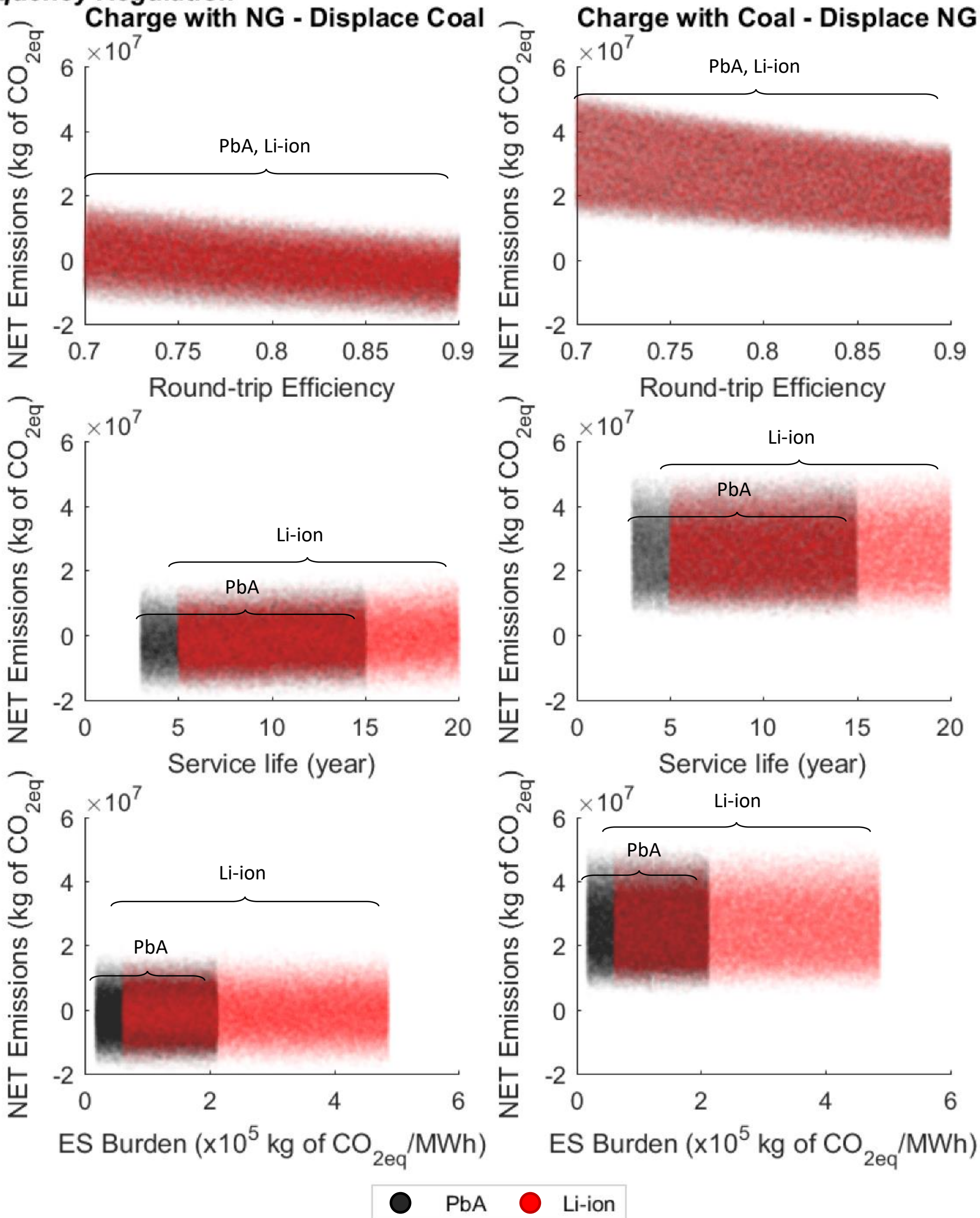


Fig. 4-3 Impacts on life cycle CO_{2eq} emissions due to assumptions for energy storage round-trip efficiency, energy storage service life, energy storage production burden, annual degradation in energy storage capacity and round-trip efficiency, heat rate of charging technology, and heat rate of displaced technology in time-shifting application (minimum size scenario). Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation (left column), 2) energy storage is charged with coal, and displaces natural gas generation (right column)

Frequency Regulation



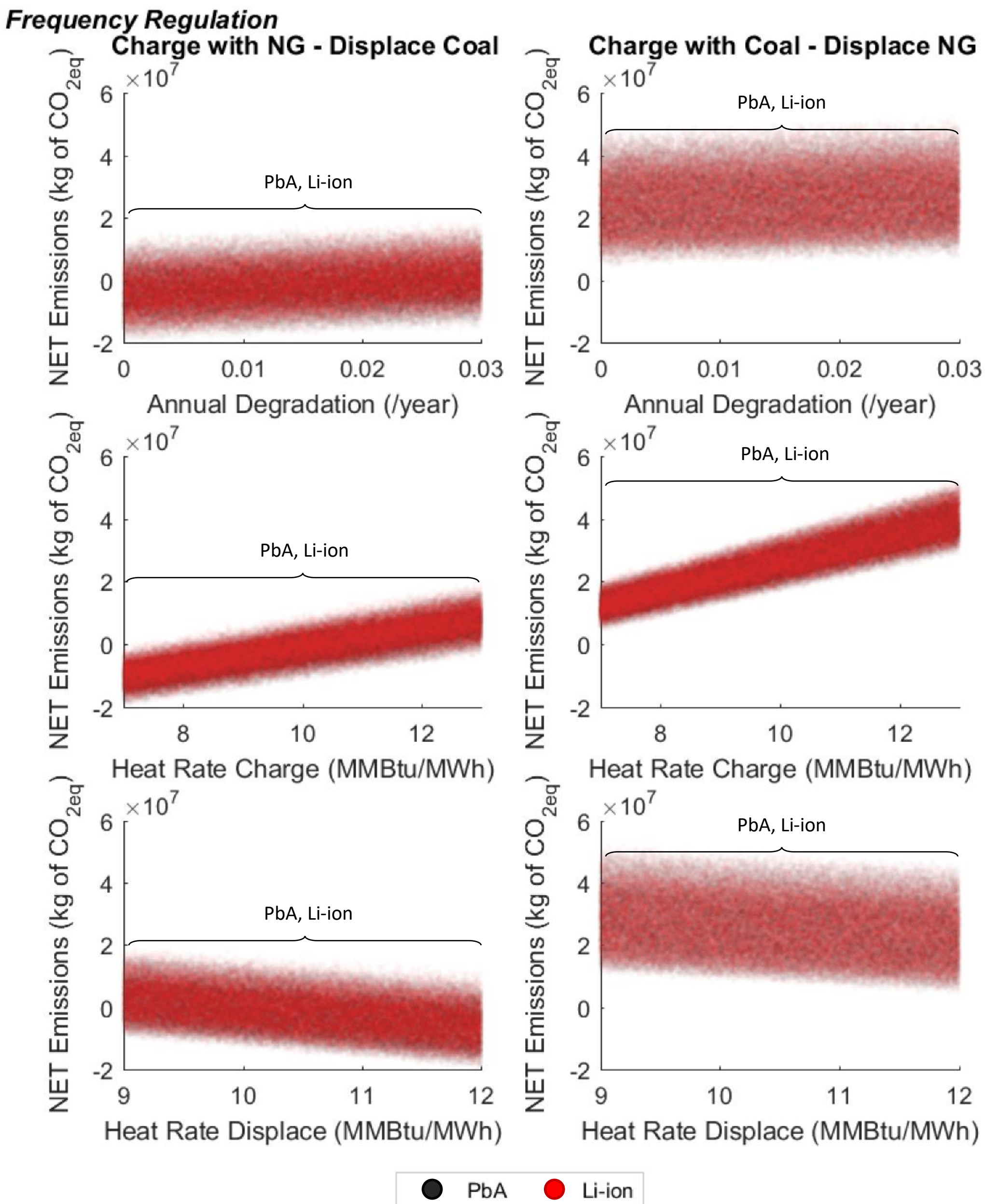
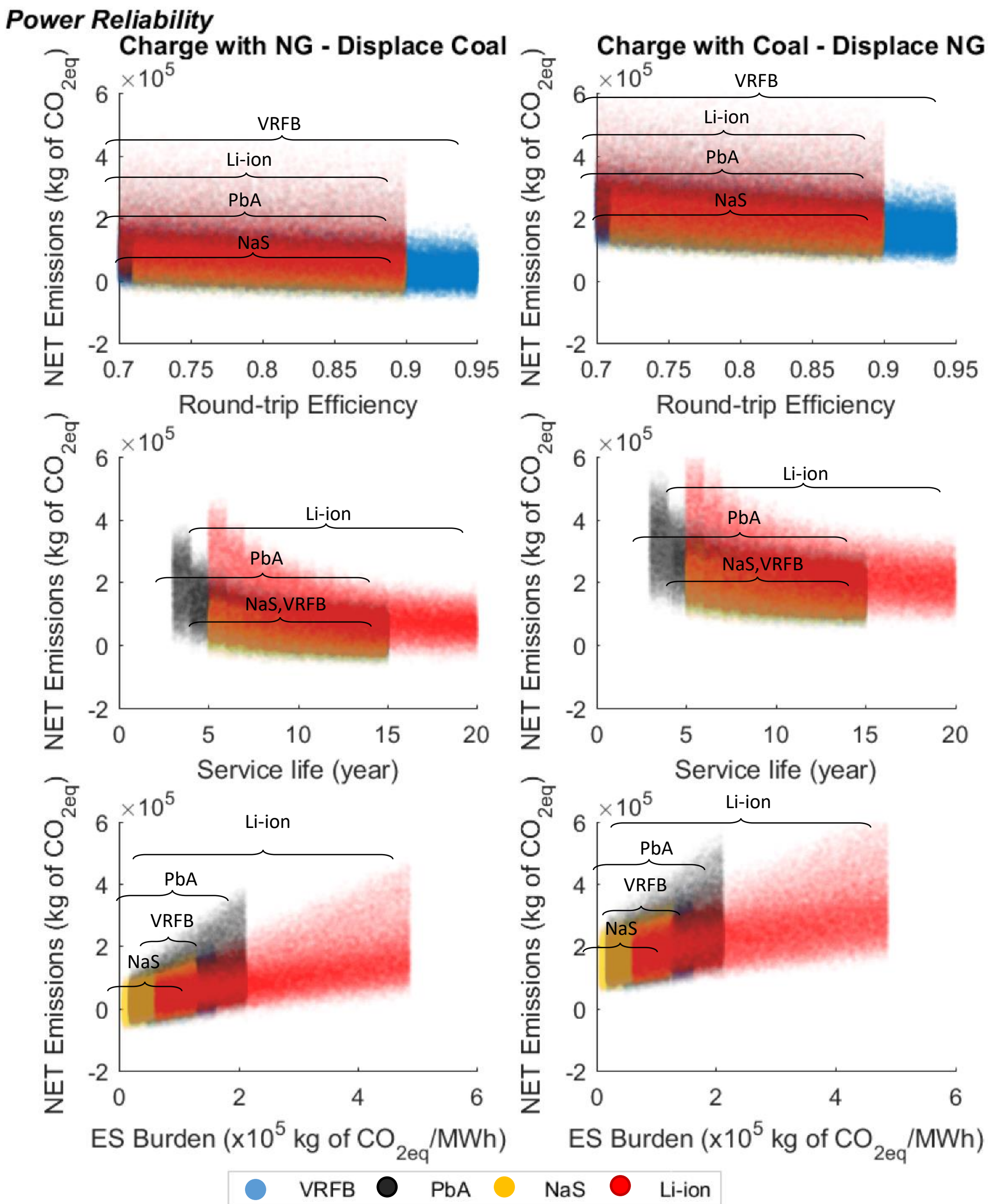


Fig. 4-4 Impacts on life cycle CO_{2eq} emissions due to assumptions for energy storage round-trip efficiency, energy storage service life, energy storage production burden, annual degradation in energy storage capacity and round-trip efficiency, heat rate of charging technology, and heat rate of displaced technology in frequency regulation application (minimum size scenario). Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation (left column), 2) energy storage is charged with coal, and displaces natural gas generation (right column)



Power Reliability
Charge with NG - Displace Coal
Charge with Coal - Displace NG
VRFB
Li-ion
PbA
NaS
NaS,VRFB
NET Emissions (kg of CO2eq)
×10^5
Round-trip Efficiency
Service life (year)
ES Burden (x10^5 kg of CO2eq/MWh)
VRFB
PbA
NaS
Li-ion

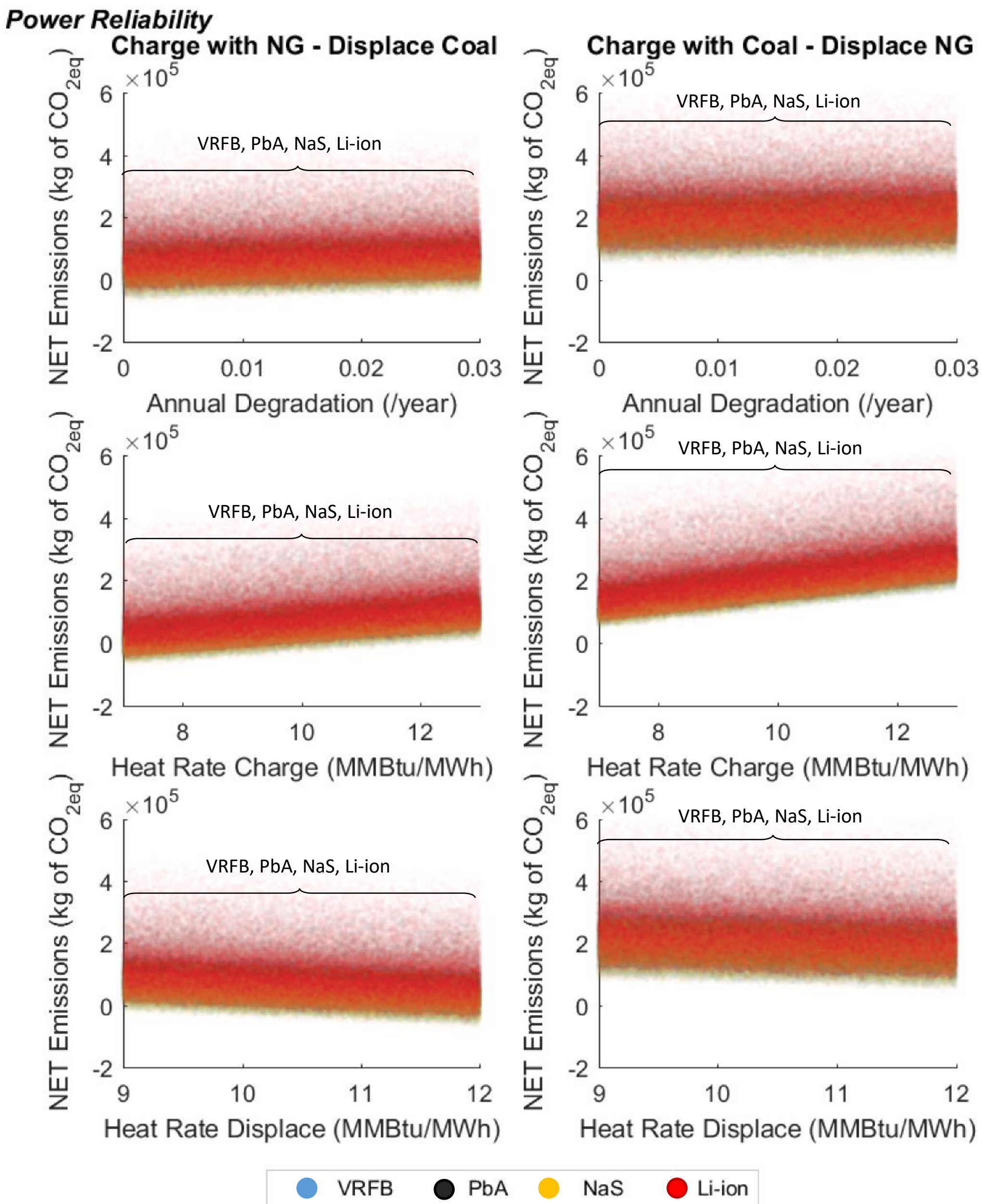


Fig. 4-5 Impacts on life cycle CO_{2eq} emissions due to assumptions for energy storage round-trip efficiency, energy storage service life, energy storage production burden, annual degradation in energy storage capacity and round-trip efficiency, heat rate of charging technology, and heat rate of displaced technology in power reliability application (minimum size scenario). Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation (left column), 2) energy storage is charged with coal, and displaces natural gas generation (right column)

4.5. Discussion

In this study, model equations are developed to analyze the impact of selected parameters on environmental performance of energy storage systems during their production and deployment in the electric grid. The selected parameters represent key factors addressed in twelve principles for green energy storage in grid applications [2], including round-trip efficiency, energy storage service life, annual degradation in energy storage capacity and round-trip efficiency, heat rates of charging and displacing technologies, and production burden of energy storage. In this study, first the grid application and potential energy storage alternatives were determined. Next, motivated by twelve principles for green energy storage, two sets of parameters were identified: energy storage system parameters and grid application parameters. The interactions between these parameters were evaluated using a universal set of equations to analyze their dominance over environmental performance.

The impacts of selected parameters on net emissions are summarized in Table 4-6. This table simplifies and clarifies the relative differences of the parameters' influence across time-shifting, frequency regulation, and power reliability applications based on our baseline assumptions. As shown in this table, the energy storage round-trip efficiency, annual degradation, and generator heat rate have a moderate to strong influence over emissions in time-shifting and frequency regulation applications due to high utilization of energy storage.

On the other hand, energy storage production burden and service life have a strong influence on net emissions in the power reliability application. In this application, upstream emissions dominate due to fewer cycles of energy storage during its operation in this application. Lower utilization of energy storage also leads to far fewer net emissions in this application compared to the other two case studies.

Table 4-6 Influence of parameters on net CO_{2eq} emissions in time-shifting, frequency regulation, and reliability applications

	Time-shifting	Frequency Regulation	Power Reliability
Round-trip efficiency	◆	◆	●
Annual degradation	●	●	■
Heat rate charge	◆	◆	●
Heat rate displace	◆	◆	●
Service life	■	■	◆

Energy storage production burden	■	■	◆

Strong influence ◆ Moderate influence ● Weak influence ■

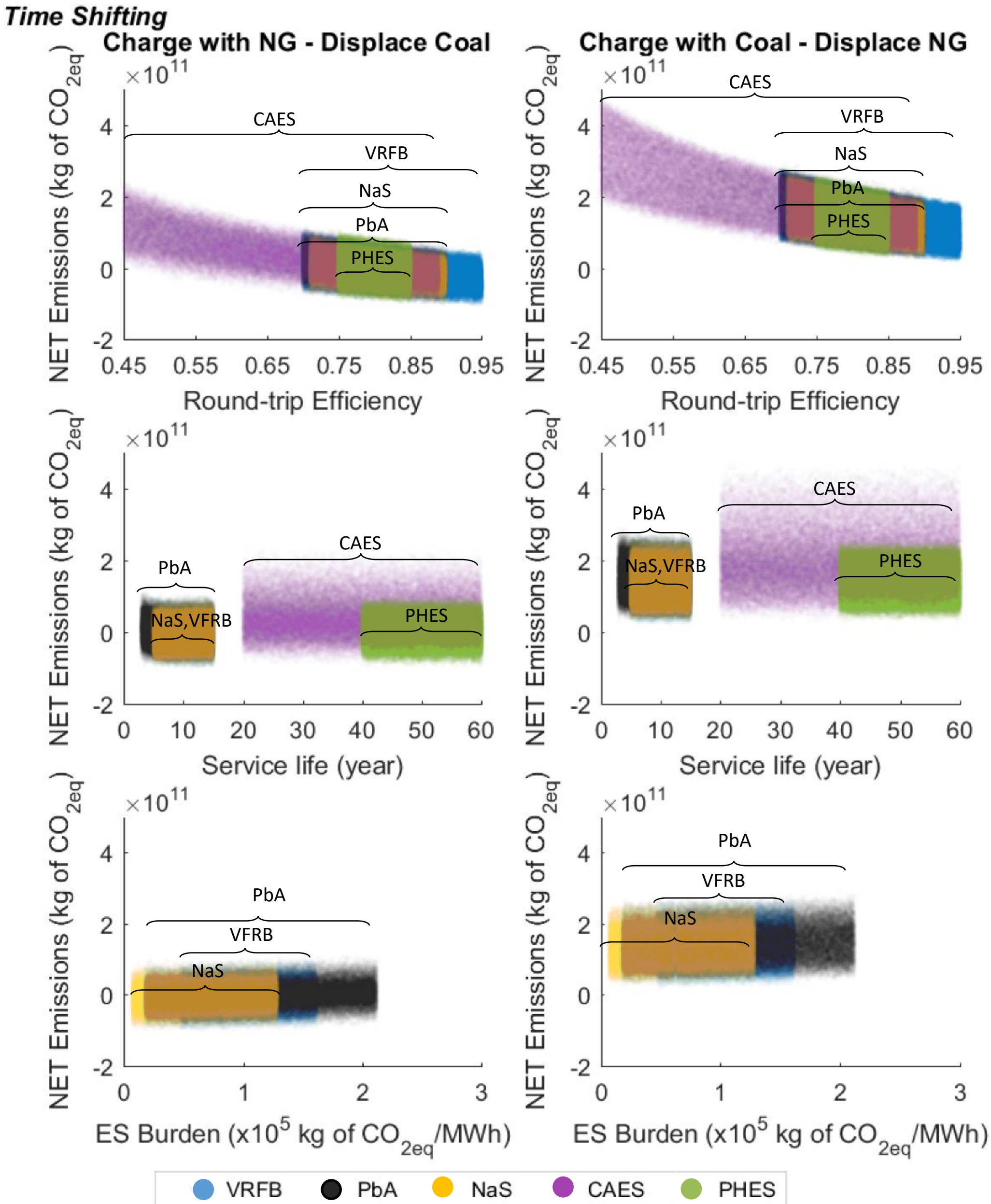
To evaluate the results of enhanced environmental performance of energy storage integration and also to analyze some real world applications, we have assumed two scenarios: In the first scenario, energy storage is charged with natural gas, and the stored electricity displaces coal based electricity generation. In many real world applications, this is not the standard practice, given that natural gas is often more expensive that coal. To charge the energy storage with natural gas and displace coal based generation, there would likely need to be an inversion of coal and gas prices (e.g. driven by a carbon tax or a CO_2 cap) that could incentivize coal to gas switching. In the second scenario, energy storage is charged with a higher emitting generation such as coal and displaces natural gas. In this case, the relative influence of parameters is the same. However, this scenario leads to more net emissions during the operation of the energy storage system, fundamentally altering the approach for environmental pollution mitigation.

There are major uncertainties associated with the upstream emissions of natural gas [67]- [71], particularly the amount of methane leakage during natural gas production. If the life cycle emissions of the charging generation prove to be higher than displaced generation due to these emissions, the results would change the energy storage integration strategy.

In addition to environmental incentives, the economies of energy storage technologies are also a key driver in selecting the suitable technology for a specific application. The comparison among environmental and economic benefits of different storage technologies across grid applications is the focus of future research that will build upon our findings in this chapter.

As shown in this study, the integration of energy storage systems in different grid applications may not necessarily lead to environmental improvements. The environmental outcomes depend on the grid application and storage technology parameters. Understanding the interaction among such parameters, as analyzed here, can guide different stakeholders, who develop and manage energy storage systems. They include energy storage designers, operators, and utilities. This analysis can help them more systematically improve environmental performance by focusing on the most influential parameters in the development and deployment of energy storage systems.

Appendix A. The results of LHS modeling in maximum case scenario



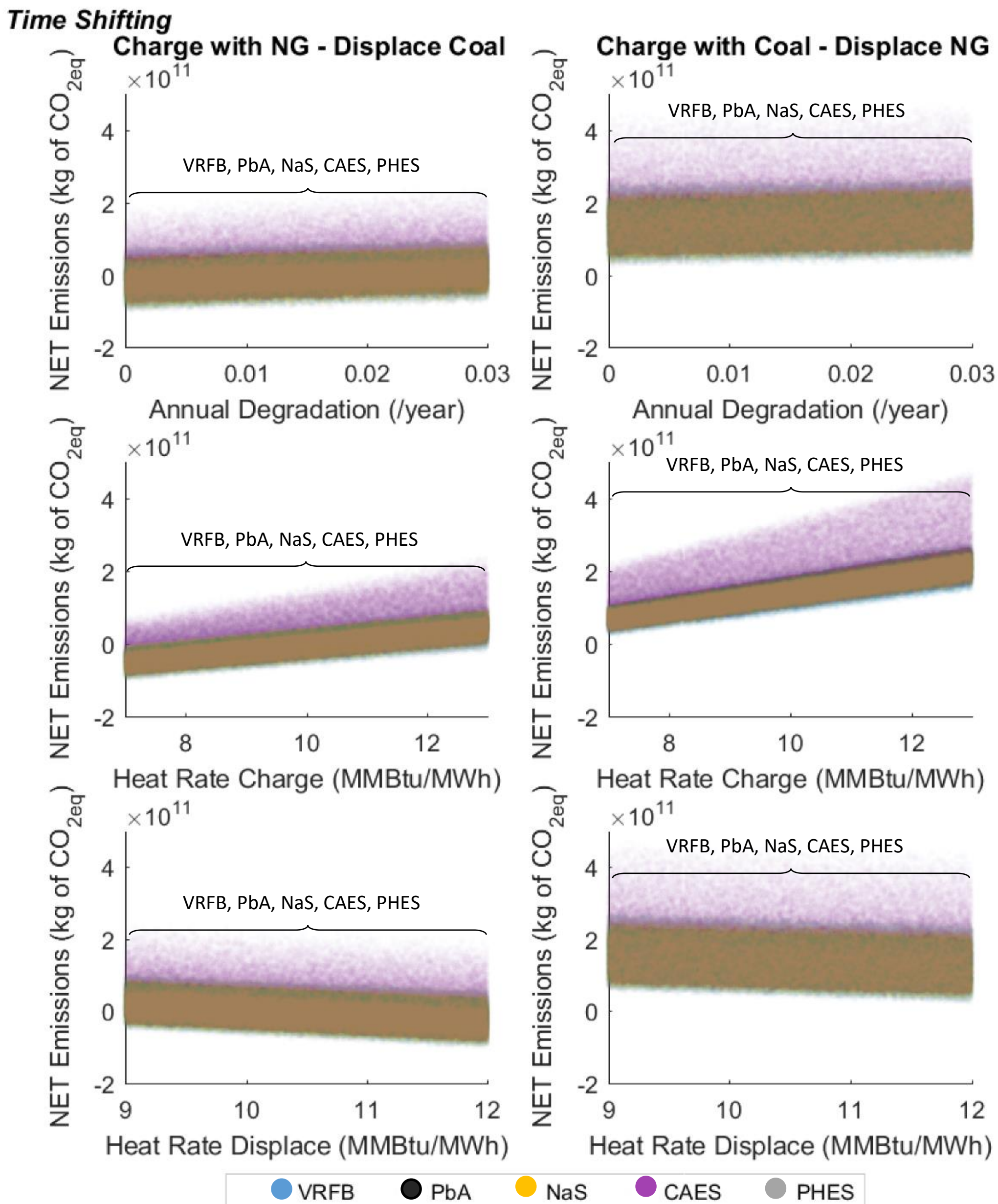
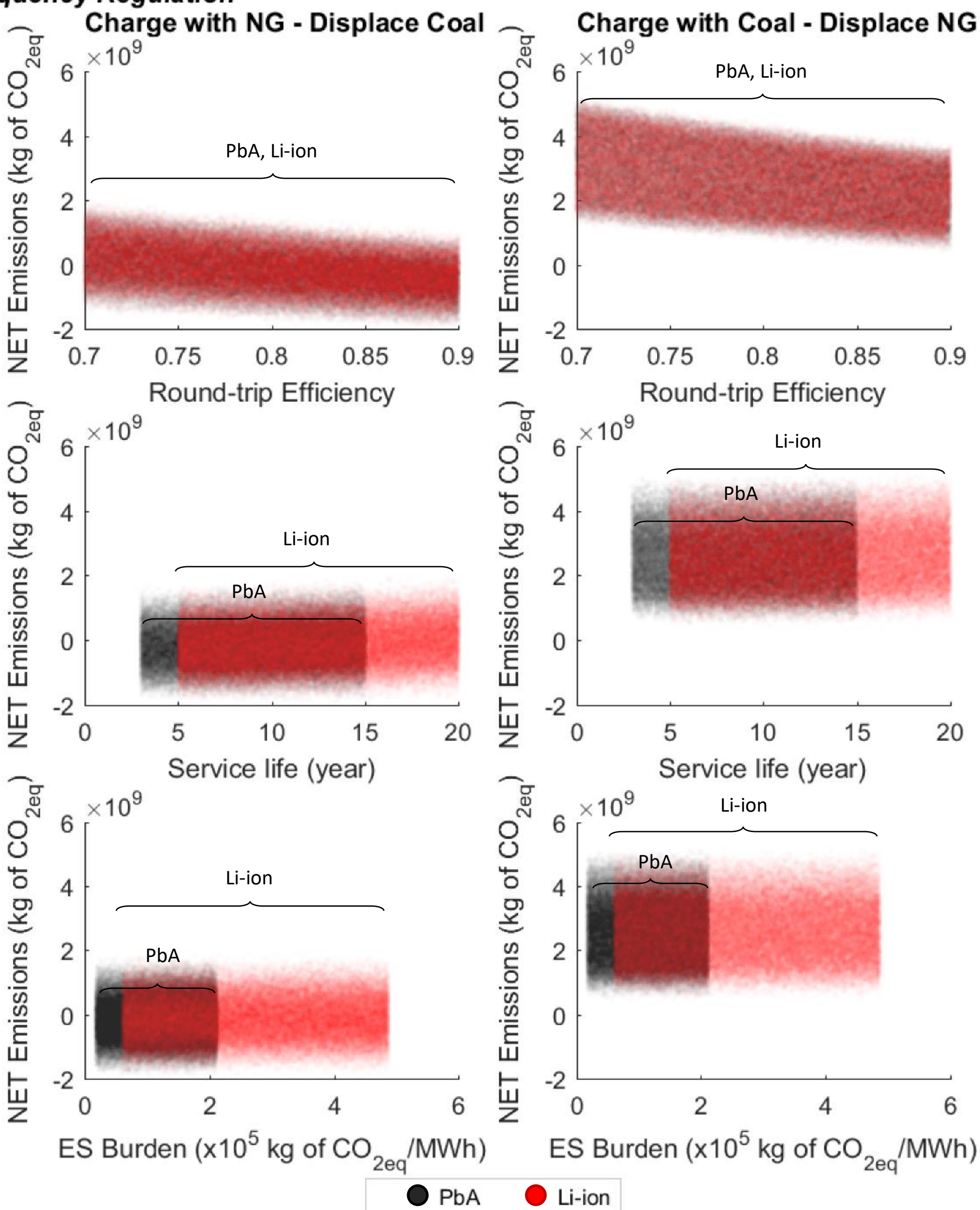


Fig. 4-6 Impacts on life cycle CO_{2eq} emissions due to assumptions for energy storage round-trip efficiency, energy storage service life, energy storage production burden, annual degradation in energy storage capacity and round-trip efficiency, heat rate of charging technology, and heat rate of displaced technology in time-shifting application (maximum size scenario). Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation (left column), 2) energy storage is charged with coal, and displaces natural gas generation (right column)

Frequency Regulation



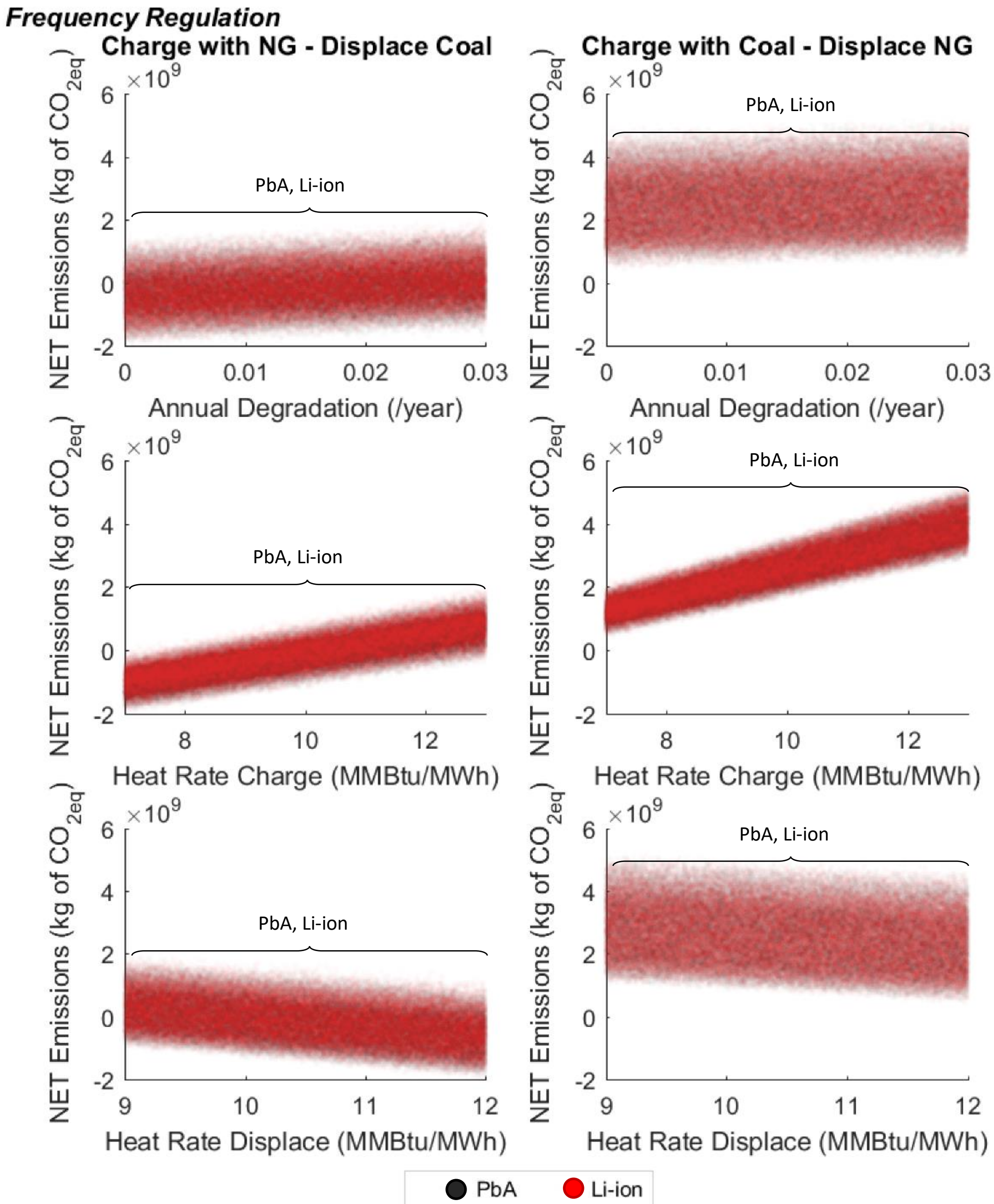
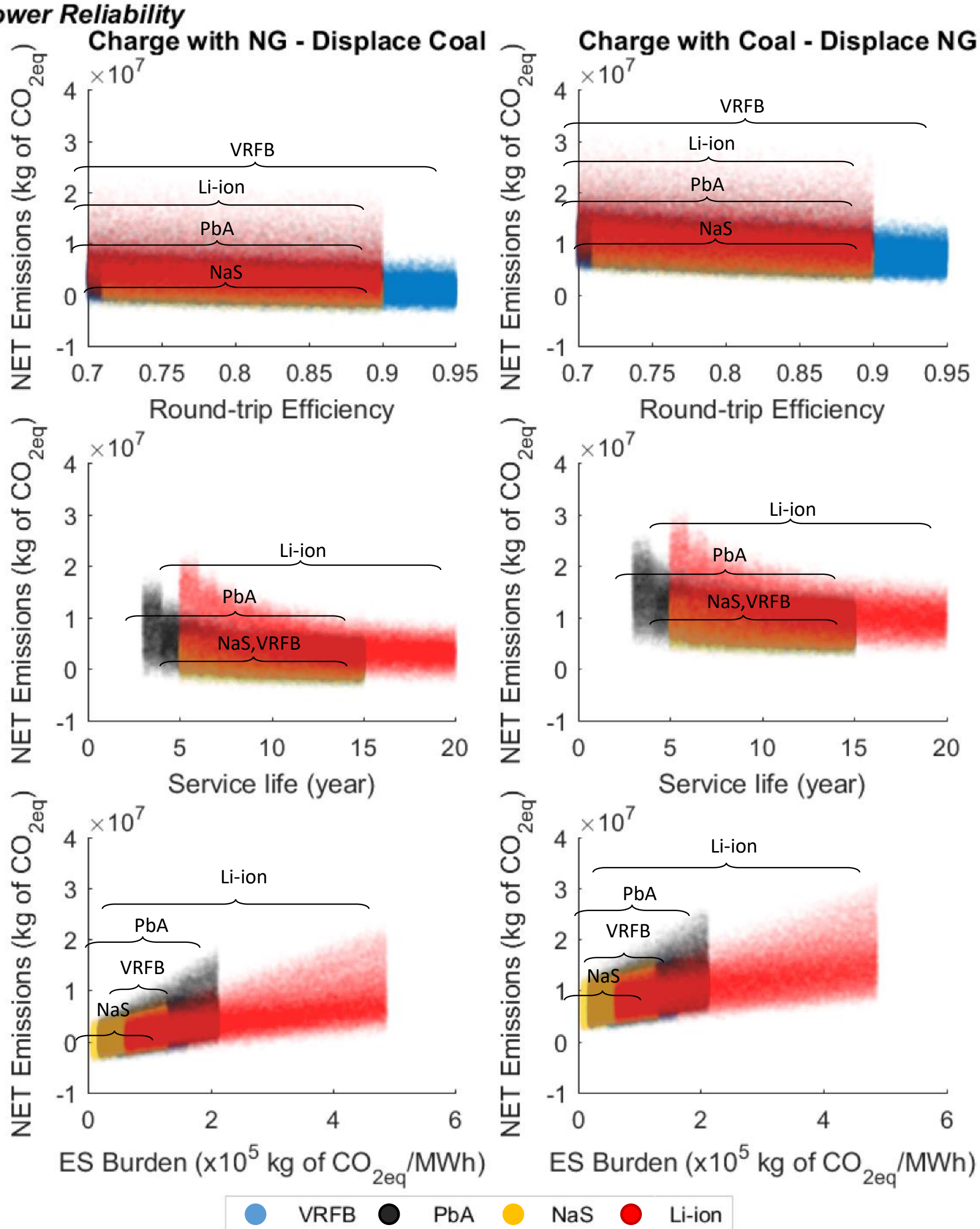


Fig. 4-7 Impacts on life cycle CO_{2eq} emissions due to assumptions for energy storage round-trip efficiency, energy storage service life, energy storage production burden, annual degradation in energy storage capacity and round-trip efficiency, heat rate of charging technology, and heat rate of displaced technology in frequency regulation application (maximum size scenario). Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation (left column), 2) energy storage is charged with coal, and displaces natural gas generation (right column)

Power Reliability



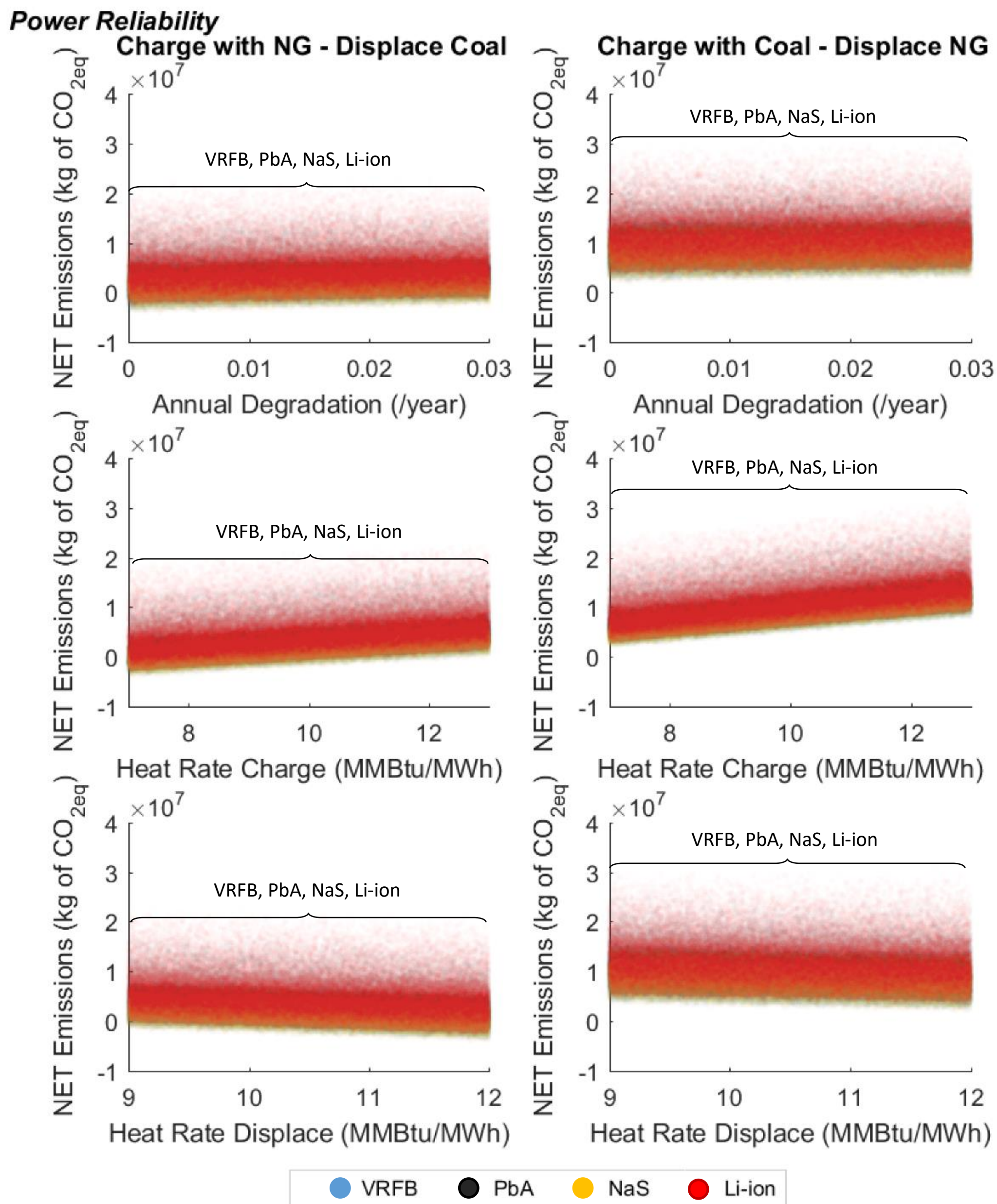
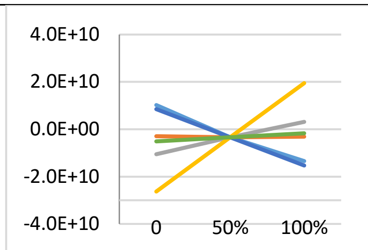
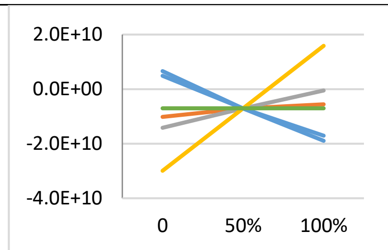
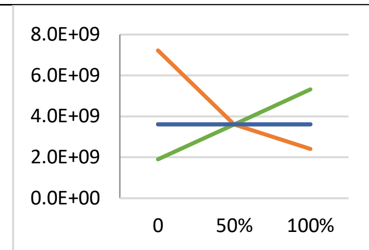
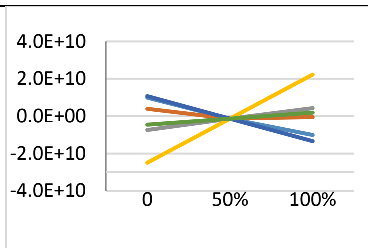
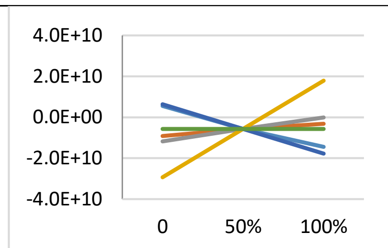
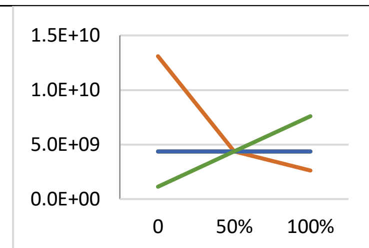
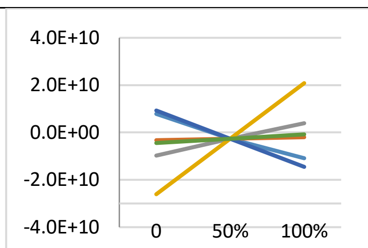
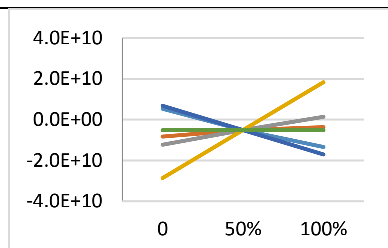
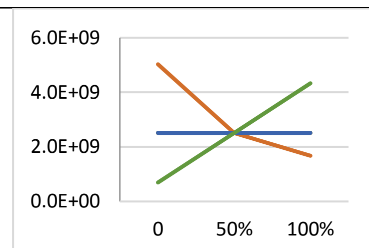
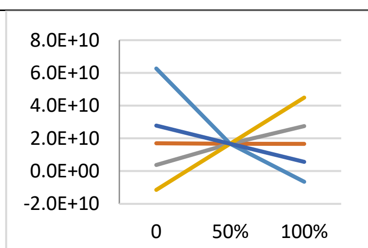
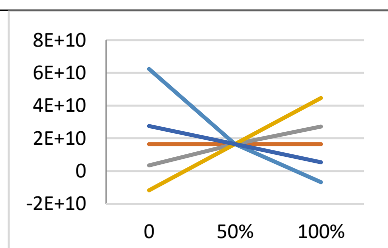
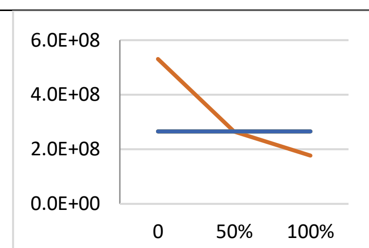
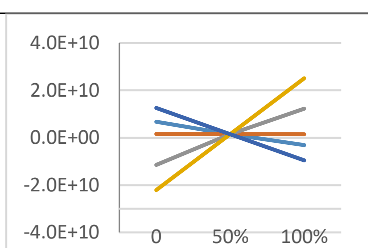
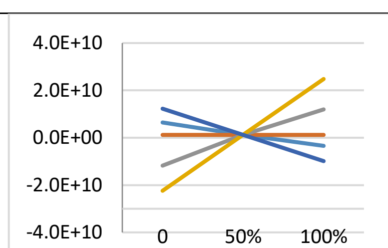
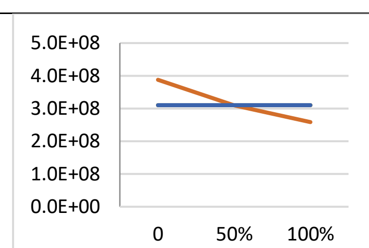


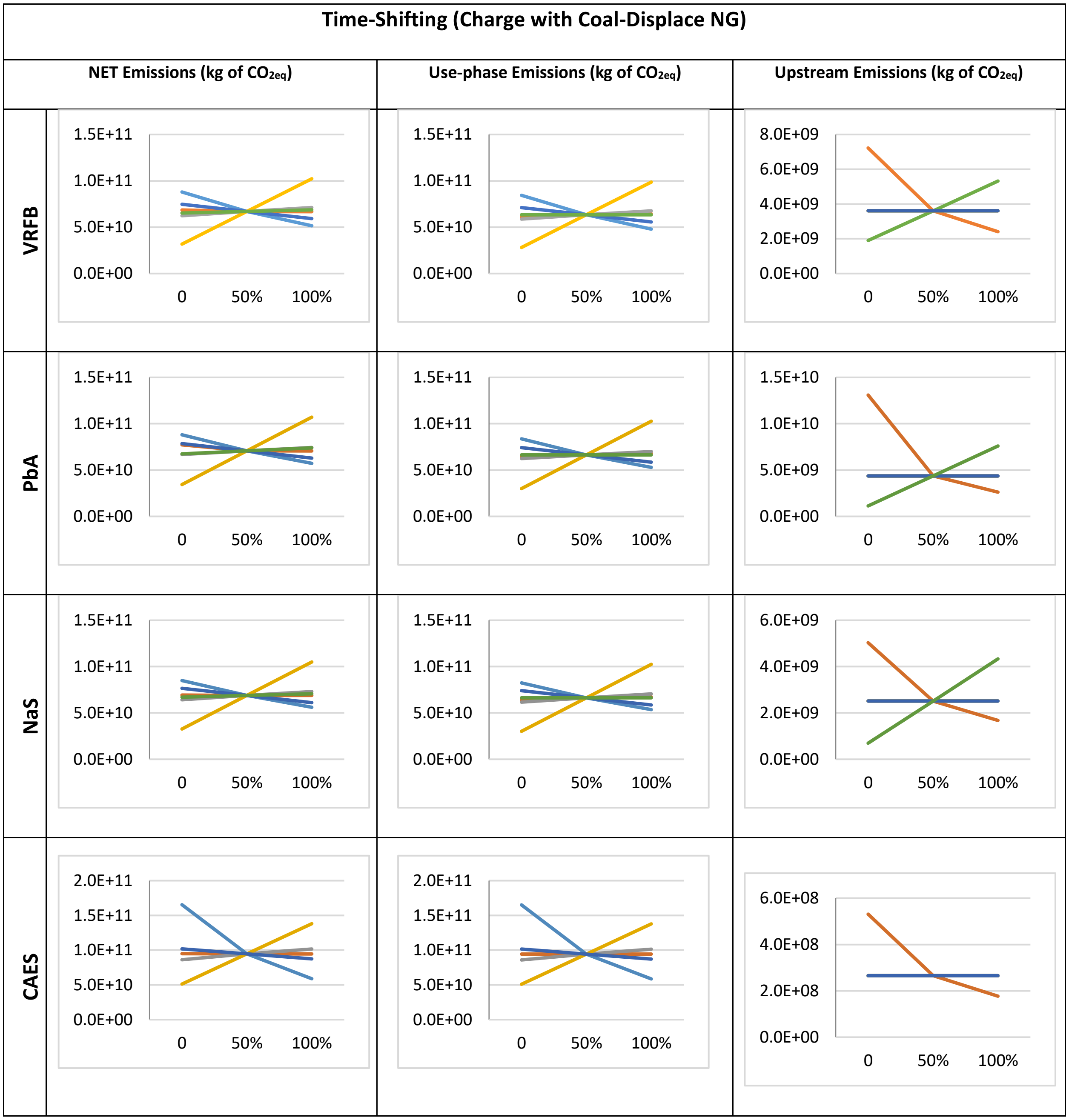
Fig. 4-8 Impacts on life cycle CO_{2eq} emissions due to assumptions for energy storage round-trip efficiency, energy storage service life, energy storage production burden, annual degradation in energy storage capacity and round-trip efficiency, heat rate of charging technology, and heat rate of displaced technology in power reliability application (maximum size scenario). Two scenarios are assumed: 1) energy storage is charged with natural gas, and displaces coal based electricity generation (left column), 2) energy storage is charged with coal, and displaces natural gas generation (right column)

Appendix B. Spider diagrams for net, use-phase, and upstream emissions

Time-Shifting (Charge with NG-Displace Coal)			
	NET Emissions (kg of CO_{2eq})	Use-phase Emissions (kg of CO_{2eq})	Upstream Emissions (kg of CO_{2eq})
VRFB			
PbA			
NaS			
CAES			
PHES			

Round-trip efficiency — Service-life — Degradation — Heat Rate Charge — Heat Rate Displace — ES Burden(kg/MWh)

Fig. 4-9 Impacts of each parameter on net, use-phase, and upstream emissions in time-shifting application. “ES Burden” stands for energy storage production burden. It is assumed that energy storage is charged with natural gas and displaces coal based electricity generation. X-axis represents the minimum, average, and maximum values for each parameter. (VRFB=vanadium redox flow battery, PbA= lead-acid battery, NaS= sodium-sulfur battery, CAES= compressed air energy storage, PHES= pumped-hydro energy storage)



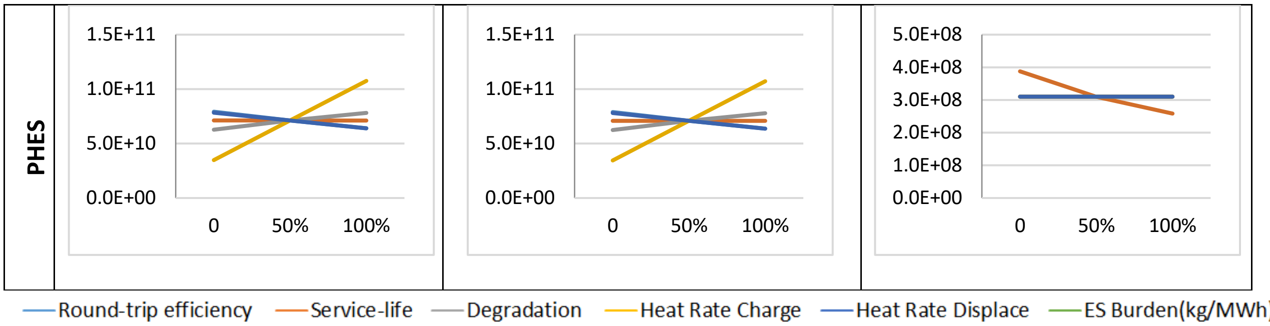


Fig. 4-10 Impacts of each parameter on net, use-phase, and upstream emissions in time-shifting application. "ES Burden" stands for energy storage production burden. It is assumed that energy storage is charged with coal based electricity generation and displaces natural gas. X-axis represents the minimum, average, and maximum values for each parameter. (VRFB=vanadium redox flow battery, PbA= lead-acid battery, NaS= sodium-sulfur battery, CAES= compressed air energy storage, PHES= pumped-hydro energy storage)

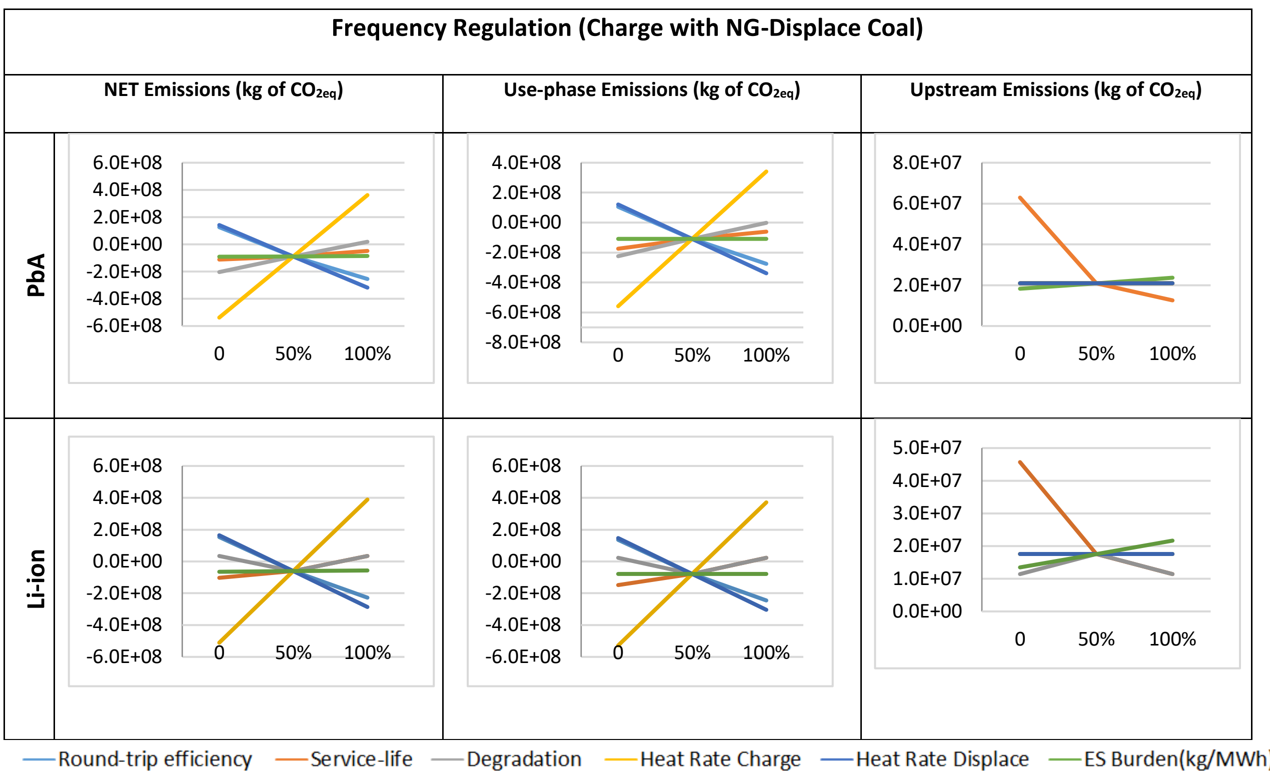


Fig. 4-11 Impacts of each parameter on net, use-phase, and upstream emissions in frequency regulation application. "ES Burden" stands for energy storage production burden. It is assumed that energy storage is charged with natural gas and displaces coal based electricity generation. X-axis represents the minimum, average, and maximum values for each parameter. (PbA= lead-acid battery, Li-ion= lithium-ion battery)

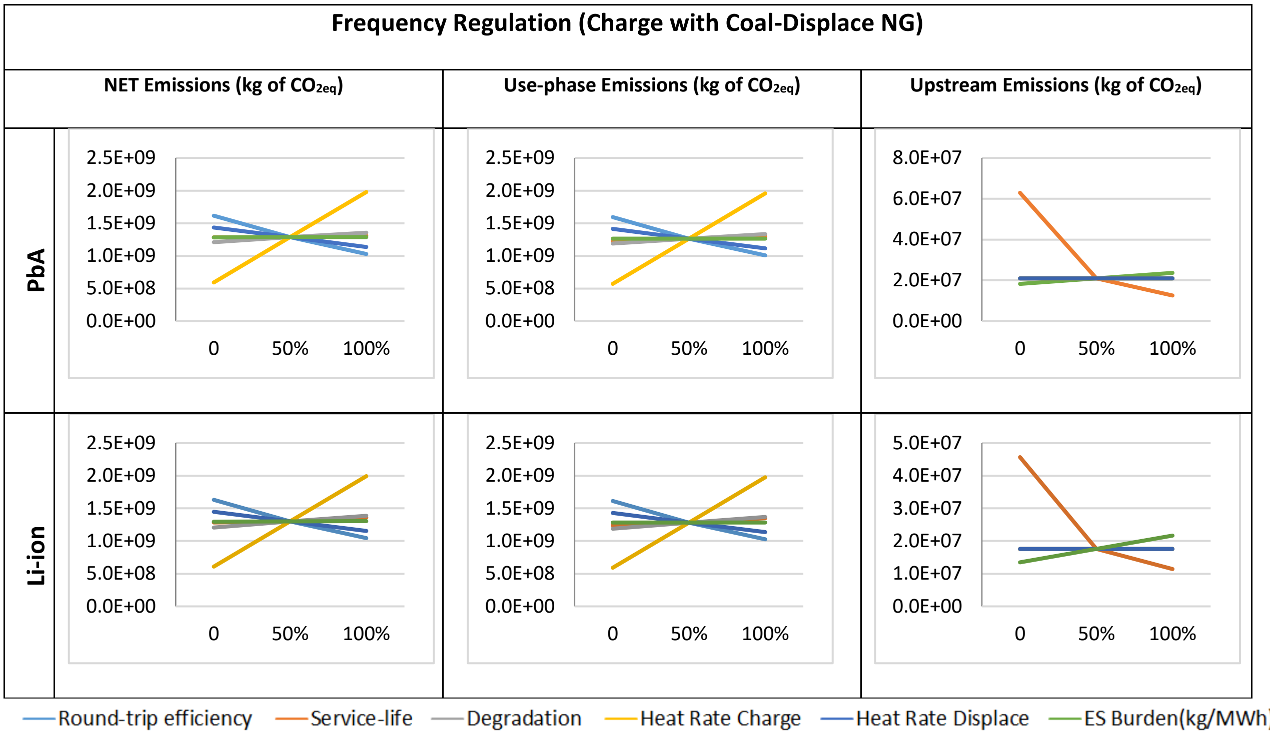
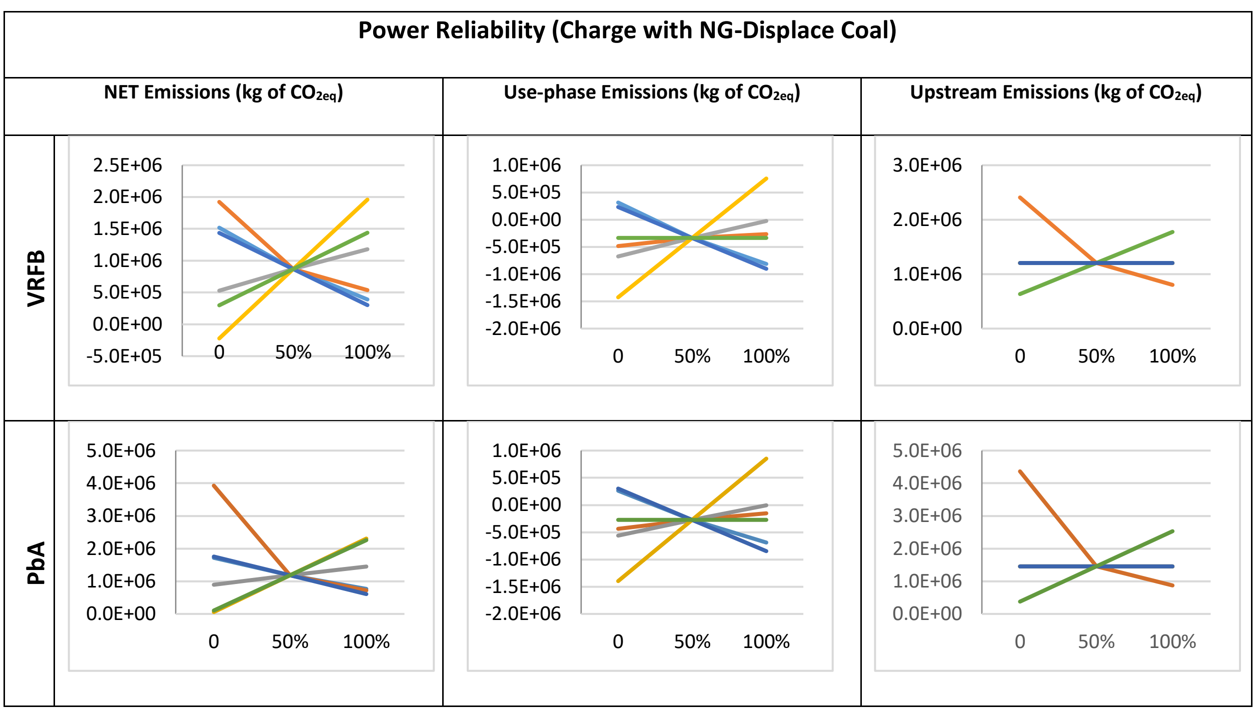


Fig. 4-12 Impacts of each parameter on net, use-phase, and upstream emissions in frequency regulation application. "ES Burden" stands for energy storage production burden. It is assumed that energy storage is charged with coal based electricity generation and displaces natural gas. X-axis represents the minimum, average, and maximum values for each parameter. (PbA= lead-acid battery, Li-ion= lithium-ion battery)



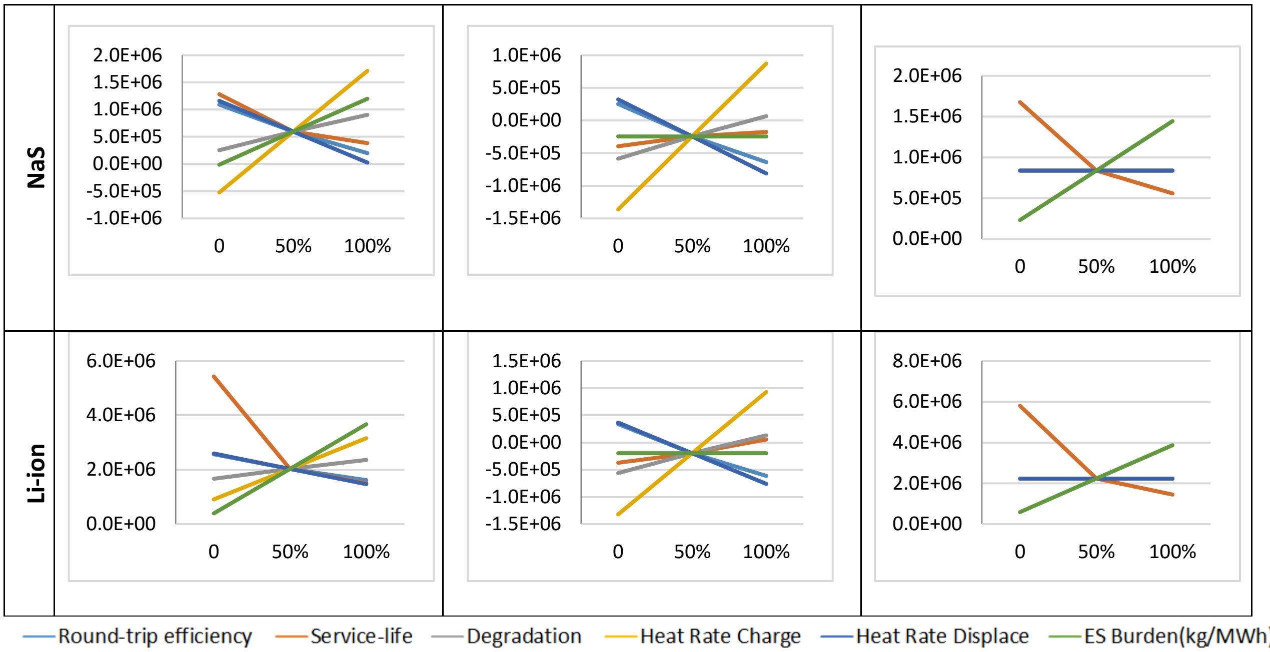
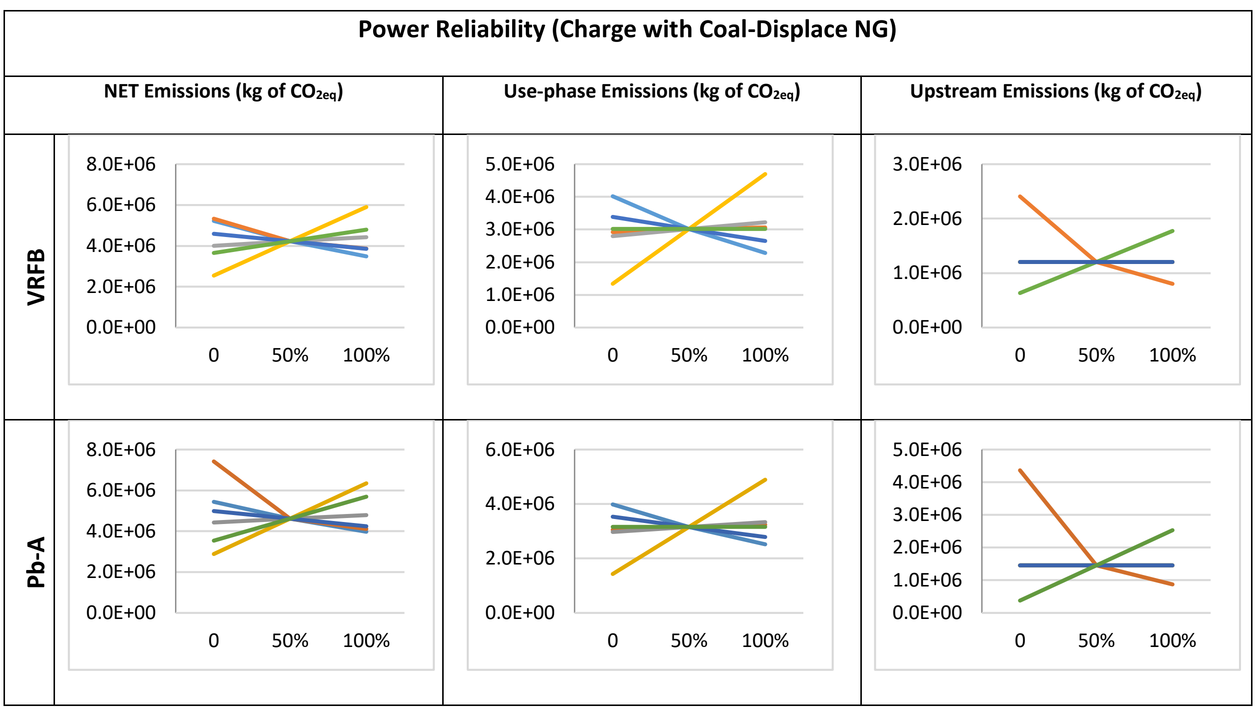


Fig. 4-13 Impacts of each parameter on net, use-phase, and upstream emissions in power reliability application. "ES Burden" stands for energy storage production burden. It is assumed that energy storage is charged with natural gas and displaces coal based electricity generation. X-axis represents the minimum, average, and maximum values for each parameter. (VRFB=vanadium redox flow battery, PbA= lead-acid battery, NaS= sodium-sulfur battery, Li-ion= lithium-ion battery)



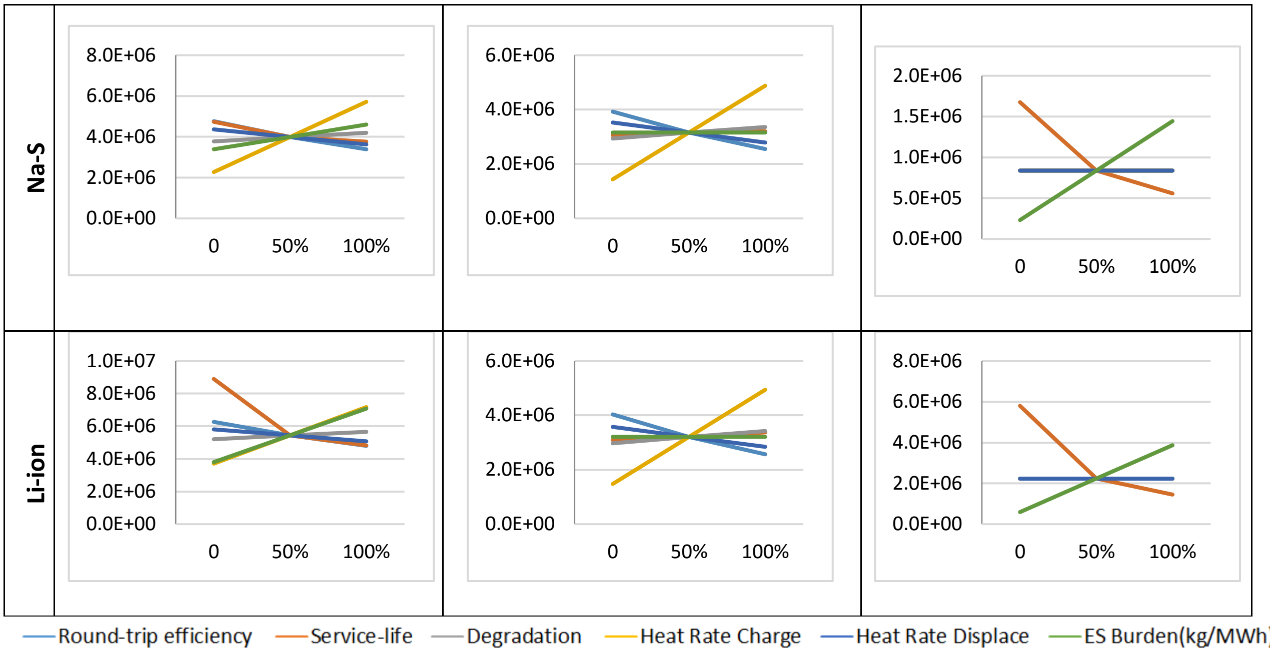


Fig. 4-14 Impacts of each parameter on net, use-phase, and upstream emissions in power reliability application. "ES Burden" stands for energy storage production burden. It is assumed that energy storage is charged with coal based electricity generation and displaces natural gas. X-axis represents the minimum, average, and maximum values for each parameter. (VRFB=vanadium redox flow battery, PbA= lead-acid battery, NaS= sodium-sulfur battery, Li-ion= lithium-ion battery)

Appendix C. List of twelve principles for green energy storage systems in grid applications

1. Charge clean and displace dirty.
2. Energy storage should have lower environmental impact than displaced infrastructure.
3. Match application to storage capabilities to prevent degradation.
4. Avoid oversizing energy storage systems.
5. Maintain to limit degradation.
6. Design and operate energy storage for optimal service life,
7. Design and operate energy storage with maximum round-trip efficiency.
8. Minimize consumptive use of non-renewable materials.
9. Minimize use of critical materials.
10. Substitute non-toxic and non-hazardous materials.
11. Minimize the environmental impact per unit of energy service for material production and processing.
12. Design for end-of-life.

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CHAPTER 5

Energy storage for time-shifting and greenhouse gas reductions under varying renewable penetrations- A CAISO case study

Abstract

Given the complex nature of power systems, the integration of large-scale energy storage for grid applications such as energy time-shifting may lead to a wide range of environmental and economic outcomes. In this study, we present an optimization model to examine the role of cost-effective energy storage in bulk energy time-shifting in California Independent System Operator (CAISO), while accounting for greenhouse gas (GHG) emissions. In this model, we consider renewable penetrations of 0, 10 GW, and 20 GW of wind energy, and 0, 20 GW, and 40 GW of solar energy. Natural gas generation, level of solar and wind energy delivered to demand, energy storage sizing, and energy storage operation are optimized to find the minimum total system costs, while subject to energy storage technical requirements and the load balance constraints. Total system costs include the fuel operating costs, energy storage capital costs, and GHG emissions costs. By assuming four emissions taxes of 0, \$50/ton of CO_2, \$100/ton of CO_2, and \$200/ton of CO_2, we investigate how monetizing the generators marginal emissions with an emission tax would influence optimal results. We analyze nine energy storage technologies including pumped-hydro energy storage (PHES), compressed air energy storage (CAES), and six battery technologies (including lead-acid, lithium-ion, sodium-sulfur, and flow batteries). These technologies are characterized by their round-trip efficiency, service life, and capital costs. Simulations are run for each technology to show at each level of emissions tax and installed capacity of wind and solar, how much energy storage is deployed. The findings show that the size, operation, and curtailment reduction are very dependent on the capital cost of energy storage technologies. Increasing the installed renewable capacity and the emissions tax would make energy storage more cost-effective. Among storage technologies, PHES and diabetic compressed air energy storage (DCAES) with assumed lower capital costs, are deployed in more scenarios and renewables curtailment reduces significantly after integrating these technologies. We also investigate how much the capital cost of relatively expensive technology such

as lithium-ion (Li-ion) needs to be reduced to achieve widespread deployment for this application.

Table 5-1 Nomenclature

Nomenclature		
A. Sets and Parametrs		
Problem-size Parameters	I	set of generators
	T	set of hours
Storage Parameters	η^c	charging efficiency of storage
	NG_{price}	price of natural gas [$/mmBtu]
	NG_{em}	emissions rate of natural gas [t/mmBtu]
	NG_{use}	natural gas use by storage system [mmBtu/MWh]
	C^Q	cost of storage power capacity [$/MW]
	C^S	cost of storage energy capacity [$/MWh]
	R	rate to annualize capital cost
	R	discount rate
	n	energy storage service life
System Parameters	$c_{t,i}$	hour-t marginal cost of generator i [$/MWh]
	$e_{t,i}$	hour-t marginal emission of generator i [ton/MWh]
	β	emission tax ($/ton)
	$K_{t,i}$	hour-t capacity of generator i [MW]
	L_t	hour-t load [MW]
	$minload$	minimum dispatchable load level [MW]
	$nuclear_t$	hour- t nuclear output [MW]
	$import_t$	hour- t imported power [MW]
	$geothermal_t$	hour- t geothermal output [MW]
	$biomass_t$	hour- t biomass output [MW]
	$biogas_t$	hour- t biogas output [MW]
	$hydro_t$	hour- t hydroelectric output [MW]
	$windCap$	installed wind capacity [MW]
	$solarCap$	installed solar capacity [MW]
	$windAvailable_t$	hour-t wind capacity factor
	$solarAvailable_t$	hour-t solar capacity factor
B. Variables		
$g_{t,i}$		hour-t production level of generator i [MW]
$\bar{Q} \geq 0$		storage power capacity [MW]
$\bar{S} \geq 0$		storage energy capacity [MWh]
q_t^c		MW charged into storage in hour t
q_t^d		MW discharged from storage in hour t
s_t		ending hour-t state of charge of storage device
$stoloadlevel_t \geq 0$		hour-t storage load level [MW]
$windProduction_t$		hour-t delivered wind capacity [MW]
$solarProduction_t$		hour-t delivered solar capacity [MW]

5.1. Introduction

The development and deployment of grid-scale energy storage systems have improved substantially due to technology improvements and policies such as California's energy storage mandate [1], [2]. These technologies can be utilized for different grid applications such as time-shifting the peak load to avoid investments in new generator capacity and the emissions associated with the peak generators [3]. Several studies have optimized the size and operation of an energy storage within a specific grid system to achieve the best economic and environmental. However, they have not systematically investigated how imposing an emissions tax would change these optimal results across technologies. As Denholm et al. discuss, analysis is required to estimate the impact of high renewable penetration on the value of energy storage [4]. In this study, we address these topics by comparing the operation of nine specific energy storage technologies to minimize the total system costs of California Independent System Operator (CAISO), under varying penetrations of solar and wind power generation, while assuming four CO_2 emissions tax levels on the system.

Extensive work has been done to highlight different characteristics of energy storage technologies and identify their potential grid applications. For example, Aneke and Wang, and Kyriakopoulos and Arabatzis provided a comprehensive review of the specifications and performance characteristics of several energy storage technologies and highlighted their potential grid applications [5], [6]. They showed how parameters such as round-trip efficiency and service-life would range substantially across technologies. For example, based on their reviews, the round-trip efficiency can vary between 50% (the lower bound for CAES) to 98% (the upper bound for lithium-ion battery). In a detailed review of battery choices, Dunn et al. specified varying characteristics across sodium-sulfur (NaS), lithium-ion (Li-ion), and redox-flow batteries [7]. They concluded that a successful future for these technologies depended on using low cost materials in order to decrease the installed costs of batteries while improving their performance and durability. Gallo et al. provided a comprehensive review of energy storage technologies, while arguing that no single energy storage excels in all technical parameters and therefore selection should be done on a case-by-case analysis [8]. Also, they highlighted the economic feasibility and a required regulatory environment as the two main barriers for the development of these technologies.

The integration of energy storage systems into the grid can have different environmental and economic impacts [9], [10]. These impacts depend on the grid performance requirements, location, and energy storage characteristics such as sizing and operation within the power grid. As discussed by Sardi et al., the cost of energy storage systems, particularly batteries, is the major obstacle to their adoption. In this regard, the current deployment of energy storage is generally uneconomical, as the overall energy storage installment cost is higher than the total benefits obtained from its deployment [11]. In another study, Abeygunawardana et al. discuss that at the current market prices of energy storage devices, in most cases, it is not quite cost-effective to utilize energy storage for distribution upgrade deferral application alone [12]. However, combining benefits for one or more complementary storage applications may provide the extra value needed to justify the use of storage for distribution deferral alone. In two separate studies, Hittinger and Azevedo show that energy storage is not fundamentally a green technology, the emissions effect of utilizing energy storage to penetrate more renewable energy varies by location [13], [14]. In an examination of energy arbitrage application in Texas, Carson and Novan showed that energy storage integration would increase the average daily greenhouse gas (GHG) emissions due to an increase in off-peak fossil fuel generation [15]. In another study, Hiremath et al. emphasized the significance of energy storage operation in the overall environmental performance of these technologies, especially when they had different characteristics parameters [16].

These examples demonstrate the need for optimizing the operation of an energy storage to achieve the desired economic and environmental outcomes. In this regards, many studies have optimized the operation and also size of an energy storage system for a given grid application from an economic point of view. For example, Ho et al. optimized the scheduling and capacity of an energy storage system to achieve minimum investment cost using integer linear programming in a distributed energy generation system [17]. Their results indicated that for renewable integration application, energy storage with high capital costs was advised to operate in daily cycles (vs. weekly cycles) due to their size limits. In another study, Parra et al. optimized the size of lead-acid (PbA) and Li-ion batteries for time-shifting application in a 100-home community in cases of time-of-use or real-time-pricing tariffs [18]. Their results showed that time-of-use tariff is much more attractive for demand-shifting in that community. Similarly, several other studies have proposed optimization model for the size and operation of energy storage systems to minimize total electricity cost or maximize the investor's profits [19], [20], [21], [22]. Their case studies range from a micro-grid to electricity markets such as Alberta or European grids, taking into account market uncertainties as well as operational and transmission constraints.

Several studies have also optimized the siting of energy storage technologies within a power grid. For example, Blanco et al. identified the optimal location of an energy storage system in western electricity coordinating council to achieve the minimum operating and investment costs [23]. Pandzic et al. proposed a near-optimal method to find the optimal siting of distributed storage systems, considering economic and technical aspects [24]. They concluded that the benefits of storage investments are correlated with the volatility Localized Marginal Prices in the systems. Dvorkin et al. determined the optimal size and location of an energy storage to minimize the total system operating and investment costs, indicating that these optimal choices were sensitive to the investors' profits constraints [25].

In addition to economic analyses, several studies have included environmental emissions accounting in their optimizations. For example, Hemmati et al. developed a multistage generation expansion plan for a test system to minimize the total costs including the emissions cost [26]. Their results showed that adding energy storage into the test system would decrease the planning costs as well as environmental pollution due to the reduced need for installing peak demand capacity. In another optimization, Fisher and Apt minimized the energy costs and maximized the revenue, taking into account the marginal emissions for behind the meter energy storage [27]. They found that the most negative environmental impacts of the system could be related to the internal energy losses in the storage system, rather than timing of charging and discharging. J. de Sisternes et al. modeled Texas electric grid to determine the optimal portfolio of generation capacities including energy storage operation to meet the demand in 2035 at the minimum cost, subject to system requirements, operational limits, and a mass-based CO_2 limit [28]. In their analysis, the capacity of two generic energy storage technologies was defined exogenously, therefore, they did not consider the capital cost of the energy storage system. In a linear programming mode, Arciniegas and Hittinger optimized the operation and location of an energy storage to maximize revenue and reduce CO_2 emissions across 22 eGrid locations [29]. Their results showed that adding CO_2 emissions in the objective function would result in a great reduction in the storage related emissions at a minimal expense to the owner.

This study contributes to the literature by developing an optimization model to evaluate the role of nine energy storage technologies with varying parameters in minimizing total system costs of CAISO, while accounting for the GHG emissions. These technologies are differentiated by their round-trip efficiency, service life, and capital costs. This novel approach investigates which storage technology is cost-effective to be integrated into the CAISO when the renewable energy generation and the emissions tax are increased exogenously. Wind and solar installed capacity are examined at installed capacities of 0 GW, 10 GW, and 20 GW of wind energy, and 0 GW, 20 GW, and 40 GW of solar energy. Emissions tax is examined at \$0/ton of CO_2, \$50/ton of CO_2, \$100/ton of CO_2, and \$200/ton of CO_2. In this optimization, natural gas generators' output, the amount of solar and wind energy delivered to demand (after curtailment), energy storage sizing, and energy storage operation are optimized to minimize the total system costs. Total costs include the natural gas operating fuel costs, energy storage capital costs, and GHG emissions cost as a tax imposed on the system. Simulations are run for each technology to investigate how the optimal results would change across technologies. In this linear program model, in case of zero deployment of energy storage, the breakeven capital costs (energy or power related components) are calculated to estimate the cost reductions needed for economic deployment. We also analyze wind and solar curtailment to offer new understanding on the ability to achieve high penetrations of renewables using specific energy storage technology.

5.1.1. Case study: Energy Time-shifting in CAISO

Throughout this case study, we examine the application of energy storage for bulk energy time-shifting in CAISO. Due to the rapid increase in renewable energy and also the state's recent actions towards advancing energy storage [1], [30], California has become an interesting case study to analyze the impact of energy storage integration. In this regard, Solomon et al. evaluated the opportunities for the higher utilization of renewable energy in California in scenarios with and without energy storage integration [31]. In another two comprehensive studies by National Renewable Energy Laboratory (NREL), value of energy storage was estimated in California with high penetration of renewable energy [32], [33]. This study is novel, however, because we compare the operation and size of nine specific energy storage technologies to minimize the total system costs of CAISO, under varying penetrations of renewable penetration.

For the electric energy time-shifting, we examine nine energy storage technologies that offer the most suitable characteristics for this application: adiabatic compressed air energy storage (ADCAES), diabatic compressed air energy storage (DCAES), pumped-hydro energy storage (PHES), lead-acid battery (PbA), Li-ion battery, NaS battery, vanadium redox flow battery (VRFB), polysulfide bromide battery (PSB), and zinc–bromine battery (ZBB) [3], [34]. Table 5-2 summarizes the potential energy storage technologies and their assumed characteristics. For the purpose of this study and in order to create the ideal case for the energy storage systems, the maximum round-trip efficiency, the maximum service life, and the minimum capital costs possible for each technology are assumed. The assumptions are provided through a comprehensive literature review of storage systems parameters [3], [5], [6], [7], [8], [19], [34], [35], [36], [37], [38], [39].

Table 5-2 Selected energy storage systems and their parameters assumptions

	High round-trip efficiency (%)	High service life (year)	Low capital cost ($/MW)	Low capital cost ($/MWh)
pumped-hydro storage (PHES) [5], [6], [8], [34], [35], [37]	85	60	441,000	5,000
adiabatic compressed-air energy storage (ACAES) [5], [6], [8], [34]	95	60	700,000	40,000
diabatic compressed-air energy storage (DCAES) [5], [6], [8], [34]	60	60	400,000	2,000
lead-acid (PbA) battery [6], [7], [8], [34], [35]	90	15	222,000	200,000
vanadium redox flow battery (VRFB) [6], [8], [34], [35]	95	15	398,000	150,000
Li-ion battery [6], [34], [39]	98	20	400,000	600,000
sodium-sulfur batteries (NaS) [5], [6], [8], [34], [35], [39]	90	15	350,000	350,000
polysulfide bromide battery (PSB) [8], [35]	85	15	330,000	120,000
zinc–bromine battery (ZBB) [5], [8], [35]	75	10	178,000	150,000

5.2. Methodology

5.2.1. Energy System Assumptions

This chapter examines the operation of specific energy storage systems, when utilized for bulk energy time-shifting in CAISO across one year. Specific parameters of natural gas generator in CAISO including hourly load (MW), operating time (hour), fuel consumptions (MMBtu), CO_2 emissions rate (t), and rated capacity (MW) are obtained from EPA Clean Air Markets Program Data and U.S. Energy Information Administration (EIA) forms 886 and 923 [40], [41], [42]. Based on these data reports, marginal costs and marginal emissions are calculated for each natural gas generator. In addition, hourly nuclear, imports, hydro, biomass, biogas generation, imports, and load data for the year 2012 are collected from CAISO online resources [43]. In this model, we assume the minimum dispatchable load level ($minload$) to be 12,600 MW [44]. Wind and solar generations is changed exogenously based on pre-defined hourly generation profiles and assumed total installed capacities of 0, 100 GW, and 20 GW for wind energy, and 0, 20 GW, and 40 GW for solar energy [45], [46]. The wind generation is based on NREL WIND Toolkit, which includes meteorological conditions and turbine power for more than 126,000 sites in the U.S. for the years 2007–2013 [45]. At the time of this study, the most recent available data in NREL WIND Toolkit was for 2012, therefore the studied year in this study is assumed to be 2012. All wind sites production data across the state of California is collected from the toolkit. For each hour, we summed up the total wind production across all the wind sites and calculated the wind capacity factor ($windAvailable(t)$) as follows:

$$windAvailable(t) = \frac{total\ wind\ production\ in\ hour\ t}{sum\ of max\ capacity\ of each\ site} \qquad (Eq. 1)$$

This ratio gives the average state-wide capacity factor for the given hour.

To estimate the state-wide solar capacity factor, we used available NREL meta data. This data set included 5636 points (with specific latitude and longitude), assuming an annual solar generation profile of a fixed tilt mount type with maximum power capacity of 4 MW per location [46]. The hourly state-wide solar capacity factor ($solarAvailable(t)$) is calculated as follows:

$$solarAvailable(t) = \frac{total\ solar\ \ production\ in\ hour\ t}{4 * 5636} \qquad (Eq. 2)$$

5.2.2. Optimization

In this optimization, hourly natural gas generator production level ($g_{t,i}$), storage power and energy capacities ($\bar{S}, \bar{Q}$), hourly operation of energy storage (q_t^c, q_t^d, s_t), and the hourly delivered wind and solar energy ($windProduction_t$, $solarProduction_t$) are optimized to minimize the total system costs (Eq. 3). Total costs include the natural gas marginal costs, monetized GHG emissions cost, and annualized energy storage capital costs. We model 237 natural gas generators of CAISO (I=237), and assume that their marginal costs ($C_{t,i}$) in \$/MWh, marginal emissions ($e_{t,i}$) in ton of CO_2/MWh, and rated capacity ($K_{t,i}$) in MW stay constant across the entire hours of the year (T=8760 hours). As mentioned earlier, we assume four values of emissions tax (β) in \$/ton of CO_2 to monetize the natural gas marginal emissions. Each energy storage capital cost has two components: costs driven by storage capacity (\$/MWh) and costs driven by rated power (\$/MW). The capital charge rate (R) is estimated using Eq. 3 for each storage technology to annualize its capital costs, assuming 10% discount rate (DR):

$$R = \frac{DR}{1 - (1 + DR)^{\ n}} \qquad (Eq. 3)$$

For the specific case of DCAES, additional natural gas use in the storage system and its associated fuel and emissions cost are added to the objective function. In this case, we make the following assumptions: heat rate of natural gas (NG_{use}) is 4.2 MMBtu/MWh, natural gas emissions rate (NG_{em}) is 0.058 ton of CO_2/MMBtu, and finally natural gas fuel price (NG_{price}) is \$3.68/MMBtu (equal to the price of the fuel in 2012) [47], [48], [49]. In case of other storage technologies, $NG_{use} = NG_{em} = 0$.

Eq. 4 shows the objective function, which is to minimize the total system costs, estimated as follows:

$$\min \quad R*(C^Q\bar{Q}+C^S\bar{S})+\sum_{t\in T} NG_{use}*(NG_{em}*\beta+NG_{price})*q_t^d$$
$$+\sum_{t\in T}\sum_{i\in I}(c_{t,i}+e_{t,i}*\beta)*g_{t,i} \qquad (Eq.4)$$

In this optimization, the constraints are load balance, dispatchable minimum load, natural gas generator maximum capacity, energy storage state of charge (s_t), energy storage state of charge limit ($\bar{S}$), energy storage charging (q_t^c) and discharging (q_t^d) limits, energy storage load level, and wind and solar production limits. These constraints are shown in Equations 5 to 15 respectively:

$$\text{s.t.} \sum_{i\in I} g_{t,i}+q_t^d$$
$$= L_t - nuclear_t - import_t - geothermal_t - biomass_t - biogas_t - hydro_t$$
$$+ q_t^c; \qquad \forall t \in T; \quad (Eq.5)$$

$$\sum_{i\in I} g_{t,i} + nuclear_t + geothermal_t + biomass_t + biogas_t + hydro_t + stoloadlevel_t$$
$$\geq minload; \quad \forall t\in T; \quad (Eq.6)$$

$$\text{s.t} \quad 0 \leq g_{t,i} \leq K_{t,i}; \qquad \forall t \in T, i \in I; \qquad (Eq.7)$$

$$s_t = (if\ t \geq 2 \quad s_{t-1} \ \ else\ 0) + \eta^c q_t^c - q_t^d; \qquad \forall t \in T; \qquad (Eq.8)$$

$$0 \leq s_t \leq \bar{S}; \qquad \forall t \in T; \qquad (Eq.9)$$

$$0 \leq q_t^c \leq \bar{Q}; \qquad \forall t \in T; \qquad (Eq.10)$$

$$0 \leq q_t^d \leq \bar{Q}; \qquad \forall t \in T; \qquad (Eq.11)$$

$$0 \leq stoloadlevel_t \leq (if\ t \geq 2 \quad s_{t-1} \ \ else\ 0); \qquad \forall t \in T; \qquad (Eq.12)$$

$$0 \leq stoloadlevel_t \leq \bar{Q}; \qquad \forall t \in T; \qquad (Eq.13)$$

$$0 \leq windProduction_t \leq windAvailable_t * windcap; \qquad \forall t$$
$$\in T; \qquad (Eq.14)$$

$$0 \leq solarProduction_t \leq solarAvailable_t * solarcap; \qquad \forall t \in T; \qquad (Eq. 15)$$

In this analysis, we only assume the efficiency losses during the charging of energy storage system. Therefore, discharging efficiency of storage technology is assumed to be one across technologies, and the charging efficiency (η^c) is assumed to be equal to the round-trip efficiency of each technology (shown in Table 5-2), as is done in another study by Sioshansi et al. [50].

5.2.3 Scenarios

In this model, installed wind and solar capacities are increased exogenously from 0 to 10 and 20 GW of wind energy, and 0 to 20 and 40 GW of solar energy. It is also assumed that the imposed emission tax on the system could be 0, \$50/ton of CO_2, \$100/ton of CO_2, or \$200/ton of CO_2. Fig. 5-1 shows the matrix of thirty-six scenarios developed by these assumptions:

Solar cap (GW)	emissions tax= 0 Wind cap (GW)		
	0, 0	0, 10	0, 20
	20, 0	20, 10	20, 20
	40, 0	40, 10	40, 20

Solar cap (GW)	emissions tax= \$50/ton Wind cap (GW)		
	0, 0	0, 10	0, 20
	20, 0	20, 10	20, 20
	40, 0	40, 10	40, 20

Solar cap (GW)	emissions tax= \$100/ton Wind cap (GW)		
	0, 0	0, 10	0, 20
	20, 0	20, 10	20, 20
	40, 0	40, 10	40, 20

Solar cap (GW)	emissions tax= \$200/ton Wind cap (GW)		
	0, 0	0, 10	0, 20
	20, 0	20, 10	20, 20
	40, 0	40, 10	40, 20

Fig. 5-1 Scenarios for the optimization model

Thirty-six simulations are run for each technology including ADCAES, DCAES, PHES, PbA, Li-ion, NaS, VRFB, PSB, and ZBB to investigate how the optimal results would change across technologies, carbon tax levels, and renewable penetration.

5.3 Results

Fig. 5-2 shows the relative size of the selected technologies that are deployed in different combinations of installed wind and solar capacity, assuming 0, \$50/ton of CO_2, \$100/ton of CO_2, and \$200/ton of CO_2 emissions tax. As shown in this figure, increasing the wind and solar capacities as well as the emissions tax make the deployment of energy storage more cost-effective. Among technologies, PHES technology with \$441/kW and \$5/kWh capital costs is deployed in almost all combinations, and its optimal size in relatively larger compared to other technologies. On the other hand, an expensive technology such as Li-ion battery (with highest round-trip efficiency compared to other technologies) is deployed only in scenarios with high level of installed wind and solar capacities and high emissions tax of $200/ton of CO_2. In scenarios with no wind and solar capacity, the integration of none of the storage technologies is cost-effective for this application even when an ambitious emissions tax of $200/ton of CO_2 is imposed. The latest update of renewable energy progress report by California Energy Commission indicates that as of October 2017, the share of wind capacity in California was 5.6 GW and the share of solar capacity was 16.2 GW [51]. Given these renewable penetration levels, the results of this optimization model (in case of 20 GW of solar and 10 GW of wind penetrations) show that there needs to be an emission tax of $50/ton of CO_2 imposed on the system to make the deployment of energy storage cost-effective for this application.

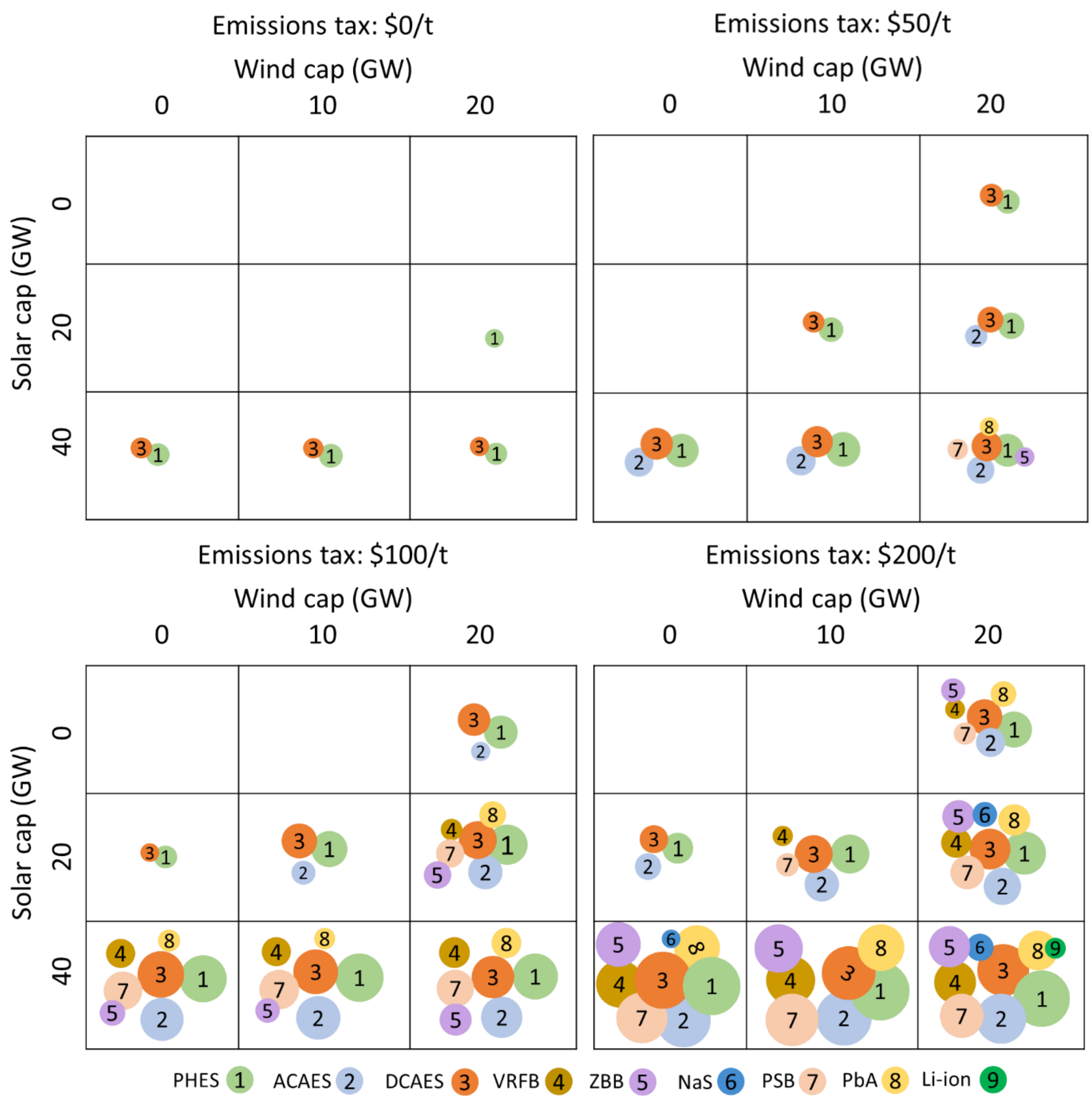

Fig. 5-2 Optimal size (in MW) of nine energy storage technologies in different combinations of installed wind and solar capacity in CAISO, assuming 0, \$50/ton, \$100/ton, and \$200/ton of CO_2 emissions taxes

The optimal operation of each storage technology, net load (load minus variable wind and solar) in MW, and marginal clearing price (MCP) in \$/MWh (computed as the dual variable of the constraint load balance in Eq.5) are displayed in Fig. 5-3. The results are for the first day of March. It is assumed that the total wind and solar capacity equals 20 GW each, and the emissions tax is \$100/ton of CO_2. The peak of energy storage charging occurs during the day hours with the minimum net load, making the valley smaller. These results show that storage technologies with lower energy capital cost ($/kWh) such as PHES and CAES are charged for a longer period of time due to their larger capacity which allows for more charging capability of these technologies. However, expensive battery technologies such as PbA tends to charge during shorter periods.

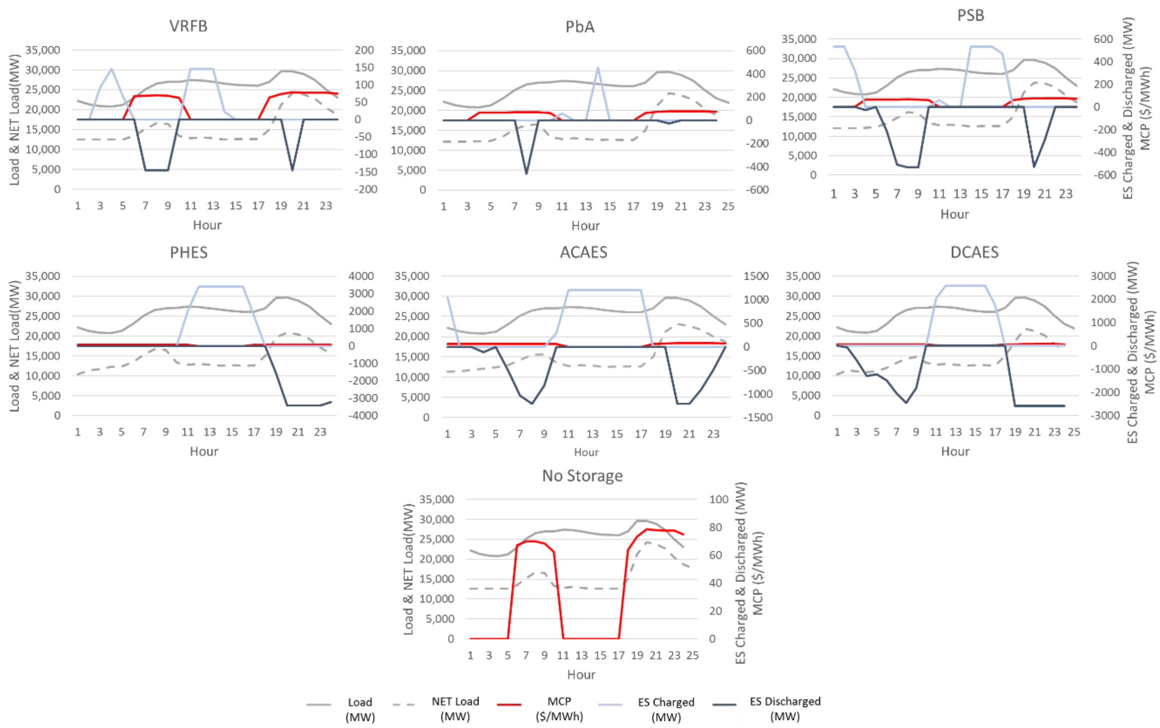

Fig. 5-3 Optimal operation of six storage technologies on March 1st in CAISO, assuming 20 GW of wind capacity, 20 GW of solar capacity, and $100/ton of CO_2 emissions tax. MCP ($/MWh), ES charged ($\boldsymbol{q_t^c}$ in MW), and ES discharged ($\boldsymbol{q_t^d}$ in MW) are shown in the secondary vertical axis. (NaS, Li-ion, and ZBB are not deployed under this level of renewables penetration)

Next, renewable (wind and solar) curtailment between the scenarios without and with energy storage is analyzed and the results are presented in Fig. 5-4. This figure is consistent with previous results as increasing the emissions tax leads to less curtailment through making the energy storage deployment more cost-effective. After integrating energy storage within the system, curtailment decreases much more substantially in case of cheaper technologies such as PHES and CAES.

Fig. 5-4 Renewable (wind and solar) curtailment before and after deploying specific technologies in CAISO, assuming 0, \$50/ton of CO_2, \$100/ton of CO_2, and \$200/ton of CO_2 emissions tax ("W" stands for wind, "S" stands for solar, and the numbers on top of bars show the emissions tax level)

Fig. 5-5 shows the hourly, daily, seasonal, and annual curtailment patterns in a scenario that PHES technology is deployed in CAISO. Two renewable penetration levels of middle (10 GW of wind, 20 GW of solar) and maximum (20 GW of wind, 40 GW of solar) are shown in this figure along with assuming minimum and maximum emissions tax levels of 0 and \$200/ton of CO_2. The curtailment rate is much higher in the spring season, when the electricity demand is lower. The minimum curtailment is during the fall season. Increasing the emissions tax to its maximum value reduces the daily, hourly, seasonal, and annual curtailment significantly (which is also consistent with Fig. 5-4).

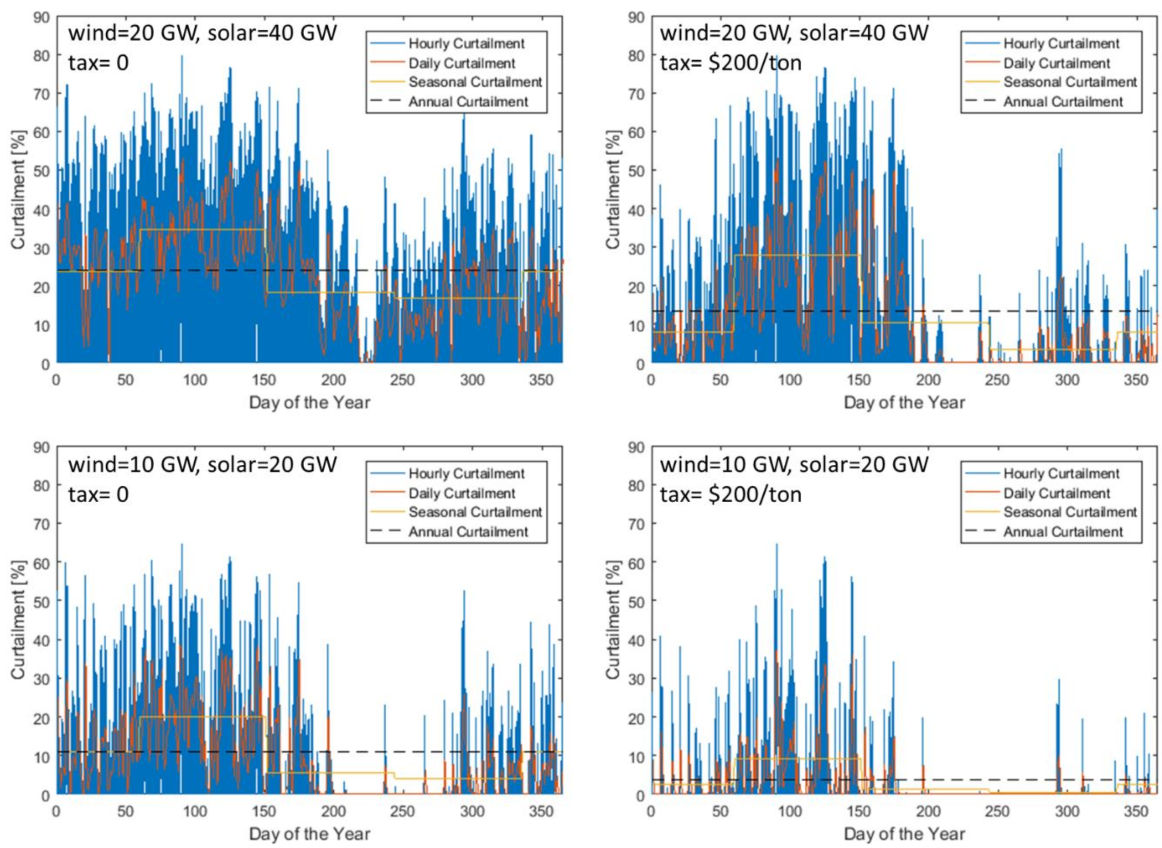

Fig. 5-5 Renewable (wind and solar) curtailment in case of PHES deployment with middle and maximum renewable penetration level, assuming 0 and \$200/ton of CO_2 emissions tax

Fig. 5-6 shows the reduced cost of Li-ion battery (\$/kWh), assuming 20 GW of solar penetration and 10 GW of wind penetration, across four emissions tax levels. For example, in order to deploy cost-effective Li-ion battery in the case of zero emissions tax, its energy related capital cost needs to be reduced around \$70/kWh from its \$600/kWh value. With increasing the emissions tax level, this breakeven cost is decreased.

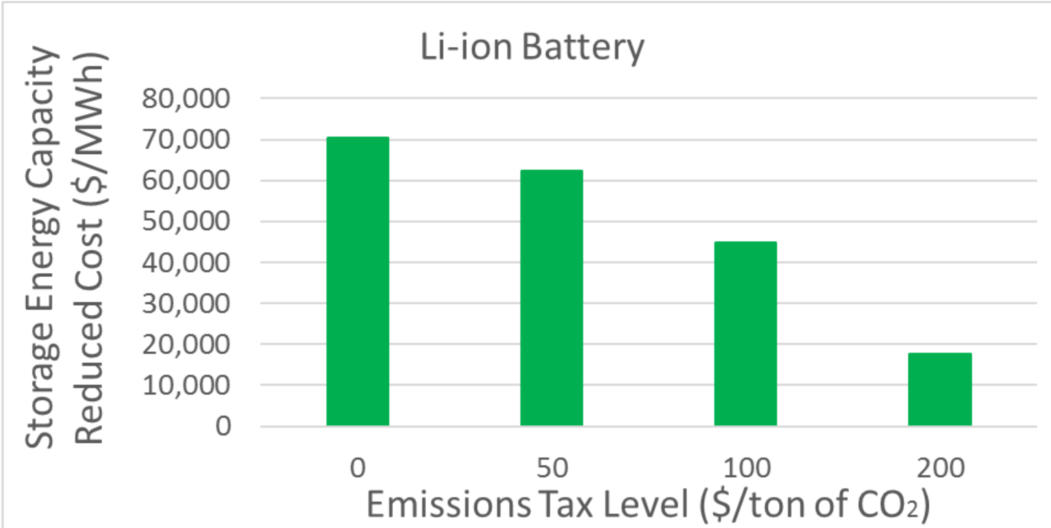

Fig. 5-6 Li-ion energy capacity reduced cost, assuming 20 GW of solar penetration and 10 GW of wind penetration

5.4 Discussion

We present an optimization model to investigate the role of cost-effective energy storage in bulk energy time-shifting in California grid. For this application, we examine nine specific energy storage technologies including PHES, two types of CAES, and six battery systems. Our results determine the optimal size and operation of each technology to achieve the minimum systems cost, while accounting for GHG emissions, under high renewable penetrations with different CO_2 tax levels. As results show, the capital cost of energy storage systems is the main obstacle to the wide deployment of such technologies. Even in the case of a high emissions tax, and high wind and solar capacities, the deployment of an expensive but efficient technology such as Li-ion is limited. This technology specific study can guide different stakeholders such as energy storage operators and electric utilities about their technology choices. As mentioned, the results of this study demonstrate that increasing the emissions tax makes the integration of energy storage more cost-effective. In another study, Yong and Macdonald showed that an emissions tax regime set by the government and the willingness to commit to it, has a positive influence on the size and the direction of firm level investment in clean technologies [52]. Therefore, adding an emissions tax to the already established energy storage mandate of California could have beneficial economic and policy implications [1].

There are some limitations in this study that can be examined in future research. One of these limitations is that we only investigate GHG emissions; however, there are other environmental impacts that need to be considered. For example, while our results show the promising application of PHES due to its low costs, there are some concerns regarding other environmental impacts (beyond GHG emissions) of such technology. These impacts could include causing changes in landscape, increasing the risk for spreading or causing mortality of species, and impacts on biological production, among others [53]. In addition to these controversial environmental impacts, PHES is location dependent and requires sites with specific topological and/or geological characteristics [6], [54]. The deployment of CAES is also limited due to the lack of suitable spacious locations or underground formations [6], [55]. Further examination of these limitations gives a more comprehensive understanding of deployment potential of PHES and CAES.

The optimization model developed in this study could also be expanded to other grid examples, which have higher share of fossil fuel generation in contrast with CAISO, which we assume has no coal generation. We have assumed no degradation of energy storage throughout its operation. While Arbabzadeh et al. has shown that annual degradation in round-trip efficiency and capacity of energy storage do not have significant impact on environmental impact of integrating energy storage for time-shifting application [34], a future study can examine the impact of degradation in capacity and round-trip efficiency on the cost-effective operation of energy storage in the specific case of CAISO.

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CHAPTER 6
Conclusions

Energy storage systems represent a rapidly evolving technology that can address grid challenges such as integrating variable renewable energy into the grid or balancing the difference between the electricity demand and supply [1]. While energy storage can help reduce the consumption of fossil fuels, reduce the greenhouse gas emissions (GHG), and therefore increase the grid sustainability, its adoption poses unique sustainability challenges that need to be studied through systematic sustainability assessment. The main focus of this dissertation is to develop robust sustainability frameworks to assess the environmental and economic impacts of utilizing grid-scale energy storage systems.

The first study of this dissertation was an initial case study of energy storage for wind integration in an off-grid configuration. The insights from this case study and additional literature review led to the development of principles for green energy storage in the second study. An in-depth analysis of key parameters of energy storage and the electric grid, which were highlighted in principles, was conducted in the third study. And finally, an optimization model of energy storage operation was developed and applied in a case study of the California grid. Throughout these studies, it is demonstrated that environmental and economic impacts of energy storage development and deployment depend heavily on the technology characteristics, the grid application performance requirements, and the electric grid profile.

6.1. A case study of energy storage integration within an off-grid configuration (Chapter 2)

One of the promising applications of energy storage is to increase the penetration of variable renewable energy such as wind or solar energy into the grid. A substantial body of research has studied the application of energy storage for renewable integration within both an electric grid or an isolated micro-grid [2]- [12]. However, these studies have not examined the economic and environmental trade-offs between renewable curtailment and energy storage utilization and they do not address emissions target, which is an important decision-making criterion. Also, among energy storage technologies, vanadium redox flow battery (VRFB) offers high energy density and efficiency [13]. However, there is not a comprehensive life cycle GHG emissions assessment of VRFB development and deployment.

The second chapter of this dissertation addressed these gaps by examining the trade-offs between environmental and economic impacts when utilizing VRFB to integrate wind energy and exploring the role of energy storage in achieving very low emissions targets. This study contributes to the literature by assessing the total life cycle GHG emissions and total cost of the system's components including VRFB. Generation mixes are optimized to meet emissions targets at the minimum cost and to determine at which target the value of energy storage outweighs the cost of wind curtailment, i.e. when energy storage is preferable over additional wind capacity. The results demonstrate that while adding VRFB reduces GHG emissions, its integration is economical to reach only very low emissions targets.

6.2. Principles for green energy storage in grid applications (Chapter 3)

Twelve principles of green chemistry and twelve principles of green engineering have made significant contributions in addressing valuable strategies for the green design of chemical materials and engineering products [14], [15]. While these and other studies [16]- [19] have successfully provided guidance and structure for green design, energy storage technologies pose unique environmental challenges that are not fully addressed by those approaches. Due to this gap, those who design, maintain, and operate energy storage systems lack a systematic set of principles that can lead to improved environmental outcomes.

Inspired by and building off the twelve engineering principles, a novel set of principles were developed in this chapter to fill the research gap and guides integration, operation and maintenance, and design of energy storage systems. Indeed, the development and operation of energy storage systems may lead to either positive or negative environmental impact. This robust set of principles shows how material and design choices in addition to operation and integration strategies influence environmental outcomes from developing and deploying of energy storage systems. By providing insights into and improve the environmental outcomes when integrating energy storage systems, these principles for green energy storage guide various designers, decision makers, and utility operators on design choices and deployment scenarios.

6.3. Key parameters for driving environmental performance of grid-scale energy storage (Chapter 4)

We demonstrated that the integration of energy storage systems leads to different and sometimes unfavorable environmental outcomes. These outcomes depend on the energy storage parameters and the characteristics of the electric grid. While other studies have examined the environmental impacts of energy storage integration [20]- [27], these existing assessments have not systematically evaluated the influence of various parameters on environmental performance of energy storage technologies. This chapter contributes to the literature by illustrating how the environmental outcomes of integrating energy storage could change across the full range of six parameters. This novel parametric analysis was applied to time-shifting, frequency regulation, and power reliability applications due to their distinct characteristics. This framework can be used as a guideline to determine, systematically, when and how to choose storage systems to achieve positive environmental outcomes. Key findings of this study show that among selected parameters, energy storage round-trip efficiency and charging and displaced generator heat rates dominate in time-shifting and regulation applications, whereas energy storage service life and production burden dominate in power reliability.

6.4. Optimization model for deployment of energy storage within CAISO (Chapter 5)

An extensive body of research has optimized the size and operation of an energy storage to reach the minimum costs within an electric system [28]- [31]. However, there still remains a gap in the literature in examining different energy storage technologies with varying capital costs to investigate which technology is built within specific system constraints to reach the minimum total costs. This chapter contributes to the literature by developing an optimization model for utilizing selected energy storage technologies to time-shift the peak load of CAISO, while accounting for GHG emissions accounting. This model determines the optimal state of charge, optimal size of each energy storage, optimal amount of wind and solar delivered to demand, and the optimal natural gas generators output in order to minimize the system total costs (including GHG emissions costs), while meeting the electric grid system constraints. This study is novel because it investigates how the optimal results would change across technologies and it develops scenarios with different combinations of emissions tax and total installed capacity of the renewable energy (i.e. wind and solar). It is determined which storage technology is built in each scenario. The findings show that increasing the installed capacity of wind and solar energy would make it more economic for the energy storage to be built and among nine technologies determined, PHES and D-CAES are the ones that are built in most scenarios.

6.5. Recommendations for Future Research

While different environmental impacts such as toxicity, scarcity, and criticality are examined qualitatively in the twelve principles chapter, the main focus of the studies conducted in this dissertation was on the GHG emissions indicator as it is widely used to assess the sustainability of the grid. However, future research can examine other sustainability impacts associated with the production and deployment of grid-scale energy storage technologies in more details. For example, James et al. used a water consumption indicator along with CO_2 and NO_x emissions to evaluate the sustainability of combined cooling, heating, and power systems [32]. They argue that energy-water nexus is one of the critical issues in provisions of urban utilities. It takes water to create energy and energy to treat and distribute water and traditional energy generation systems usually have higher water footprints [32]. Therefore, a future examination of water use can determine how integrating energy storage into the power grid can change water consumption rates. In the U.S. as a whole, anthropogenic SO_2 emissions come mainly from power plants and other coal combustion facilities [33]. Sulfate aerosols from SO_2 account for 50%-60% of the ground level particulate matter ($PM_{2.5}$) [33]. Comparing electricity produced from shale gas and coal, Chun et al. showed that human toxicity impacts (dominated by particulate matter) of coal are lower [34]. Therefore, future research can investigate local air pollutant and human toxicity impacts when integrating energy storage into the grid particularly when coal is being substituted with cleaner generation.

There has been increased attention toward the end-of-life strategies for energy storage systems such as batteries. These end-of-life approaches include reusing, reassembling, and recycling energy storage systems [35]. Careful analysis of environmental outcomes and economic impacts is necessary to select the best end-of-life approach which represents another area for future research. One of the promising re-use applications is the second use of vehicle batteries in stationary applications. A future study can examine the optimal service life of energy storage systems along with a comprehensive comparison between the environmental impacts associated with the use of a degraded old battery and the environmental burdens associated with the production and deployment of a new battery.

In future studies, the robustness of twelve principles developed in Chapter 3 can be examined further by applying them to additional models of grid applications and by considering new operation and maintenance conditions. For example, Principle #6 is about designing and operating energy storage for optimal service-life in order to guide replacement strategies and reduce environmental burdens. However, given growing technology improvements and efficient maintenance, only selected components of an energy storage system might need to be replaced after the system reaches its service-life. This would alter the environmental outcomes, compared to a case, in which the entire energy storage system is replaced. Therefore, it becomes important to identify which components are being replaced in order to estimate the optimal service-life and the total life cycle environmental impacts.

List of principles can be extended to include the principles for mobile applications of energy storage in addition to the stationary applications. There has been a tremendous growth in the application of batteries in electric vehicles [36]. However, there are important concerns regarding mobile applications of energy storage systems that need to be addressed when expanding the principles. For example, weight of the energy storage technology is a key design parameter that influences the fuel economy and has to be studied carefully [36].

Chapter 5 optimization model can be tested with other grid examples that have different grid characteristics from CAISO. CAISO represents a clean grid profile with natural gas as the main fossil fuel generation resource. Therefore, another grid example which has a higher share of coal generation is expected to change the results substantially. The reason is that the difference in marginal emissions and marginal costs between off-peak and peak generators would be larger, making the integration of energy storage more attractive. The optimization model can also be tested with future cost trends for energy storage technologies in order to analyze how the optimal results would change with potentially lower energy storage capital costs. Lower costs are expected to make deployment of energy storage economic under lower emissions tax.

Investigating how the models and results of this dissertation can be used to guide the development of effective policy and decision strategies, may be a potential future policy analysis. For example, as shown in Chapter 5, increasing the emissions tax makes the integration of energy storage more cost-effective. In another study, Yong and Macdonald showed that an emissions tax regime set by the government and the willingness to commit to it, has a positive influence on the size and the direction of firm level investment in clean technologies [37]. A future policy analysis can investigate the economic implications of various emissions tax policies combined with the already established energy storage mandate of California, which requires 1.3. GW of energy storage by 2020 [38].

Principles for green energy storage as well as sustainability assessment frameworks including parametric analysis and optimization models are developed in this dissertation. The goal is to systematically guide the environmental and economic performance of grid-scale energy storage systems. This research provides the robust foundation for the future research on energy storage systems.

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