Title

Environmental Benefit-Detriment Thresholds for Flow Battery Energy Storage Systems

Author

Tian, Shan

Publication Date

2020

UNIVERSITY OF CALIFORNIA,
IRVINE

Environmental Benefit-Detriment Thresholds for Flow Battery Energy Storage Systems

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

Shan Tian

Thesis Committee:
Professor G. Scott Samuelsen, Chair
Professor Julie M. Schoenung
Assistant Professor Iryna V. Zenyuk

2020

DEDICATION

To people who helped me in my life

致
伟大的母亲

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

NOMENCLATURE

AB	Assembly Bill
ADP	Abiotic resource Depletion Potential
AP	Acidification Potential
BESS	Battery Energy Storage Systems
BOP	Balance of Plant
CAES	Compressed Air Energy Storage
CED	Cumulative Energy Demand
CF	Characterization Factors
DOD	Depth of Discharge
E3	Energy Environmental Economics
EPA	Environmental Protection Agency
EROEI	Energy Returned on Energy Invested
ESS	Energy Storage Systems
FE	Freshwater Eutrophication
FU	Functional Unit
GER	Global Energy Requirement
GHGs	Greenhouse Gases
GWP	Global Warming Potential
HiGRID	Holistic Grid Resource Integration and Deployment
HT	Human Toxicity
HTP	Human Toxicity Potential
IFB	All-Iron Flow Batteries

IOUs	Investor-Owned Utilities
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Li-ion	Lithium-ion
LU	Land use
MAEC	Maximum Allowable Energy Capacity
MBEC	Maximum Benefit Energy Capacity
ME	Marine Eutrophication
MW	Megawatt
NaS	Sodium-Sulphur
NRE	Non-Renewable Energy Requirement
NREL	National Renewable Energy Laboratory
PHS	Pumped Hydro Storage
PM	Particulate Matter
POF	Photochemical Ozone Formation
PV	Photovoltaic
RE	Renewable Energy Requirement
RFB	Redox Flow Battery
SB	100 Senate Bill100
SES	Stationary Energy Storage
TE	Terrestrial Eutrophication
VRFB	Vanadium Redox Flow Batteries
V2O5	Vanadium Pentoxide

V2G	Vehicle-to-Grid
WECC	Western Electricity Coordinating Council
WRD	Water Resource Depletion
ZBFB	Zn-Br Flow Batteries

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor: Professor Samuelsen for giving me the opportunity of conducting the research. This thesis would not have been possible without his support and efforts. His generous help in the personal and professional aspects shaped me in the past two years.

I also would like to thank my committee member Professor Julie Schoenung. I was lucky to have her precious advice along with the period of time when the work was conducted. Thank you to Professor Iryna Zenyuk, for your support and encouragement.

I would like to thank Dr. Brian Tarroja for his mentoring along with this work and research. He is the one who led me into the fun research world. He has eyes to find out sparkling stars in the research universe. Thank you to Dr. Kate Forrest and Sarah Wang, you gave me enormous help in my way of learning HiGRID.

I would like to thank Haoyang He, who is an incredible partner to work with, without your excellent work, this thesis would not have good results.

All the lab mates in APEP provided a wonderful environment to study and do research. Thank you.

My Family and friends, you are always my emotional support and my source of happiness.

ABSTRACT OF THE THESIS

Environmental Benefit-Detriment Thresholds for Flow Battery Energy Storage Systems

By

Shan Tian

Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2020

Professor G. Scott Samuelsen, Chair

While energy storage systems (ESS) are required to integrate and manage renewable resources on the electric grid, ESS can result in life cycle environmental impacts associated with (1) the production of the system, (2) the use of the system, and (3) the end-of-life of the system. As more energy storage capacity is deployed, the grid benefits and associated life cycle environmental impacts may not scale the same. For example, thresholds of energy and power capacity may exist beyond which additional energy storage results in a negative environmental impact. To explore this question, this study addressed the use-phase environmental impacts of three flow-battery energy storage systems. Dynamic electric grid modeling tools were used to establish the use-phase environmental benefits and impacts on Global Warming Potential (GWP), Particulate Matter (PM) emissions, Acidification Potential (AP), and Fossil Fuel Cumulative Energy Demand (CED) as the aggregate ESS power and energy capacity installed on the electric grid is increased. For an electric grid with a high percentage of renewable resources, the results reveal that (1) the use-phase impact can be as, or more significant than, the production - phase depending on the grid composition, (2) the combined power and energy capacities for flow battery systems where the net environmental benefits are a maximum, and

(3) that power and energy capacities must be limited to certain thresholds in order to ensure that flow-battery storage provides net environmental benefits.

Chapter 1: INTRODUCTION

1.1 Energy Storage Need

As the primary energy resource in the world, fossil fuels are responsible for environmental consequences such as climate change and air pollution. As a result, alternative clean energy options are being sought to ease those environmental issues. Renewable energy is a promising alternative due to low environmental impacts and the provision of a sustainable supply. California, a leader in this clean energy campaign, has been a pioneer in facilitating the integration of renewable power generation into the electric grid.

California, for example, has mandated greenhouse gases (GHGs) emissions to be reduced to 40 percent below 1990 levels by 2030 [1]. Moreover, Senate Bill 100 (SB100) requires retailed electricity to be 100% from eligible renewable energy resources and zero-carbon resources by 2045 [2]. The dominant renewable energy resources entering the market are wind and solar, each of which introduce a new dynamic to the grid. Both vary diurnally in power output, and both are subject to intermittency due to the variability in wind as a function of time, and varying cloud cover that can diminish solar output. Furthermore, electricity from solar and wind is not dispatchable and is a “must-take” resource. The introduction of diurnally varying and intermittent renewable energy from wind and solar requires the traditional base load of power to be more dynamic with high-ramping rates. An example is the “duck curve” shown in Figure 1-1. The net load (vertically axis) is the difference between the demand and electricity supply demanded from the traditional base load generators. The “belly” of the duck occurs in the mid-afternoon corresponding to the maximum output from the solar resources. After mid-afternoon, the increase in the net load of the grid must be served by rapidly ramping dispatchable resources, thereby creating the neck of a duck. Fast ramping requires a rapid spooling up of power plants with spinning reserves and start-up of peaker power plants, both of which result in a higher emission rate of greenhouse gas and criteria pollutants [3].

In order to address these issues, energy storage systems (ESS) are emerging. ESS can store electrical energy when the generation from renewable resources exceeds the load, and release energy when the load demand is high and renewable energy is not available. By doing so, ESS can shift load and help release the ramping tension on traditional power plants. In addition to load shifting, storage can also provide other energy management attributes including renewable self-consumption, backup power, and voltage and frequency regulation. Today and in the future, ESS is an essential component to enhance the reliability and resilience of the grid.

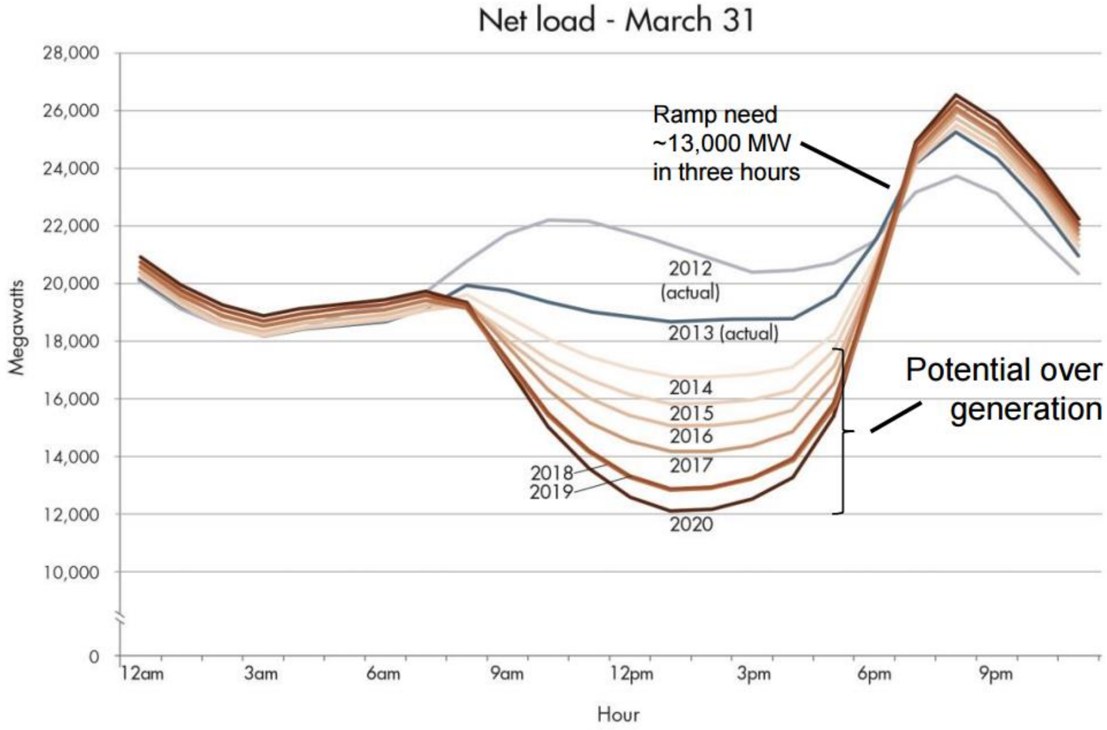


Figure 1-1 "Duck Curve" in California from CAISO [4]

1.2 Battery Energy Storage

To evaluate energy storage technologies that are required to support and manage renewable energy, a brief introduction of energy storage technologies is presented. Depending on discharge time, the function of energy storage technologies include 1) power quality support, 2) transmission and distribution grid support/ load shifting, and 3) bulk power management. Load shifting and bulk power management are especially important for electric grids with a high penetration with surplus renewable generation. From Figure 1-2, pumped hydro storage (PHS) and compressed air energy storage (CAES) are considered as bulk power management because their discharge time spans from hours to days. However, pumped hydro and compressed air energy storage require a high capital cost and construction times of ten years or more. In addition, the potential of the two technologies depend land amenable to reservoirs and caves, the use of both of which may have a substantial impact on the local environment. Pumped hydro storage is also vulnerable to drought.

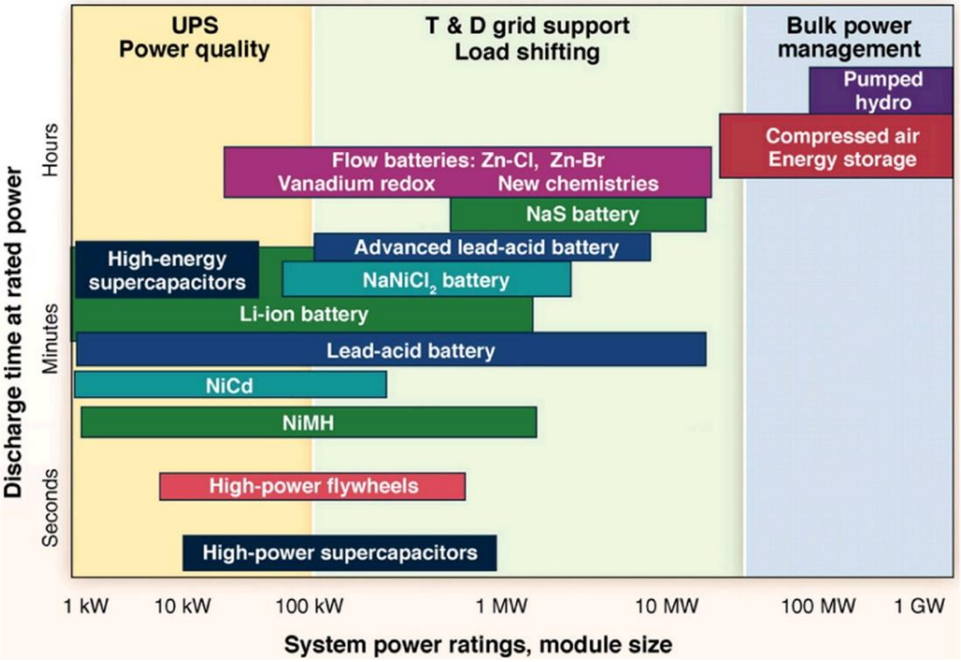


Figure 1-2 Different Roles of Energy Storage [5]

In the U.S., most of the PHS systems were installed in the 1970s (Figure 1-3). Even though PHS has a larger power capacity than battery storage today, the increase in battery storage is decreasing this gap and, due to the limitations of the bulk power management technologies, battery storage is expected to play a significant role in meeting the demand for large scale energy storage systems.

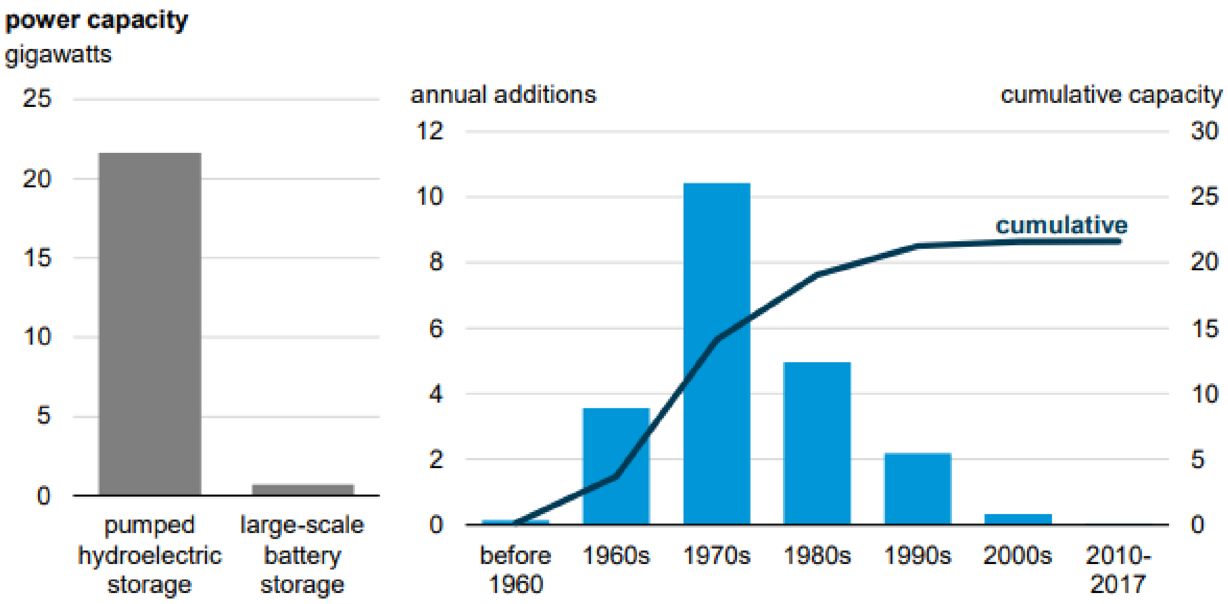


Figure 1-3 U.S. Hydroelectric Pumped Storage Capacity (1960-2017) [6]

Usually, the energy-to-power ratio is constrained for the design of the battery. Batteries tend to have discharge times from seconds to minutes which make them suitable for power quality control applications, like frequency regulation. Figure 1-4 below shows the range of power and energy capacity of various energy storage technologies. For large scale energy storage, the redox flow battery (RFB), lithium-ion battery (Li-ion) and sodium-sulphur (NaS) battery, CAES, PHS, and hydrogen storage have the capability to discharge more than hours. Among all the battery energy storage technologies, NaS batteries and RFBs and Li-ion have the capability of hour long storage with high power output.

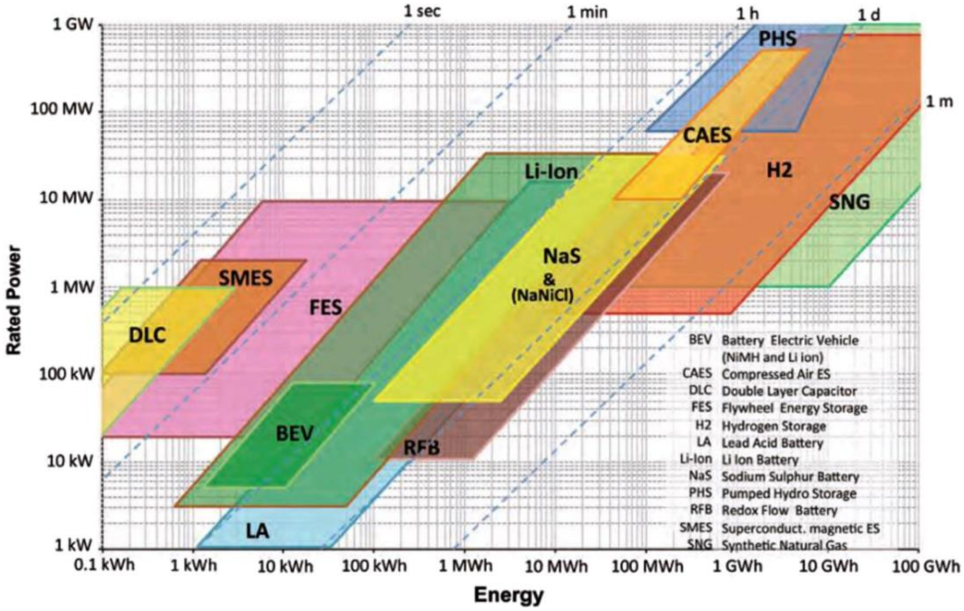


Figure 1-4 Power and Energy Characteristic of Energy Storage System [7]

Li-ion batteries are commercialized and widely used in mobile devices and electric vehicles. In recent years, Li-ion technology has been applied into utility-scale applications, which are related to ancillary services in grid scale. Li-ion batteries have high energy density and high efficiency which make them suitable for ancillary services such as frequency regulation and short-term (30-minutes or less) spinning reserve applications [8]. Two characteristics, however, limit the role of Li-ion batteries in meeting all the requirements needed to complement solar and wind generation. First, the self-discharge and degradation of Li-ion batteries can shorten lifetime and limit the extent to which Li-ion batteries can support long-duration storage. Second, the aggregated power and energy capacity of unit Li-ion batteries is not sufficient to absorb the large amounts of otherwise curtailed wind and solar. For these reasons, other technologies must be considered. RFB technology is an attractive candidate for this purpose.

RFBs have different characteristics compared to lithium-ion batteries. In RFBs, the electrolyte is stored externally in tanks, which enables the battery to decouple the power and energy capacity.

The energy capacity of RFBs can be easily scaled with the increasing volume of the tank. Increasing the electrolyte flow rate of the pump can raise the power capacity. The other benefit of RFBs is the lower degradation rate compared to other batteries. RFBs can operate at 100% depth of discharge (DOD) [8]. The downside of RFB is the low energy density due to the weight of the electrolyte tanks. These characteristics of RFBs make them suitable for applications like load leveling, seasonal storage, transmission congestion relief, and peak-shaving [8].

However, Li-ion batteries have an installation cost advantage compared to flow batteries [9]. For example, the installation cost of Li-ion batteries has decreased by 73% from 2010 to 2016 for mobile applications and, in 2017, Li-ion batteries occupied 59% among all the electrochemical storage technologies (Figure 1-5).

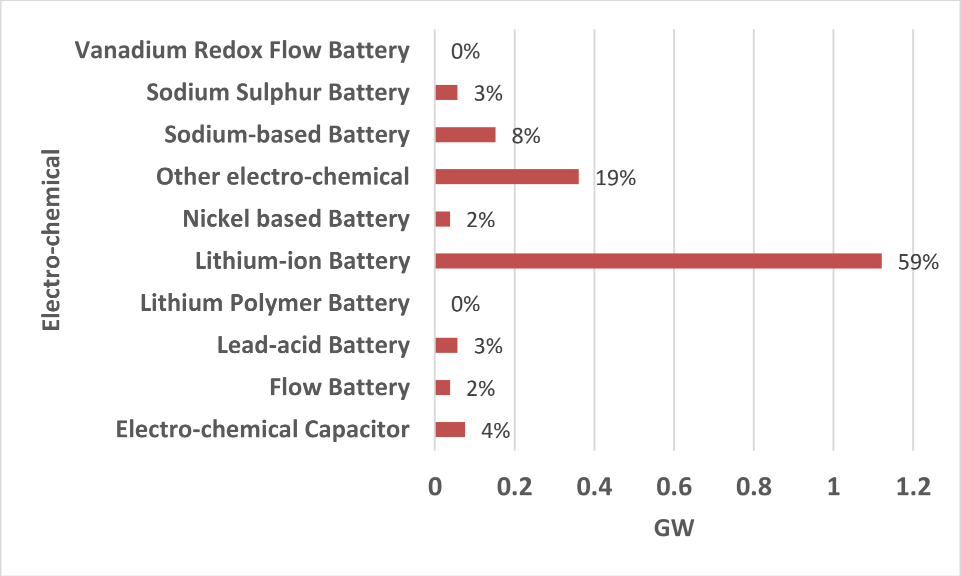


Figure 1-5 Lithium-ion Battery Occupies 59% Market among All Electrochemical Technologies in Mid-2017 [9]

While flow batteries are in their early stage of commercialization, the market is growing fast. The announced contracted and under construction storage capacity of flow batteries is 23,280 kW, which is more than a third of lithium-ion battery total power capacity [9].

The capital cost of an energy storage system comprises the energy storage equipment, power conversion equipment, power control system, the balance of plant, and installation cost. The primary cost difference between the two battery types is the energy storage equipment cost. For Li-ion batteries, DC systems include internal wiring, temperature, and voltage control systems. For RFBs, the DC system is composed by electrolyte storage tanks, stacks with membrane and containers, along with cycling pumps and battery management controls [8]. Li-ion shows a lower capital cost per kWh in general. However, from a life cycle cost point, when applied to the same kind of application, Li-ion shows much higher prices (655 $/kW-yr), compared to flow batteries like vanadium redox flow batteries (VRFB) (362 $kW-yr) and Zn-Br flow batteries (229 $/kW-yr) [1][10].

It is expected that the cost will decrease by 54-61% for Li-ion batteries by 2030 [9]. The cost of flow battery technologies is expected to drop as large as 66%, which will make per kWh installation cost of RFBs comparable to Li-ion batteries (Figure 1-6). All these features show a positive future for the commercialization of flow batteries.

---

[1] The EUR to USD currency of 1.329165 (2014) is used [70].

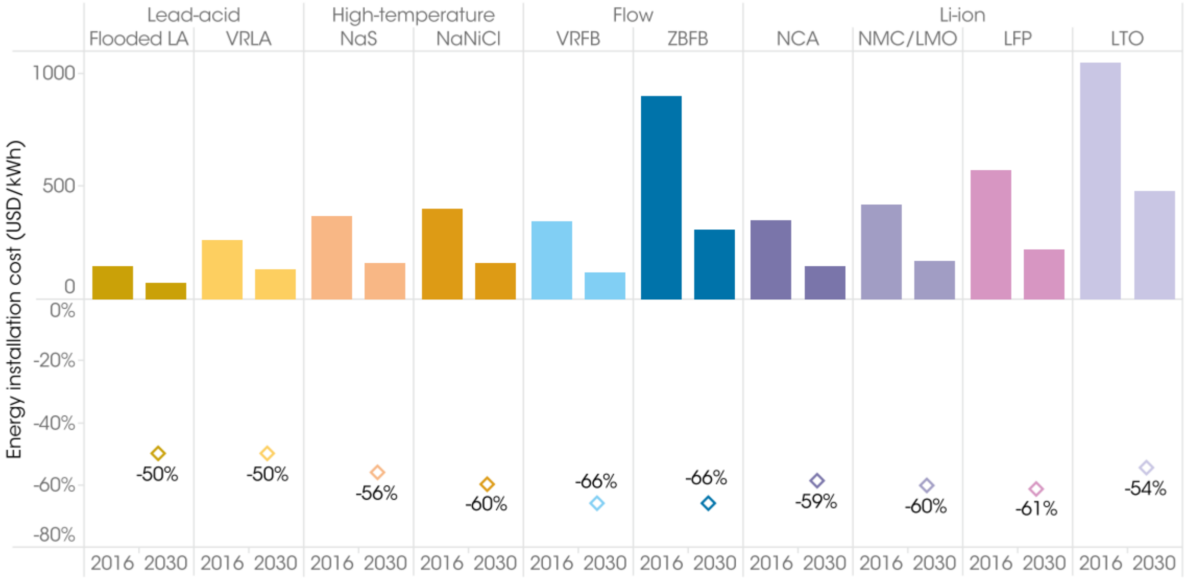


Figure 1-6 Energy Cost Reduction Potential from 2016-2030 for Different Technologies [9].

Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromide flow battery; NCA = nickel cobalt aluminum; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

1.3 Redox Flow Batteries

This section presents an introduction of RFBs, a type of electrochemical device that converts the electricity to chemical energy and vice versa. As shown in Figure 1-7, a redox flow battery system yields oxidation and reduction between two active materials [11]. It consists of two external tanks, two electrodes, a membrane, and a flow circulation system. It is different from usual batteries in that its power capacity and energy capacity are decoupled by having external electrolyte tanks to store soluble electrolytes. While the electrolyte dictates the energy capacity, the electrodes and cells are responsible for the power capacity. For this reason, redox flow batteries have the potential to scale energy capacity easily and serve both grid energy storage systems and distributed energy storage systems. Also, flow batteries have a high depth of charge/discharge and high cycle life.

Even though the RFB technology is not as mature compared to Li-ion batteries, it is considered to result in a lower environmental impact when applied for electric grid operation [12].

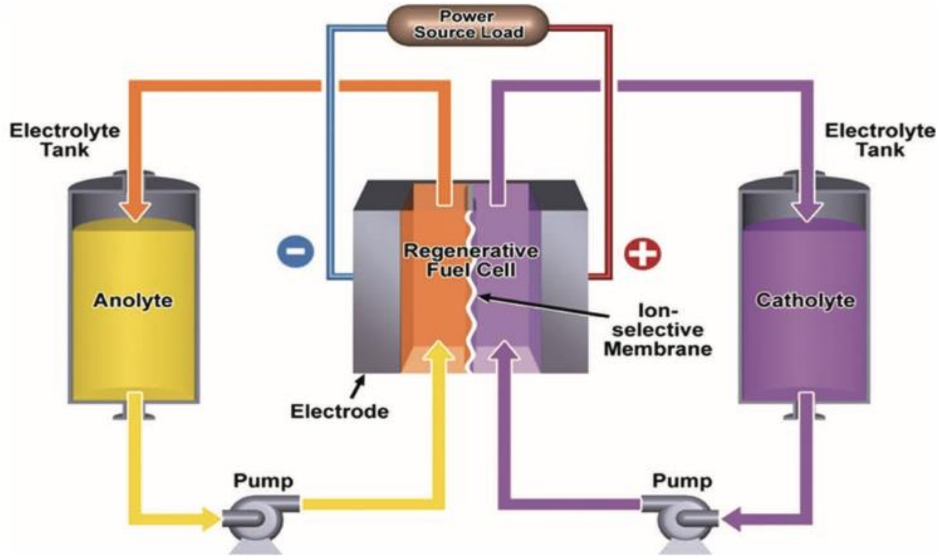


Figure 1-7 Flow Battery Structure [11]

1.4 Size Determination

While energy storage, coupled with the renewable power generation, has the potential to achieve a zero-emission grid, the production, construction and maintenance of renewable and storage resources may have significant impacts on the environment. Environmental issues related to battery production and recycling have been brought to public attention with regard to metals like lithium, zinc, and lead that are used in batteries. In addition, batteries have a limited lifetime, which will increase the demand on raw material usage [13]. As a result, the production and use of the battery can have significant environmental impact even though battery energy storage systems are intended to mitigate emissions by complementing renewable power generation resources. To this end, studies have shown that bulk energy storage is increasing the United States electricity system carbon emissions [14].

Can energy storage bring environmental benefits? If batteries do bring overall benefits, will there be thresholds for the scale of batteries deployed in the grid? These questions should be answered before policy and decision makers incentivize the deployment of energy storage systems. This study addresses some aspects of these questions.

1.5 Life Cycle Assessment

With the increasing attention on societal and environment sustainability, a number of environment impact assessment methodologies have emerged to project the impacts of specific products, such as carbon footprint, energy returned on energy invested (EROEI), and life cycle cost (LCC). The carbon footprint focuses on the direct or indirect greenhouse emissions related to all procedures in the product's life cycle. EROEI is the ratio of the amount of usable energy delivered from an energy source divided by the amount of energy used to obtain that energy source. Compared to carbon footprint analysis and EROEI which only focus on one indicator, life cycle assessment (LCA) considers interactions between supply chains of products and the environment over the overall life cycle.

LCA is a set of procedures for establishing the economic, energy, and environmental impacts in the three phases in the life of a product: (1) materials extraction and manufacturing, (2) use, and (3) disposal/recycle/repurpose [15].

The life cycle is a consecutive and interlinked stages of a product from material extraction of natural resources to the end-of-life [15]. Typical life stages are showing as Figure 1-8. Life cycle inventory (LCI) is the dataset inventory of procedures involved in the life cycle of a product. It contains all flows in and out the product system including energy use, raw material use, emissions and waste in the life cycle. It is a data collect section of the LCA.

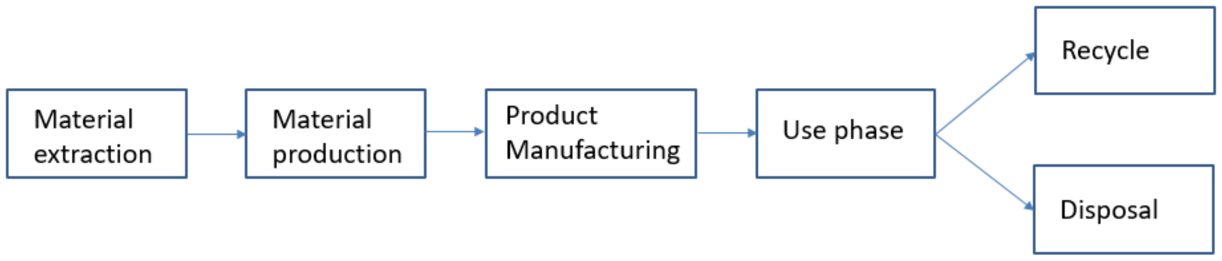


Figure 1-8 Life Cycle of Products

LCA can be used to:

- Support the product design,
- Compare products having similar functions,
- Interpret the environmental impact of products or services,
- Frame the policy and legislation for policymakers.

This study uses LCA to explore the environmental impacts of battery storage and the potential grid benefit associated with the deployment of energy storage.

1.6 Holistic Grid Resource Integration and Deployment (HiGRID) Tool

To evaluate the deployment of energy storage into the electric grid, a simulation tool is required. In this study, the Holistic Grid Resource Integration and Deployment (HiGRID) tool is adopted to assess the potential benefit as well as the battery performance. Developed at the University of California, Irvine Advanced Power and Energy Program, HiGRID is a multi-module platform that simulates the dispatch of grid resources to meet the electric load demand in California and, in parallel, establishes the emissions and impact of integrating advanced energy technologies on the California electric grid [16]. As a special attribute, HiGRID allows the simulation of the charging profile of BESS with different levels of renewable energy integration. As a result, HiGRID can capture the impact of battery deployment on shifting loads and the associated grid emissions.

1.7 Goals and Objectives

The goals of this research are to:

1. Characterize the use-phase environmental impacts of different flow battery systems in the context of the electric grid, and evaluate the significance of the flow battery use-phase impacts in the overall life cycle stages.

2. Determine the flow battery power and energy capacity thresholds from an environmental perspective using California as an example.

To meet these goals, the following objectives were followed:

1. Integrate the flow battery module coupled with different energy storage systems into the Holistic Grid Resource Integration and Deployment (HiGRID) model.

2. Use HiGRID to determine GHG emission factors used in batteries' environmental impact analysis.

3. Develop and integrate the flow battery use-phase inventory with an established production phase inventory that emanated from a collaborative LCA research initiative to reveal the significance of use-phase impacts.

4. Evaluate trade-offs of deploying flow batteries. Identify the existence of Maximum Allowable Energy Capacity (MAEC) and Maximum Benefit Energy Capacity (MBEC).

5. Determine the Maximum Allowable Energy Capacity (MAEC) and Maximum Benefit Energy Capacity (MBEC) for VRFB deployment in California.

Chapter 2: BACKGROUND

2.1 Trends in Stationary Battery Markets

Battery Energy Storage System (BESS) are promising technologies for integrating more renewables. The growth of the BESS market is accelerating. From the Annual Energy Outlook with projections to 2050 [17], the large-scale battery storage capacity is predicted to grow to 40 GW from 2020 to 2050 (Figure 2-1).

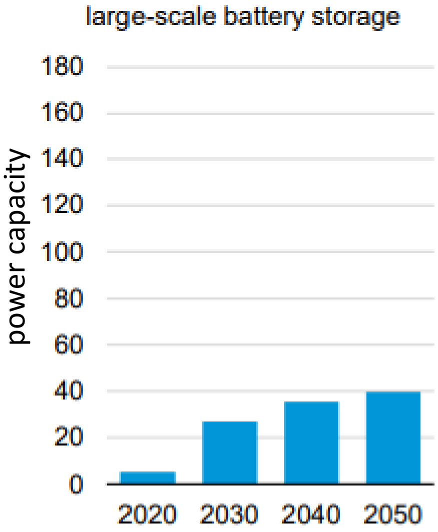


Figure 2-1 U.S Large-Scale Battery Storage Capacity Projections [6]

Studies have been conducted various battery storage markets. For example, the report: Electricity storage and renewable: costs and markets to 2030 from International Renewable Energy Agency (IRENA) [9] predicts that, renewable capacity will double between 2017 and 2030, and the storage capacity of the stationary battery will increase by a factor of 17 compared to the estimated level of 2017. The total capacity has the potential to reach between 100 GWh and 421

GWh worldwide depending on assumptions, and the majority of BESS will be providing electricity time-shift services for increasing self-consumption or peak shaving in 2030.

California is a pioneer in encouraging deployment of BESS. California established a 1,325 MW energy storage procurement mandate by 2020 for the state's three investor-owned utilities (IOUs) – Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric - under Assembly Bill (AB) 2514 [18]. Additionally, a new target in 2050 calls for 500 MW of behind-the-meter storage with the passage of AB 2868 [19].

2.2 Development of Redox Flow Battery

Among all stationary battery energy storage technologies, NaS batteries and lead-acid batteries comprise the majority of energy storage devices deployed to date. While the redox flow battery is an emerging application technology, its characteristics still need to be investigated in order to achieve better performance. Since the principles of flow batteries were first publicized in the 1970s in Japan, many other countries have investigated flow battery energy storage systems. The flow batteries of interest in this thesis are vanadium redox-flow batteries (VRFB), zinc bromide flow batteries (ZBFB), and all-iron flow batteries (IFB), each at a different level of commercialization.

2.2.1 Vanadium Redox Flow Battery

The Vanadium redox flow battery is an all liquid phase battery, which means all reactive materials are liquid phase. By using the same elements in both sides of the cell, the occurrence of membrane crossover is avoided. The relatively fast kinetics of the vanadium redox chemistry allow for high charge rate. The VRFB was invented at the University of New South Wales in

1986, and was the first flow battery to reach commercial completion [3]. The system temperature is 10 - 40℃. The efficiency can reach as high as 90% with a 1kW VRFB stack. Based on current technology, VRFBs have the highest potential for large-scale commercial applications among the three battery systems due to their system scale (megawatt (MW) capacity). Sumitomo Farm in Japan reported an overall round - trip energy efficiency of approximately 80% and cycle life of over 270,000 cycles for a wind energy storage program. VRFBs are scaled up to a MW capacity already. Dalian Institute of Chemical Physics and Rongke Power Co., Ltd in China reported a VRFB system of 5 MW/10 MWh in a 50 MW wind farm. It exhibited more than 3.5 years of stability and reliability in the VRFB system [4]. UET (UniEnergy Technologies), a company in the U.S., reported that a 100 kW/400 kWh VRFB system had been deployed as a part of a national research project [5].

2.2.2 Zinc Bromide Flow Battery

The zinc bromide flow battery (ZBFB) is a type of hybrid redox flow battery. A hybrid flow battery means one or more electro-active components is a solid layer [20]. The zinc metal is in charge of energy capacity during the charge stage. As such, the energy and power capacities of the ZBFB are not fully decoupled. The ZBFB can deliver 100% depth of discharge with running temperature around 50 ℃ without active cooling. The first commercial project of ZBFB for energy storage was a 50 kW photovoltaic (PV) system with a 50 kW/100 kWh battery system in New York [21]. Zinc bromide hybrid flow batteries have been used in Australia to support remote lines. These batteries were also installed in parallel with a photovoltaic concentrator system. Redflow, a company in Australia, can provide 600 kWh energy with no storage capacity loss over ten years [22]. In the U.S., the Primus Power Company supported the ZBFBs as powertrains combined with a solar inverter as an advanced microgrid system [6].

2.2.3 All-iron Flow Battery

All-iron flow battery uses iron as an electrolyte. It is a hybrid redox flow battery since the negative electrode is involved in reactions [23]. It is reported that the round-trip efficiency of IFBs can reach as high as 97% [7]. Also, the power density of IFBs has been demonstrated as five times higher than comparable battery technologies. ESS, a U.S. company, has announced to supply a 60 kW/225 kWh IFB system as a part of an integrated microgrid at Fort Leonard Wood in Missouri [8]. They offer IFBs that have a lifespan of more than 20 years. The low costs of less than $20/kWh is another benefit of the system.

2.3 Life Cycle Assessment of Batteries

2.3.1 LCA and LCI of Stationary Batteries

With the rapid development of electric vehicles and mobile devices, an increasing amount of LCA studies have been conducted around portable batteries like lithium-ion batteries. Notter *et al.* [24] laid a foundation of Li-ion batteries LCA for electric vehicles, the results from which show the importance of the use-phase of the mobility batteries. Majeau-Bettez *et al.* [25] studied batteries with three different kinds of chemicals used in the vehicles, which enriched the inventory of Li-ion batteries. Zackrisson *et al.* [26] compared two different solvents during cell manufacturing for lithium-iron-phosphate battery from LCA standpoint. These three papers provide Li-ion LCIs which are widely used among other literature. Moreover, the U.S. Environmental Protection Agency (EPA) [27] published a study that assessed the impact of recycling and a next-generation technology – carbon nanomaterials for Li-ion batteries. It also presented the environmental and human health impacts of the life cycle of Li-ion batteries. The study identifies three potential directions to improve the impacts of Li-ion batteries: substitute cathode material, process electrode without solvent, and recycle metals from the batteries.

Unlike Li-ion batteries, redox flow batteries have very different fields of application. The low energy - density (kWh/kg) of flow batteries make them unsuitable for mobile devices. On the other hand, RFBs are appropriate for stationary applications like grid support and load shifting. Life cycle analyses of redox flow batteries are relatively sparse and for certain types of flow battery chemistries, non-existent. Prior studies on flow batteries for energy storage have relied primarily on VRFBs [12], [28], [29], [30]. Flow batteries have shown good environmental performance in terms of per MWh or per kWh energy storage, and the calculated environmental impact of vanadium batteries has been shown to be lower than that of the lead-acid batteries [28]. Characteristics of vanadium batteries such as net energy storage efficiency and long cycle-life were also shown to be higher than lead-acid batteries. The long lifetime and excellent recyclability make vanadium batteries a viable option for stationary energy storage, outscoring LTO type Li-ion battery (lithium-iron-phosphate) among all categories considering the benefit of recycling. Even without recycling, VRFBs still show lower environmental impact in global warming potential (GWP), human toxicity potential (HTP), and abiotic resource depletion potential (ADP) except for acidification potential (AP) [29]. VRFB technology has a lower proportion of production impact in the life cycle cumulative energy demand (CED) and GWP impacts compared to other technologies like NaS [12]. Only a limited number of life-cycle stages of different kinds of redox flow batteries are reported [28]. Even though more studies are addressing environmental issues of RFBs, the manufacturing data of different RFBs are still sparse and need to be enriched, especially since the rapid evolution of the technology updates the database every year.

This thesis is built on the LCI of three types of flow batteries presented in He [31]. The inventories developed by [31] are formed by data provided by manufacturers. The impacts from production processes are calculated in this study from the LCI cited in He [31].

2.3.2 The Significance of Use-phase Impacts

The literature has emphasized the importance of the use-phase impact of battery systems in the overall life cycle impacts [12],[32]-[33], and have established that use-phase impacts depend on the electric grid composition [34], [35], [36]. The grid composition influences whether stationary batteries can reduce [37] or increase [38] grid environmental impacts. However, under both conditions, use-phase impacts are found to dominate the overall life cycle climate change impacts. For other impact categories, use-phase impacts can be less important. Longo *et al.* [12] found that the use phase contributed to the largest energy impact, but the production phase contributed to the largest environmental impact. Much of the current literature on use-phase battery impacts are directed to lithium-ion batteries [38], [37] or the comparison of a suite of different energy storage technologies [12], [34]. Oliveira *et al.* [34] performed comparative life cycle analyses of compressed air, lead-acid, lithium-ion, sodium-sulfur, hydrogen, pumped hydropower, and sodium-nickel-chloride energy storage systems for use in electric grid applications. The body of literature concerned with the use-phase importance of flow battery technologies is relatively small.

The system boundaries of a stationary battery, especially for the use-phase, is different from that of mobile devices. So far, the literature does not have a consistent functional unit (FU)[2] for stationary batteries. Some studies define the electricity used to charge the battery as the FU [12], [36]. Other studies considered the charged electricity wasted because of the round-trip efficiency of the battery, with the functional unit being the electricity delivered by the battery [29], [34]. Table 2-1 shows the summary of the boundaries in the literature. Note that electro-storage technologies in literature are a mix of all possible techniques for stationary grid applications (not only for RFBs).

In this thesis, the principal use-phase impact is the waste of electricity due to the battery inefficiency. The impact of waste electricity depends on the electricity input of the battery, which is traced to the electricity production. As a result, the use-phase inventory is an inventory of different electricity generators. Many LCA studies of stationary batteries select datasets of existing power grids or extreme/ simplified grid compositions of only solar or wind technology like what is shown in Table 2-2.

---

[2] The functional unit is defined as the service that is delivered by the product of interest. It is a basis for comparing product on equal terms [71],

Table 2-1 Functional Units and System Boundaries from Literature

Reference	Battery Application	System Boundaries	Functional Unit	Environmental Indicator
Schmidt *et al.* (2019) [36]	• Wholesale arbitrage • Area and frequency regulation • T&D upgrade deferral • Demand peak shaving • Increase of self-consumption	Manufacturing; Transportation from manufacturing to application; Electricity loss	Storing one kWh of electricity in the battery	Life cycle emission (greenhouse gas GHG)
Denholm *et al.* (2004) [39]		Generation of electricity; Storage plant operations; Facility construction;		GHG
Longo *et al.* (2014) [32]	• Renewable energy storage	Raw material, Manufacturing; Assembly operation; End of life;		GER*; NRE; RE; GWP; ODP; HT; POF; AP; TE; FE; ME; LU; WRD
Hiremath *et al.* (2015) [12]	• Complete-life utilization • Utility Time-shift • T&D deferral • Voltage Regulation • Frequency Regulation • Self-consumption • Energy Management	Raw material extraction and process; Product manufacturing; Use-phase;	One megawatt-hour of electricity delivery for 20 years	CED; GWP
L. Oliveira (2015) [34]		Construction; Disposal/end of life Usage;	One kWh of energy delivered back to the grid, from the storage system	Climate change; HT; PM, Fossil resource depletion; HT; Ecotoxicity;
S.Weber *et al.* (2018) [29]	• Renewable support	Battery production; Use-phase; End of life;	The provision of 1 MWh of electricity by the battery over the 20 year lifetime of a hypothetical renewables support application.	GWP, HTP, AP, ADP

*Global energy requirement (GER); Non-renewable energy requirement (NRE); Renewable energy requirement (RE); GWP; Ozone depletion potential (ODP); Human toxicity (HT); Photochemical ozone formation (POF); Terrestrial eutrophication (TE); Freshwater eutrophication (FE); Marine eutrophication (ME); Land use (LU); Water resource depletion (WRD).

Table 2-2 Datasets Usage from Literature

Reference	Electricity usage	Region	Datasets
Schmidt *et al.* (2019) [36]	• Existing electricity market • Wholesale	Poland, Germany, Switzerland	Ecoinvent: the market for electricity, medium voltage
Denholm *et al.* (2004) [39]	• Nuclear/Renewable • Natural gas CCGT • Coal		Economic Input/ Output database.
L'Abbate *et al.* (2019) [30]	• Italian power mix	Italy	Ecoinvent v 2.1
Hiremath *et al.* (2015) [12]	• German national electricity mix at the distribution grid level • Solar PV plants • 50% solar – 50% wind used in Europe	Germany	Ecoinvent 3.01
Longo *et al.* (2014) [32]	• Multi-Si photovoltaic system • Electricity from wind turbines in Europe • Electricity from hydropower in Italy • Italian electricity mix • European electricity mix	Europe, Italy	Ecoinvent: including the manufacturing of solar panel.
H. Elzein *et al.* (2019) [40]	• Norman grid	Normandy, France	Nuclear; coal; natural gas; hydro; wind; solar; Biomass electricity from Ecoinvent 3.2 (dynamic)
L. Oliveira *et al.* (2015) [41]	• Belgium electricity mix • UCTE • 100% Photovoltaic • 100% of wind energy mixes	Belgium	Belgium electricity mix UCTE (Ecoinvent 2.2)
S.Weber *et al.* (2018) [29]	• Wind turbines • PV installations • German grid mix	Germany	Wind, 1-3 MW turbine, onshore, DE (PV, 570 kWp, open ground, DE)

The research to date has not accounted for the dynamics of electric grid composition. To predict how the deployment of large scale of stationary battery systems will affect future grid emissions, a flexible electricity inventory with high renewable penetration is required. Most studies to date use a simplified load profile for the battery, which is the cycles per day and days per year without considering the dynamic of the load profile. Elzein *et al.* [40], for example, used an optimization method to assess the environmental impact of Li-ion use-phase based on a LCI developed for France. For the U.S., no literature is reported for either the real-time use-phase stationary battery or the LCA of the power system (Table 2).

As a result, a new LCI, based on the California grid mix, is required in order to examine the impact of battery installment in California.

2.3.3 LCA of the electricity grid

The literature regarding the life cycle inventory of electricity generation separates into two groups--emissions of each technology, and the installed capacity—and some studies focused on deciding the emission of each technology. Turconi *et al.* [42] conducted a LCA review of different electricity generators from the construction, maintenance (operation), and the end of life period. Mulongo *et al.* [43] analyzed the LCA of the whole electricity system in different regions. The methodology of deciding the emission of the FU used the emission factor times the electricity portion of the technology, then the emission is normalized to per kWh. Studies used the FU of 1 kWh electricity consumed with consideration for the electricity mix of the energy system. 1 kWh electricity datasets from different electricity resources were used to build the life cycle inventories [44]-[45]. Other studies used the installed capacity of each generation resources like wind, solar, biomass to meet a low carbon electricity system goal [46], [47]. Usually, the studies focus on the steady profile of the mix of grid resources, and a fixed capacity factor for renewable resources.

2.4 Size Determination

Sizing for BESS is application specific, depending on the type of grid system deployed. Multiple factors can influence the size of energy storage including the depth of discharge/ battery lifetime/ life cycles and the efficiency.

Numerous studies to determine battery size have been conducted, focusing mainly on the technical indicators and financial indicators. A review by Yang *et al.* [48] summarized technical and economic criteria, as well as different approaches that have been used to decide the battery size. Most of the studies are based on microgrids with installed renewable generation. For a large scale of the electricity grid, battery size varies from different grid mix and regions.

Studies have also investigated the required energy storage capacity needed for reaching particular environmental goals by considering the electricity supply and demand balance. Mahone *et al.* [49] investigated different energy technology scenarios for meeting California's goal of reducing emissions of greenhouse gases across all economic sectors to 80% below the year 1990 levels by 2050. Across the vast array of pathways which comply with the goal, energy storage systems consisting of 17 to 32 GW of 8-hr batteries (132 to 256 GWh) were required based on a technic-economic approach. Tarroja *et al.* [50] investigated the energy storage capacity needed to reach a 100% renewable energy penetration in California from a materials perspective, finding that even with other complementary technologies (such as dispatchable renewables and dispatchable loads), aggregated energy storage capacity of up to 0.6% of annual renewable energy production (2736 GWh) was required. Mileva *et al.* [51] investigated energy technology portfolios needed to reach an 80% greenhouse gas reduction from the electricity sector across the entire Western U.S. The study shows that the energy storage capacities needed are between 40 to 260 GW of 6-hr energy storage systems (240 to 1608 GWh). The National Renewable Energy Laboratory (NREL) [52] studied the energy storage capacity for the entire U.S. to reach 80% renewable energy penetration in the electricity sector. It determined that between 100 to 152 GW of power capacity in energy storage systems consisting of a variety of storage types were required.

Scholars have also explored how energy storage will change the grid emissions from the techno-economic standpoint with results that vary among different grid mix and arbitrage scenarios. ESS might increase the grid GHG emissions or slightly reduce the carbon emissions in the grid [53]. While studies have shown that energy storage will increase the total GHG emissions for ESS coupled with dense fossil fuel electricity sources, the emissions for ESS combined with nuclear and renewable sources are lower than for a fossil fuels grid [54]. With California's high renewable penetration goal, whether energy storage will benefit the grid and reduce GHG emissions, is the subject of this thesis and has not been previously addressed.

Another question is which of the three LCA phases dominate the environmental impact. From studies such as [30], the use-phase impact of energy storage is more significant than the production phase impact. However, with the deployment of renewable resources, the production phase impact may exceed the use-phase impact given that less fossil fuel will be used for the use-phase. At what point the penetration of renewable resources transitions the dominate impact of energy storage from the use to the production phase is also addressed in this thesis.

2.5 Summary

The use-phase of stationary battery storage systems plays an important role in the whole life cycle from the environmental perspective. To date, the use-phase has not been studied as much as the production phase. In addition, the literature reveals that, for the use-phase:

- A relatively small body of literature is concerned with the use-phase importance of flow battery technologies compared to other parts of life cycle.
- The functional units and boundaries of the use-phase are not consistent,
- The inventories of the use-phase are mostly static which do not reflect the dynamics of the grid, especially with large battery energy storage system commitment and levels of renewable penetration.

While a number of studies have focused on the size of ESS to achieve CO_2 reduction goals through renewable power generation, a study in which the net benefit of BESS is considered from a life cycle perspective has not been reported.

Using the California electricity grid as the platform, this thesis builds a framework for assessing the use-phase environmental impact of stationary flow batteries within the grid system, and evaluates the significance of the flow battery use-phase impact in the overall life cycle impacts in particular. This study also explores the thresholds of flow battery energy storage systems that result in net environmental benefits by accounting for the LCA of battery impacts. As such, this study is the first to assess the dynamic use-phase impacts of flow batteries on the environment for different flow battery chemistries.

Chapter 3: APPROACH

The goals of the research are to characterize the use-phase environmental impacts of different flow battery systems in the context of the electric grid, and determine the flow battery power and energy capacity thresholds from an environmental perspective using California as an example. The following tasks encompass the approach to meet the goals of this thesis.

Task 1. Integrate the flow battery module coupled with different energy storage systems into the Holistic Grid Resource Integration and Deployment (HiGRID) model.

- Integrate a flow battery energy storage system module for HiGRID.
- Determine the characteristic of flow batteries
- Establish scenarios to meet sustainable goal and determine the electricity mix charging to batteries.
- Determine the electricity mix for the use-phase inventory.

Task 2. Use HiGRID to determine GHG emission factors used in flow batteries' environmental impact analysis.

- Calculate the CO_2 and reduction potential for implementation of flow batteries in the grid.
- Change energy storage capacity and renewable resource capacity to determine emission variation due to flow battery storage deployment.
- Determine the electricity grid benefit potential of the deployment of flow battery energy storage systems.

Task 3. Develop and integrate the flow battery use-phase inventory with an established production phase inventory that emanated from a collaborative LCA research initiative to reveal the significance of use-phase impacts.

- Use Ecoinvent data related to electricity generation from different resources. Build the use-phase model.
- Comparison between the production-phase and the use-phase impacts

Task 4. Evaluate trade-offs of deploying flow batteries. Identify the existence of Maximum Allowable Energy Capacity (MAEC) and Maximum Benefit Energy Capacity (MBEC).

- Expand VRFB and electric grid life cycle inventories with different energy-to-power ratios, and calculate the LCA impacts from both the battery side and grid side to identify the MAEC and MBEC.

Task 5. Determine the Maximum Allowable Energy Capacity (MAEC) and Maximum Benefit Energy Capacity (MBEC) for VRFB deployment in California.

- Compare the environmental impacts and benefits of redox vanadium flow batteries.
- Determine different suitable capacities of energy storage systems for California Grid.

Chapter 4: METHODOLOGY

Battery energy storage systems (BESS) deployed to shift renewable energy will change the grid mix in the future. This thesis addresses (1) the use-phase environmental impacts of different flow battery systems in the context of the electric grid, and (2) the threshold of battery deployment that can bring an overall net benefit to the environment by considering the benefit and detriment of battery operation. To interpret the dynamic of BESS deployment, a grid simulation tool is employed. While BESS deployment could facilitate a reduction in GHG emissions during the use-phase by complementing solar and wind generation resources, the production life phase of batteries impact metal usage, energy use, and the environment. To analyze the combined environmental impacts from the production and use-phases, LCA is a suitable and comprehensive tool.

An overall flowchart of the methodology applied in this thesis is presented in Figure 4-1.

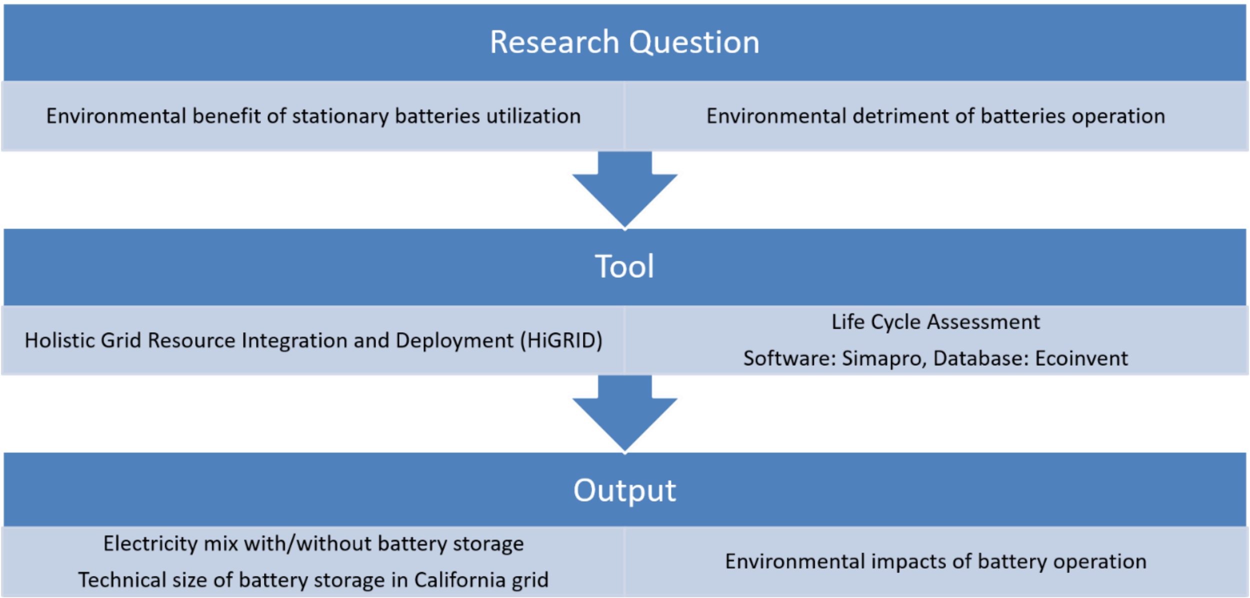


Figure 4-1 Methodology Flow Chart

4.1 Electric system modeling

BESS play important roles in the electricity grid to meet California sustainability goals. In this analysis, flow batteries are dispatched to store otherwise curtailed renewable electricity when the electricity supply exceeds the demand. Flow batteries release energy to meet the demand when the load exceeds the supply of renewable generation in later hours. The Holistic Grid Resource Integration and Deployment (HiGRID) model is used to establish the grid response to different scales of flow battery applications and provide a tool to evaluate the impact of different electricity generation technologies on the California electric grid. HiGRID determines the hourly dispatch of electricity generation and complementary technologies on the electric grid subject to the constraints of balancing supply with demand, and providing sufficient reliability services. As outputs from these processes, HiGRID produces metrics for environmental impact such as annual GHG emissions, criteria pollutant emissions, fuel usage, and the annual delivered energy by resource type.

A battery model, embedded in HiGRID, is designed for stationary energy storage systems [55]. The stationary energy storage parameters considered are round trip efficiency, ramp rate, energy and power capacities, and charge/ discharge power rating. Varying energy capacity and power capacity will change the penetration of renewables and the overall electricity mix of the grid. For this study, electric grid configurations are simulated with different energy and power capacities of flow batteries. As the use-phase environmental impact of batteries to the grid is the focus of this study, other grid components remain the same among different cases.

4.1.1 Electricity mix of battery operation

The environmental impact of the flow battery use-phase begins with the electricity that is wasted due to the self-discharging inefficiency of flow battery systems. The amount of electricity waste and the impact of the wasted electricity is assessed in this analysis.

Battery systems are designed to store the otherwise curtailed renewables, which typically occur in high renewable penetration grid in the future. To assess the impact of the future grid, two “energy resource mix” reference scenarios are considered here based on the PATHWAYS study conducted by Energy Environmental Economics (E3) [49]. The PATHWAYS study determined different technology portfolios for reaching an 80% reduction in economy-wide greenhouse gas reductions from year 1990 levels in California by the year 2050. The E3 study assesses changes in electric loads based on population growth, technology improvements, replacement rates of old technologies with new technologies, and the deployment of electric and hydrogen fuel cell vehicles. Additionally, changes in the energy resource mix for meeting loads and greenhouse gas reduction goals are determined based on resource availability and cost. Parameters used in the study included the installed capacities of electricity generation technologies and the profiles of electric loads from industrial, commercial, residential, and transportation sectors. Two scenarios from the PATHWAYS study are simulated here: a year 2030 scenario corresponding to a 50% renewable penetration, and a year 2050 scenario corresponding to a 90% renewable penetration.

By using the two scenarios listed above, the results from HiGRID are broken down by electricity generation technologies at different scales of flow battery deployment. The composition of energy resources varies as the population of flow batteries increase. Because flow batteries can decouple, power capacity and energy capacity can vary independently and thereby affect the hourly and annual impacts of each incremental increase in the capacity of flow batteries. Because the electricity mix is used in the LCA procedures to determine the use-phase impacts of flow battery operation, HiGRID can provide the amount of annually flow battery electricity delivery based on the scenario of 50% or 90% level renewable penetration. In particular, HiGRID is used to calculate the waste of electricity during the operation process s. A detailed electricity mix is used in the LCA process to decide the environmental benefit of electricity grid.

4.2 Life Cycle Assessment

A life cycle assessment (LCA) is a method to quantify the energy, economic, and environmental impacts of a whole life cycle of products through the three major life phases: production, use, and end-of-life. A general methodological framework for LCA is shown in Figure 4-2. According to ISO 14040 [15], a LCA study consists of four stages: (1) Goal definition and scoping: this step aims to define boundaries of the product’s life cycle and to what end will all processes be assessed. (2) Inventory analysis: this step describes the material and energy flows in and out of the product system. (3) Impact assessment: the inventory flows are interpreted to indicators that represent different impacts, and (4) interpretation which provides the presentation of results.

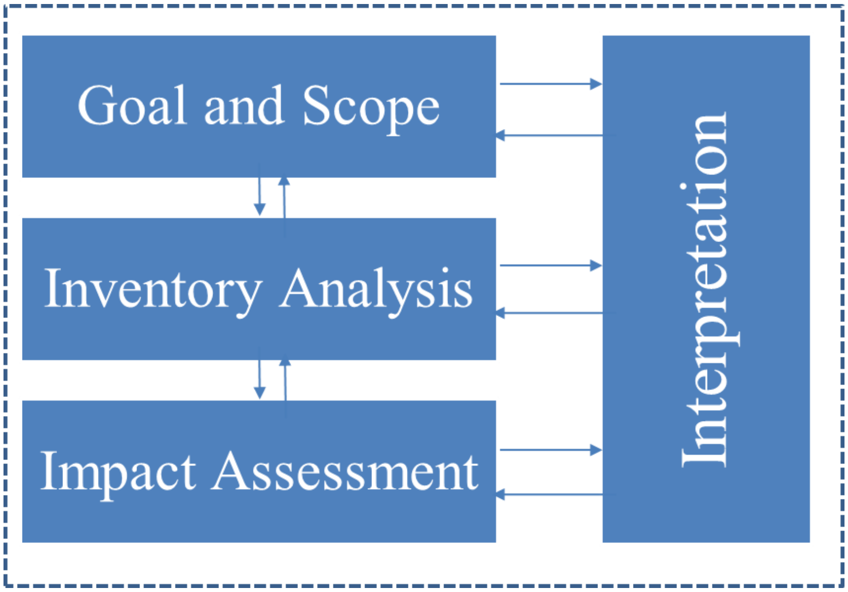


Figure 4-2 Life Cycle Assessment Framework [15]

4.2.1 Functional unit

A functional unit is a reference to which all data input and impact output are normalized, providing a basis for comparison between different products at the same level.

The functional unit selected for the flow battery LCA is 1 MWh electricity that batteries take in under the application of renewable energy shift for the period of 20 years. Due to the large implementation of renewable energy, the mismatch of electricity supply and demand will become significant. The function of stationary batteries is to store the electricity when the generation is higher than the demand which is known as the curtailed electricity. The electricity will be discharged to meet the demand when the supply is low. From all product sheets from manufacturers, flow batteries have unlimited cycles within 20 years. So this functional unit is the electricity that the flow battery at which the flow battery should be charged for the life of the flow battery.

4.2.2 System boundary

The three phases of the LCA on flow batteries are shown in Figure 4-3. In a complementary study, He [31] developed data and conducted critical research to assess environmental impacts associated with the first phase (production) for redox flow batteries. This study (1) adds the use-phase to the production phase using materials data from [31], and (2) calculates the combined environmental impacts from the two phases. (The disposal or recycling of the material is not considered in this study due to the absence of data.)

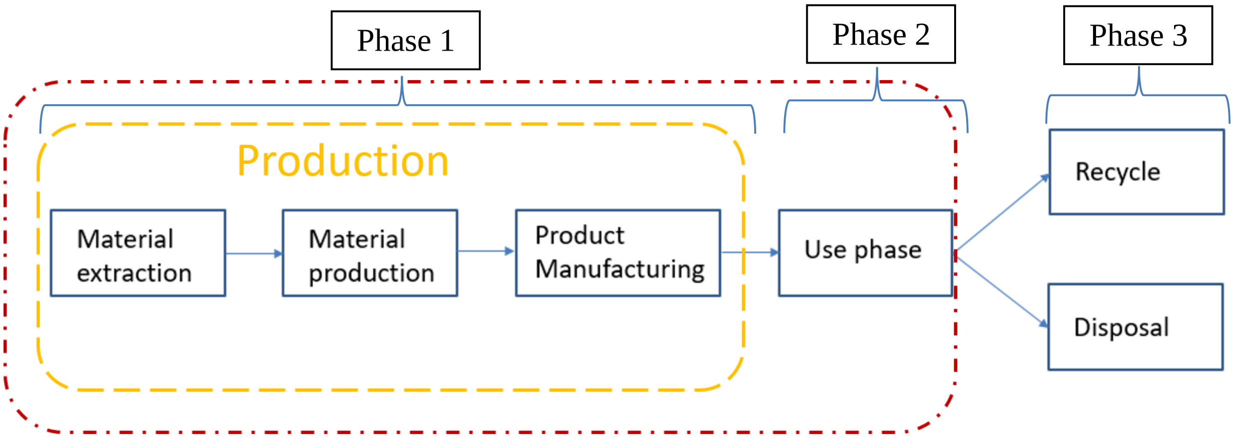


Figure 4-3 System Boundary for the Flow Battery LCA

4.2.2.1 Flow Battery Use-Phase Boundary

The schematic of the use-phase definition is illustrated in Figure 4-4. Because stationary batteries only store and release electricity, the use-phase environmental impacts of the stationary batteries are caused by the inefficiency of batteries during charging and discharging. The maintenance and replacement of flow batteries in their life time are not included in this study since they are not as frequent, complicated and consumptive as other type batteries. The manufacturers state that the replacement of pumps or other additional facilities depend on the working conditions and preventive maintenance of the user. Correcting the composition of the electrolyte is the primary requirement for maintenance. With no specific data, the maintenance is not included in the use-phase analysis.

Note, the electricity mix of the grid directly impacts the use-phase results. To calculate the negative impacts of the electricity loss, a life cycle inventory (LCI) of different electricity generators is needed.

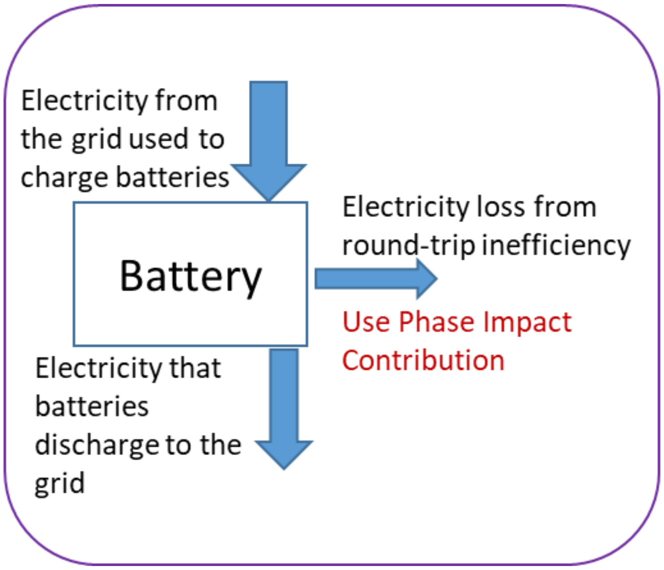


Figure 4-4 Flow Battery Use-Phase Boundary

4.2.3 Life Cycle Inventory

The production inventory is built based on manufacturers' information and the literature. In the present case, data provided in He [31] are utilized. The inventories are based on a 4h vanadium flow battery (VRFB) system, a 5h zinc bromide flow battery (ZBFB) and an 8h all-iron flow battery (IFB). Based on the per-kWh production impact calculated by [31], for each battery, this thesis assumed the impacts would scale linearly with the increase of the capacities for the same energy-to-power ratio. For the VRFB system, inventories of the power sector and the energy sector from [31] are scaled up separately for meeting the demand of various energy-to-power ratios.

A LCA inventory of the electricity system is built to convert the use-phase environmental impacts by integrating the grid simulation results and using the following California electricity resources in the year 2050: open ground solar systems, roof top solar photovoltaic, wind and geothermal, hydropower, and natural gas and biogas usage (Figure 4-5). The batteries are installed to store renewable energy and then used to offset the usage of natural gas. With the increase of wind and solar together with energy storage, natural gas usage is decreasing. Hydropower is not expected to be influenced by battery increase since the pumped hydro is used to satisfy bulk load shifting and it varies every year.

An LCA inventory includes datasets considering the resources mentioned above in California. To this end, the Ecoinvent [56] datasets listed in Table 4-1 are used. (Detailed inputs and boundaries of those datasets are included in the appendix.) The datasets represent the production of electricity by different technologies. They start with the installed plants of the technology and end with 1 kWh electricity produced from the technology. However, the datasets include the impact of construction and materials used in the power plants. Biogas used in this case is a mix of different resources such as biowaste and sewage sludge. The electricity generated from wind is decomposed into wind turbines of different size. The percentage of turbines smaller than 1 MW, from 1-3 MW and larger than 3 MW are determined by the dataset in Ecoinvent. Solar power is divided into open-ground and rooftop slanted installation photovoltaic solar panel. The rooftop solar panel is assumed to be only fixed since no axis rooftop data are provided by the Ecoinvent database. Hydropower is composed of run-of-the rivers facilities and large reservoir facilities. The efficiency of flow batteries is assumed to be 75% [57] in this case. Simapro a commercial tool for LCA analysis, is used as the LCA analysis tool. The inventory was built in Simapro with Ecoinvent [56] datasets.

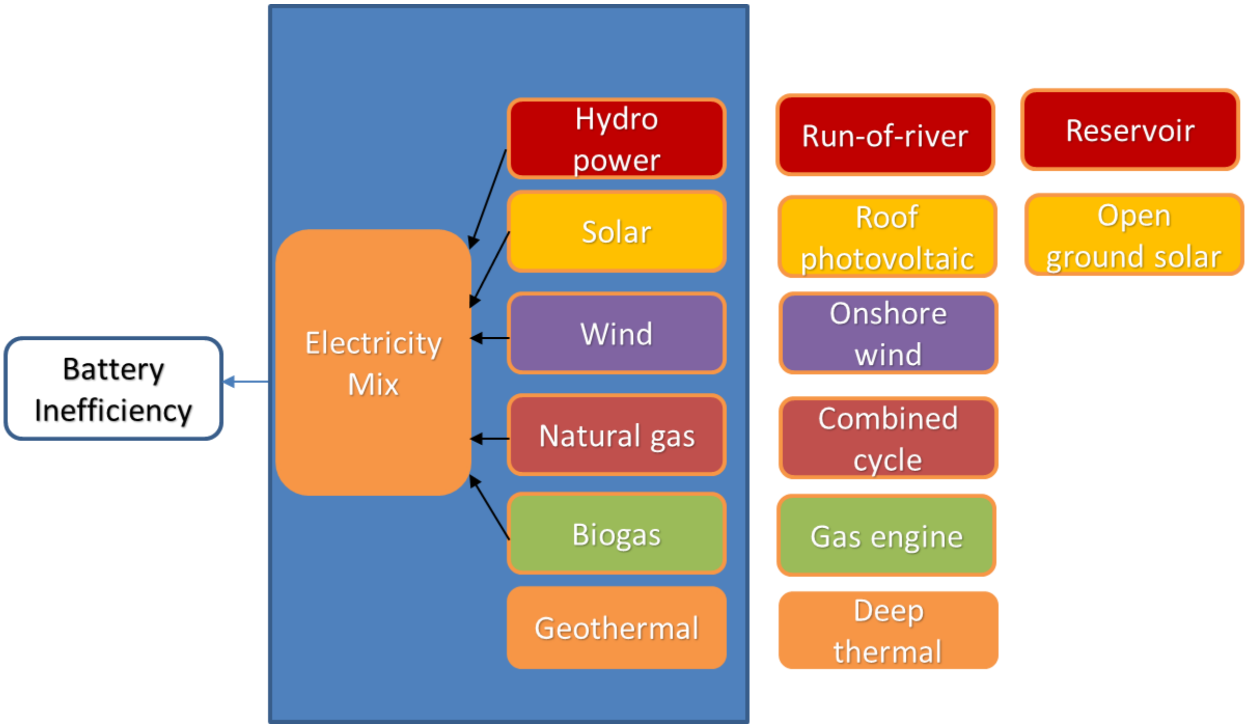


Figure 4-5 Electricity Mix in California

4.2.4 Life Cycle Impact Assessment (LCIA)

Once the inventories are established, the final step in a LCA is the life cycle impact assessment (LCIA). The goal of the LCIA is to quantify the magnitude and significance of the impacts of a product through its entire life cycle. These impacts are expressed as different indicators such as global warming potential (GWP) and fine particulate formation (PM) for environmental impacts.

Table 4-1 Datasets and Boundaries

Resource Categories	Technology	Ecoinvent 3.4 Datasets
Hydro	Run-of-river	Electricity, high voltage {WECC, US only}| electricity production, hydro, run-of-river | Alloc Rec, U
	Reservoir	Electricity, high voltage {WECC, US only}| electricity production, hydro, reservoir, alpine region | Alloc Def, S
Solar	Open ground solar, photovoltaic	Electricity, low voltage {WECC, US only}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Alloc Rec, U
	Slanted roof solar, photovoltaic	Electricity, low voltage {WECC, US only}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Alloc Rec, U
Wind	Onshore wind turbine	Electricity, high voltage {WECC, US only}| electricity production, wind, <1MW turbine, onshore | Alloc Def, U
		Electricity, high voltage {WECC, US only}| electricity production, wind, 1-3MW turbine, onshore | Alloc Def, U
		Electricity, high voltage {WECC, US only}| electricity production, wind, >3MW turbine, onshore | Alloc Rec, U
Natural Gas	Combined cycle power plant	Electricity, high voltage {WECC, US only}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Rec, U
Biogas	Heat and power gas engine	Electricity, high voltage {WECC, US only}| heat and power co-generation, biogas, gas engine | Alloc Def, U
Geothermal	Geothermal power plant	Electricity, high voltage {WECC, US only}| electricity production, deep geothermal | Alloc Rec, U

Simply stated, the LCIA scores different impacts (energy, economic, environmental) which, in the case of environmental impacts, results in an ‘environmental profile’ [58]. The general procedure for an impact assessment is 1) to select impact categories and indicators, 2) classify the inventory flows, which is a way to calculate the indicators based on different weights, and 3) normalize and weight. While normalization and weighting can be included in an impact assessment, this process is not mandatory. A general flow of the LCIA is shown in Figure 4-6 for environmental impacts:

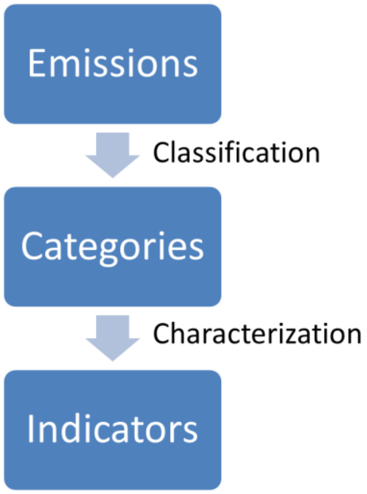


Figure 4-6 L Life Cycle Impact Assessment Flow for Environmental Impacts

In the case of environmental impact, the emissions are classified by pollutant and assigned a category. Inventory data in each impact category are then computed to scores of indicators by using characterization factors (CFs). CFs consider the fate, transport, exposure, and dose-response of chemical emissions. Indicators are usually expressed by typical chemical equivalents such as CO_2eq/kg for global warming potential [59].

4.2.4.1 Indicator selection

The selection of impact categories reflect a comprehensive set of environmental issues related to the product system [15]. In this present study, particulate matter (PM), acidification potential (AP), cumulative energy demand (CED), and global warming potential (GWP) are selected. For

CED, fossil fuel is used as natural gas is the main replacement target in California.

There are two types of indicators: midpoint and endpoint. Midpoint indicators are related to environmental issues like PM and AP, and endpoint reflects protection areas of human health, ecosystem quality and resource scarcity, such as immune system suppression, and skin cancer [58]. In the present study, midpoint indicators are addressed.

4.2.4.2 Indicator introduction

(1) Global warming potential (GWP)

The increase in greenhouse gas (GHG) in the atmosphere raises the radioactive forcing capacity (w/m^2) in the atmosphere which leads to an increase of the global mean temperature [59]. The global warming potential (GWP) of a GHG emitted from a product is a measure of how much a given mass of GHG contributes to global warming relative to an equivalent mass of carbon dioxide (kg CO_2 eq/kg) [58]. The IPCC (2013) [59] characterization factors for time horizon of 100 years was used in this study to interpret the GHG contribution in terms of the carbon dioxide.

(2) Fine particulate matter formation

PM 2.5 stands for fine organic and inorganic particulate matter with a diameter smaller than 2.5 µm [58] and includes primary and secondary aerosols that can be inhaled deeply into the lung and induce substantial negative health impact on the human respiratory system. In contrast to larger particles (e.g., PM 10), PM 2.5 is the principal cause of respiratory morbidity from PM exposure [60].

(3) Acidification potential

Inorganic substances such as sulphates, nitrates, and phosphates will cause changes in soil acidity [58]. Acidification is when the acidity of soil deviates from the optimum level of acidity for plants, it is harmful for that species. Emissions like NO_x, NH_3 and SO_2 are major contributors to acidification potential (AP), the impacts of which are expressed in kg SO_2 equivalent.

(4) Fossil Fuel Cumulative Energy Demand

Cumulative energy demand (CED) is an indicator for calculating the energy use through the life cycle of a product, distinguishing between renewable CED and non-renewable CED. Fossil fuel categories considered include hard coal, lignite, crude oil, natural gas and coal mining off-gas, peat are included in the fossil fuel categories [58]. The value of energy is expressed in MJ – equivalents.

4.2.4.3 Life cycle impact assessment tools

ReCiPe 2016 was selected for the present study, which is a LCIA tool inside Simapro [58].

(1) ReCiPe 2016

ReCiPe 2016 is a LCIA tool that provides harmonized characterization factors (CFs) at both midpoint and endpoint levels. A CF at the midpoint level is defined as a dimensionless number that calculates the strength of an amount of a substance relative to that of a reference substance [58]. Table 4-2 shows the midpoint and CF_m used in this study where the subscript “m” stands for midpoints.

Table 4-2 Overview of the Midpoint Categories and Related Impact Indicators [2]

Impact category	Indicator	Unit	CF_m*	Abbr.	Unit
Climate change	Infra-red radiative forcing increase	W x yr/m^2	Global warming potential	GWP	kg CO_2 to air
Ozone Depletion	Stratospheric Ozone decrease	Ppt x yr	Ozone depletion potential	ODP	kg CFC-11 to air
Fine particulate matter Formation	PM2.5 population intake increase	kg	Particulate matter formation potential	PMFP	kg PM 2.5 to air
Terrestrial acidification	Proton increase in natural soils	Yr x m^2 x mol/l	Terrestrial acidification potential	TAP	kg SO_2 to air

* CF_m is the characterization factor at midpoint

(2) Fossil fuel CED Ecoinvent

Characterization factor of this method is using upper heating value of fossil fuel resource.

4.3 Benefit Threshold Determination

This thesis addresses the life cycle environmental impact of batteries as a product, and compares the benefits to those that batteries can provide by releasing ramping tension of traditional power plants. The use-phase environmental impact is determined by the electricity waste associated with the inefficiency of the batteries. The grid electricity mix from which the impact depends is calculated from HiGRID. The overall electricity multiplied by the inefficiency (25% in this case) is considered as the use-phase consumption.

As shown in Figure 4-7, the net benefit is determined by comparing the original electricity mix which does not include battery energy storage with the grid mix after various scales of battery energy storage are deployed. The environmental benefit is calculated in Simapro, an inventory built using Ecoinvent. The impact calculated considers both the production contribution determined by He [31] and the use-phase contribution calculated in this study.

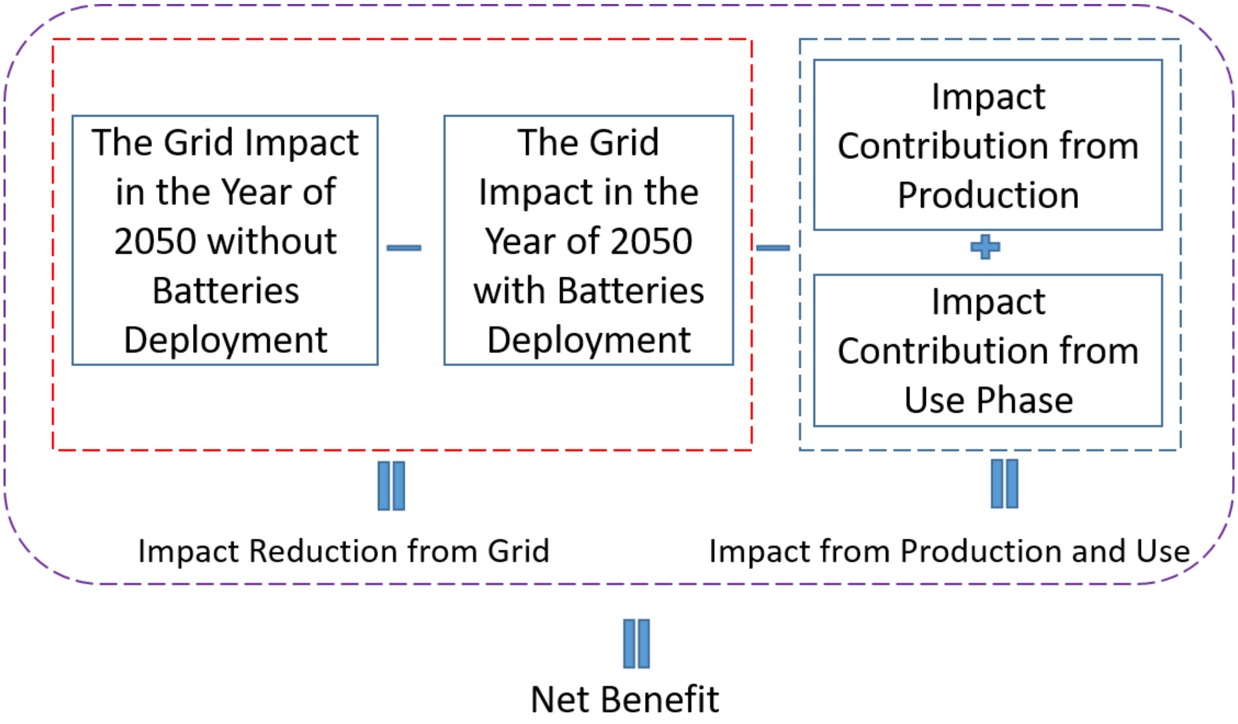


Figure 4-7 General Methodology of Net Benefit

4.4 Uncertainty and limitations

In this section, the uncertainty and limitations of the overall methodology and inventories are presented.

<u>Methodology</u>: In the threshold determination analysis, one uncertainty is the scaling up of the normalized production data of He [31]. For the present study, the following assumptions are made:

- The flow battery scaling is based on the kWh production impact reported by [31] using inventories based on an 4h VRFB system, an 5h ZBFB system, and the 8h IFB system.
- Flow batteries can only be scaled up by the number of units.
- All components in flow batteries scale linearly with the battery size.

The impact categories considered in this study are GWP, AP, ODP, and fossil fuel CED. However, other impact categories, like human toxicity, ecotoxicity, eutrophication, and abiotic depletion potential are not considered.

Production-phase inventory: The scaling of the production process in this study does not consider technology evolution or economies of scale, even though scaling is a future projection and will influence the production-associated impacts, and therefore the net benefit thresholds. While a limitation, this projects a worst-case scenario and avoids the uncertainties that may be introduced on predicting growth of the technology. Two additional limitations are (1) that transportation is not considered in the production data of He [31], and (2) the end-of-life phase is not considered even though the recycle or disposal process will likely impact the threshold.

Electricity inventory: A limitation in the California electric grid inventory is the exclusion of imported electricity into California. First, the technologies from which imported electricity is generated change hourly. Second, the power imported in 2030 is 20% of the overall electricity supply, and 2.5% in 2050 [61]. Electricity imports are sourced from regions (e.g., Utah) where coal serves as the fuel [62], coal is not considered as a resource in the electricity composition of this study which introduces uncertainty in the use-phase impact and grid benefit analyses.

Lastly, while the electricity inventory is built to project the impact of the future grid, the database is based on data collected from past and existing technologies. Even though electric power generation plants designed to last decades, for the California grid mix is already rapidly evolving with solar and wind power generation resources. As a result, this study represents a worst-case scenario.

4.5 Summary of Methodology

The methodology flow used in this study encompassed the following steps:

1) Use HiGRID to determine the size of flow battery systems for meeting the sustainability goals of California in 2030 and 2050, and obtain the original electricity mix and the mix of electricity charged into the battery system.
2) Build inventories in Simapro for various electricity grid compositions and battery systems with different energy to power ratios.
3) Calculate the environmental impacts from the grid and battery systems and obtain indicators for four indicators.
4) For selected scales of battery systems deployment, compare the combined production-phase and use-phase environmental impacts to the grid mix in the absence of battery deployment.

Chapter 5: ELECTRICITY MIX OF FUTURE GRID WITH BATTERY STORAGE

Task 1. Integrate the flow battery module coupled with different energy storage systems into the Holistic Grid Resource Integration and Deployment (HiGRID) model.

5.1 HiGRID Model and Flow Battery Module

- Integrate a flow battery energy storage system module for HiGRID

The flow battery module is a part of the stationary energy storage (SES) module developed by Josh Eichman [55]. To shift the load, the SES module can store the curtailed renewable energy and discharge it back to the grid when the electric demand is high. In the SES modules, the parameters of SES could be set to represent different energy storage technologies. As a system-level grid analysis, the overall parameters of battery systems such as efficiency, power capacity, and energy capacity, dispatch hours are considered. To better understand the impacts of batteries scale dynamic, an iterative module of flow batteries' parameters was developed easily vary parameters.

To apply HiGRID with the flow-battery modules, flow battery data are required.

Table 5-1 Vanadium Redox Flow Battery Operating Parameters

Battery type	Vanadium redox flow battery (VRFB)
Performance	Peak power: 600kW$_{AC}$
Energy capacity	2200 kWh$_{AC}$
Round trip efficiency	65%-70% AC/AC efficiency

Table 5-1 lists the peak power and maximum energy for the VRFB system. However, a real system cannot operate at both the maximum power and energy capacities at the same time. Usually, batteries perform at different power and energy capacities depending on the demand. Several operational parameters for the VRFB are listed in Table 5-2:

Table 5-2 Operational Performance for VRFB

Discharge time	2h	4h	8h
Power	600 kW_{AC}	500 kW_{AC}	275 kW_{AC}

5.2 Electricity Mix

- Establish scenarios to meet sustainable goal and determine the electricity mix charging to batteries.

Since BESS are designed to help integrate renewable energy into the electricity system, the predicted renewable capacity in the future grid needs to be established. Two scenarios from the PATHWAYS study for 2030 with a 50% renewable penetration, and the 2050 with 90% renewable penetration were adopted as the scenarios for analysis. The capacity projections for 2030 and 2050, deduced from PATHWAY [49], are shown in Table 5-3:

Table 5-3 Electric Grid Resource Capacity Inputs

Electric Grid Resource	Installed Capacity in 2030 (MW)	Installed Capacity in 2050 (MW)
Hydropower	15060	15060
Geothermal	3105	3105
Centralized Solar PV	20850	93950
Rooftop Solar PV	11800	20200
Wind	20790	118300

It can be seen that the hydropower and geothermal capacities will not increase between the 2030 scenario and 2050 scenario. The renewable increase is mainly from the capacity increase of solar PV and wind plants.

In order to access how BESS can support the integration of renewables, a suitable capacity range of BESS needs to be established as illustrated in Chapter 2. Studies that have investigated the energy storage capacity needed for reaching an 80% GHG emission goal on the California grid suggest ranges for the power capacity of BESS from 17-260 GW, and for the energy capacity from 132 to 2736 GWh [50].

The range of the energy and power capacities adopted for this study are listed in Table 5-4.

Table 5-4 Energy and Power Capacity Ranges and Increments for Installed Energy Storage System Fleet

Parameter	Range	Increment
Energy Capacity [GWh]	0 to 2880	320
Power Capacity [GW]	0 to 360	40

In the analyses, both the energy and power capacities are varied independently. While the relationship between renewable generation and the electric load demand profile remain constant, other elements of the electric grid configuration are fixed. The energy storage module uses hourly renewable and load data to determine the electricity demand signal. The module uses signals such as total demand and maximum load value to decide when to charge or discharge batteries. The charging process is simulated as follows:

- When a maximum net load occurs, the load is reduced by a small increment
- The nearest earlier minimum is increased and assessed an energy penalty due to inefficiencies of charging the system.

In order to conduct the use-phase analysis, the electricity profile charged into the battery systems is required. Combining the renewable capacity and electricity demand with the battery storage module, HiGRID is used to decide the overall electricity stored and released by the battery systems. The overall electricity storage will change with the energy and power capacities. The dynamic of the total electricity charged into the batteries with the change in the battery systems capacities are shown in Figure 5-1 for 2050 with 90% renewable penetration. The surplus renewable energy and the state of charge of battery systems are two factors considered in the module to decide the overall electricity that the battery systems absorb over the year.

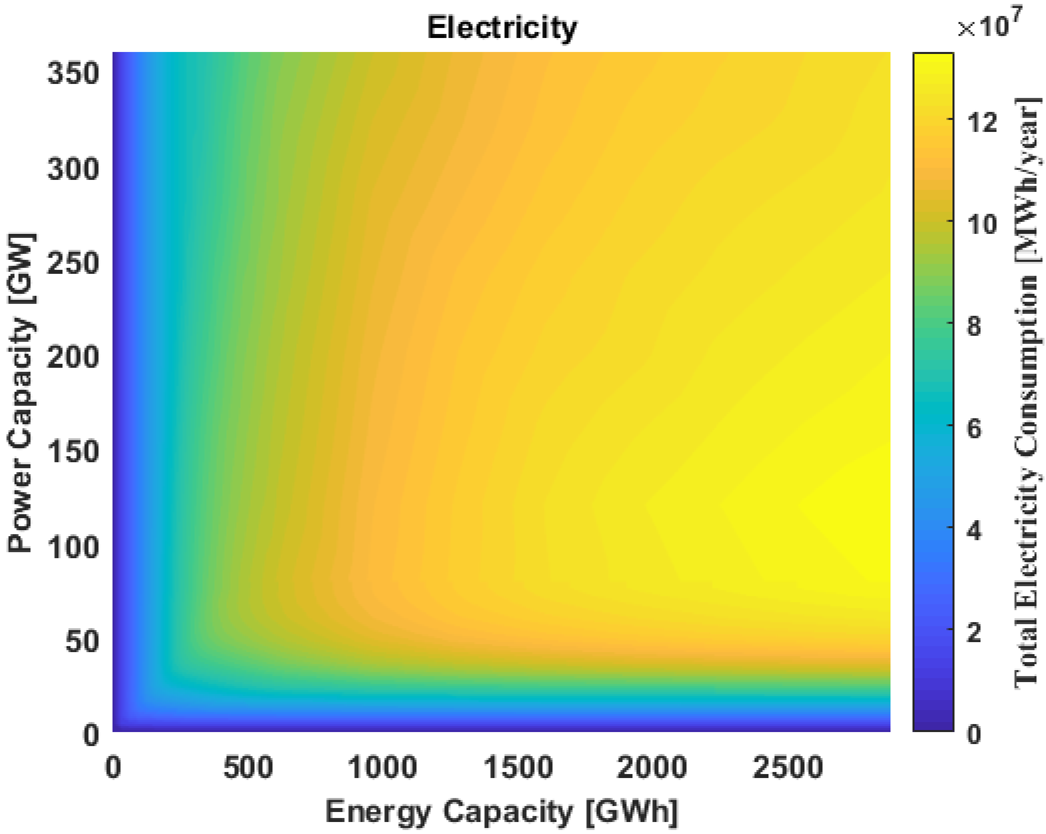


Figure 5-1 Total Electricity Taken in by Battery Systems per Year.
2050 with 90% Renewable Power Penetration

As shown in Figure 5-1, the electricity taken in to the flow battery increases as the energy and power capacities increase. It can be seen from Figure 5-1 that the power capacity dominates the trend of the overall amount of charged electricity at the range where the power capacity is lower than 50 GW. However, after a certain threshold, the increase of battery systems' energy capacity takes over the control of the overall electricity that can be taken in. The power capacity and energy capacity influence each other in a way that the threshold of power dependent varies as the energy capacity change. The power dependent threshold increases as the energy capacity increase. The BESS tend to provide load-following and load shifting for the grid to eliminate the power plant supplements. The power capacity is crucial to the system to serve this function at the beginning. Once the power capacity is high enough to supply the ramping load, the energy capacity increase can help provide multiple ramping events. In the Figure 5-1 the electricity stored is independent from both the energy and power capacities.

- Determine the electricity mix for building up the use-phase inventory.

Knowing the total electricity that goes into the BESS is required to determine the overall waste electricity. Ideally, batteries will be charged by electricity generated by renewable energy like solar and wind. However, it is impossible to distinguish the resources once the electricity is mixed into the transmission lines. Consequently, the mix of electricity taken into batteries is estimated by the overall electricity composition over a year. The relative ratio of electricity generated by different resources is applied to decide the mix of charging electricity. An example of the electricity mix taken into the battery system with the energy capacity of 32 GWh and the power capacity of 8 GW are listed in Figure 5-2. Shown is a comparison between different renewable penetrations. Year 2030 stands for 50% renewable penetration in California. Year 2050 represents 90% renewable penetration.

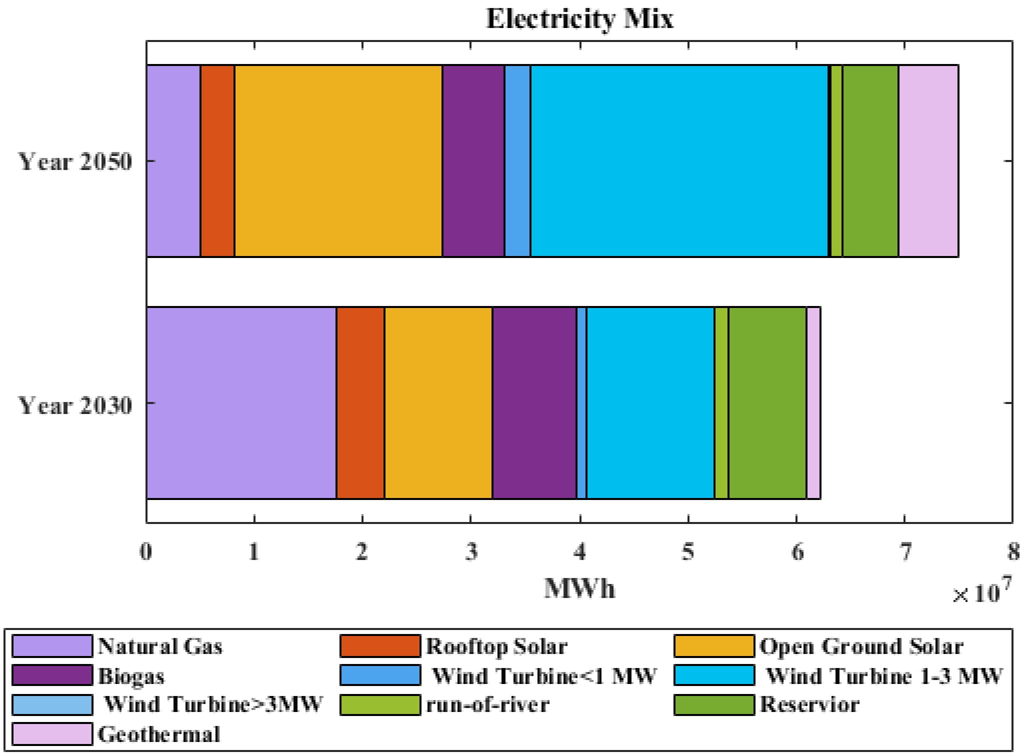


Figure 5-2 Electricity Mix of the Year 2030 and Year 2050

Figure 5-2 shows that the year 2050 takes more electricity in over a year, even though the capacities of the battery system are the same. On the one hand, more renewables will generate more surplus renewable energy that needs to be stored; on the other hand, fewer load followers in the grid mix will cause batteries to discharge more electricity into the grid. These two reasons together result in more electricity flow in and out from the battery systems. The difference between the two scenarios is the increase of electricity from wind and solar and the decrease of natural gas and biogas usage. The overall higher percentage of wind and solar generators in the grid results in the decrease percentage of hydro and geothermal sectors. Geothermal and hydropower capacity will reach their limits in those two scenarios and, with renewable penetration higher than 50%, so does the biogas. However, as wind and solar take in a large share of overall electricity generation, the portion of these resources become smaller, which induce a reduction in the mix of electricity in batteries.

A similar electricity mix was determined for all power and energy capacity cases with the goal to establish the dynamics of the electric grid at different BESS scales.

5.3 Conclusions

This chapter provides the electricity mix required for building the life cycle inventory for the use-phase. The results demonstrate that the energy and power capacities and renewable penetration influence the mix of electricity charged into the battery systems. The major variables in the future grid mix are the projected reduction in natural gas, and increase in solar, and wind resources.

Chapter 6: DETERMINE THE ELECTRICITY GRID BENEFIT POTENTIAL

Task 2. Use HiGRID to determine GHG emission factors used in flow batteries' environmental impact analysis.

6.1 Determine CO_2 in the grid

- Calculate the CO2 and reduction potential for implementation of flow batteries in the grid

From the electricity grid mix calculated in Task 1, natural gas is assumed to be the majority of fossil fuel usage in the future grid. The amount of fuel consumption is determined by the efficiency of power plants and the part-load parameters, and the associated emissions calculated by HiGRID are determined using the emission factors are listed in the Table 6-1.

Table 6-1 Emissions Factors for Greenhouse Gas Emissions

Greenhouse Gas Type	Emissions Factor	Global Warming Potential Factor
CO_2	53.06 kg CO_2 / MMBTU Natural Gas	1
N_2O	0.0001 kg CO_2 / MMBTU Natural Gas	298
CH_4	0.001 kg CO_2 / MMBTU Natural Gas	25

- Change energy storage capacity and renewable resource capacity to determine emission variation due to flow battery storage deployment.

Changing the energy and power capacities of BESS will change the usage of fossil fuels and the emission of CO_2 and criteria pollutants. The results calculated from HiGRID are shown in the Figure 6-1 and 6-2. The results vary between two years, reflecting the increase in renewable power generation from 2030 to 2050.

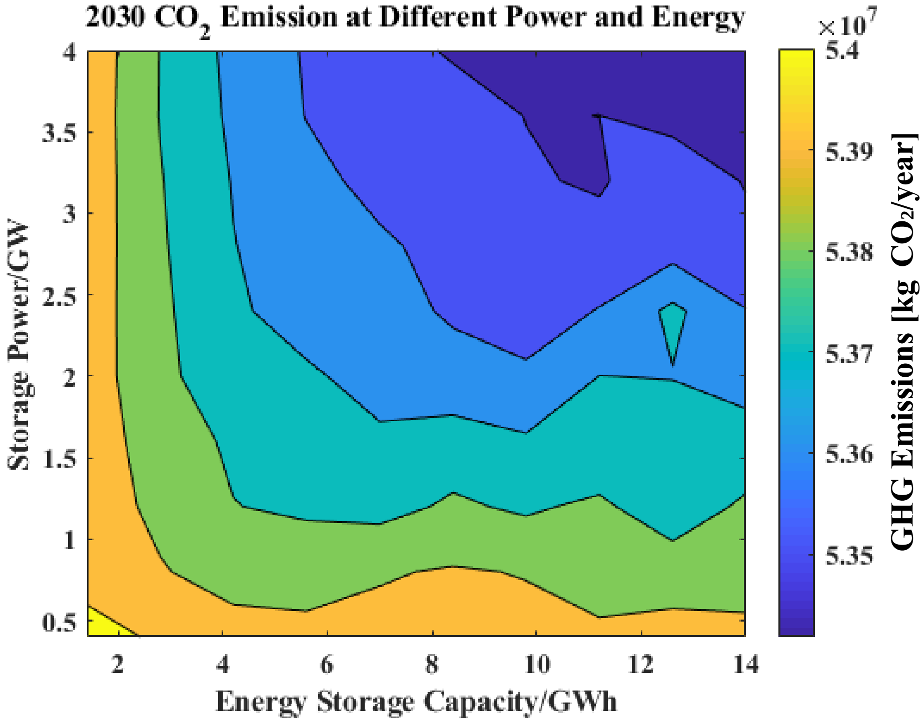


Figure 6-1 CO$_2$ Emission from the Grid

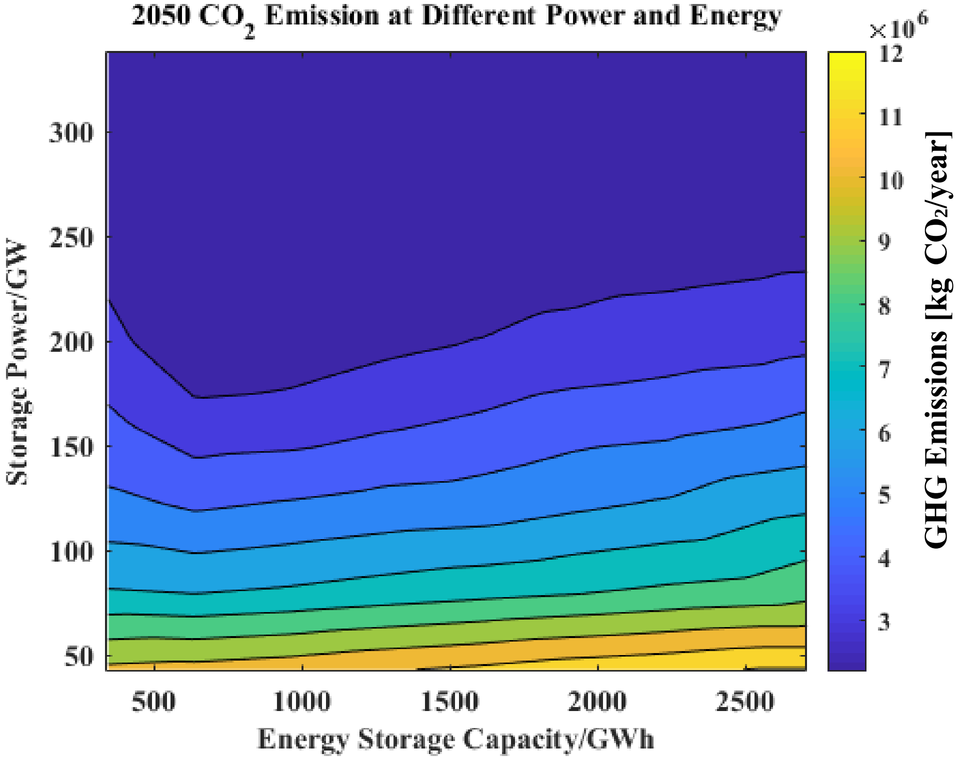


Figure 6-2 CO$_2$ Emission from the Grid

It can be seen from Figures 6-1 and 6-2 that the renewable penetration has a significant influence on the CO_2 emissions. Although the scale of the energy storage system at 2050 is larger than that at 2030, the overall CO_2 emission of 2050 is nearly half the amount of that of 2030. The trends of CO_2 emissions are different between 2030 and 2050 as well. In 2030, the reduction of CO_2 depends on both power capacity and energy capacity. However, when the power capacity reaches certain threshold in 2050, the power capacity is not playing an essential role in the emissions reduction.

The 2030 results show that the differences between various ranges of energy storage deployments are not significant. The fluctuation of the 2030 graph is more intensive than the 2050 case. The reason is that the relatively low extra renewable energy is not sufficient to cover the entirety of the mismatch between the load and demand. The electricity grid in 2030 continues to rely on natural gas as fossil fuel based peak power plants and load-following power plants remain actively involved in the system operations. Another reason for energy storage systems to not substantially impact the grid and to reduce fossil fuel usage is that the deployed power and energy capacities of battery systems are relatively small compared to 2050 case.

6.2 Determine the electricity grid benefit potential of the deployment of flow battery energy storage systems.

Energy storage provides environmental benefits by charging and storing renewable energy that would otherwise be curtailed, and displacing thereby fossil fuel-based electricity generation. The extent of the benefits depends on the total power and energy capacity of the aggregated energy storage fleet installed on the grid.

There are two different ways to quantify the benefit. One is to define the benefit as the electricity discharged to the grid from batteries by identifying the mix and calculating the life cycle impact of every generator. The other way is to calculate the impact by the difference between the original electricity grid mix without energy storage application and the electricity grid mix with different levels of BESS systems.

This section selects the second method, arguing that it is more accurate to calculate since the assumption of the electricity mix of the electricity charged into the battery is not required.

The GHG benefit due to the deployment of battery systems are presented in Figure 6-3:

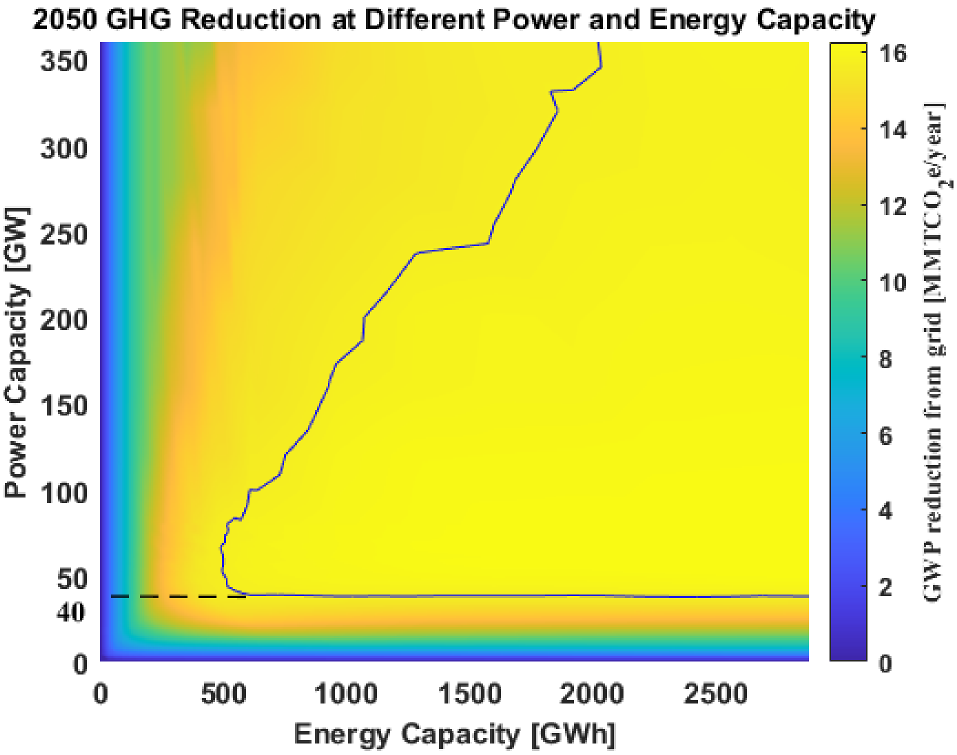


Figure 6-3 Global Warming Potential Reduction with Power and Energy Capacities

It can be seen that, after 40 GW, the power capacity does not influence the overall benefit, and the emission reduction depends mainly on energy capacity. After certain thresholds, the benefit levels off and does not change with an increase in the energy storage systems. The result shows a trend similar to that described in Chapter 5 regarding the overall electricity taken into the battery, and confirms that installing battery systems over a given threshold does not ensure a reduction of CO_2 emissions. The reduction potential has a limit of approximately 90% in renewable penetration.

6.3 Conclusions

Given that the reduction in emissions depends on the renewable capacity of the grid, it is noteworthy that:

- A 50% renewable penetration can be achieved without the deployment of battery energy storage systems [63].
- A small amount of BESS does not contribute significantly to emission reductions in a relatively low renewable penetration grid. An increase in BESS will not necessary increase the GHG intensity as suggested by Hittinger [14].
- The impact of BESS depends on the renewable penetration of the grid.
- When applied to a grid with high renewable penetration like 80%, BESS could release the ramping tension of power plants.
- Thresholds are evident above which additional penetration of BESS does not provide additional benefit to the grid.

Chapter 7: USE-PHASE ANALYSIS OF FLOW BATTERIES

Task 3. Develop and integrate the flow battery use-phase inventory with an established production phase inventory that emanated from a collaborative LCA research initiative to reveal the significance of use-phase impacts.

- Use Ecoinvent for data related to electricity generation from different resources. Build the use-phase model.

Based on the method described in Chapter 4, the electricity mix outlined in Chapter 5 is adopted to build up the use-phase inventories in Simapro. Each inventory is linked with the corresponding production inventory of He [31] based on power and energy capacities.

- Comparison between the production and the use-phase impacts

To compare the production and the use-phase impacts under two scenarios on the same standard, there are two steps. First, modify the production inventory of He [31] based on power and energy capacities needed to link with the use-phase inventories. Second, renormalize the impacts of both production phases and use-phases by the FU (the 1 MWh electricity that batteries take in).

In order to modify the inventory that reflects the characteristic of flow batteries, it is necessary to know the composition of flow batteries.

7.1 Flow Battery Components

The most important feature of flow batteries is the ability to decouple the power and energy capacity. The energy capacity, the concentration of electro-active species and the volume of the electrolyte stored in the tank, can be scaled up by increasing the size of storage tanks.

The power of a flow battery is the product of total current and the total voltage developed by the cell. The number of atoms of active chemical species that are reacted with cells determines current, and the chemical potential between the two chemical states of active elements and the number of cells that are connected determines the voltage. The numbers of cells in the stack and the number and size of the electrodes control the power capacity.

A flow battery system is composed by a cell stack, electrolyte tanks, and balance of plant (BOP) which are used for assisting the battery operation (Figure 7-1). The cell stack includes a positive and a negative electrode with an ion-exchange membrane which separates electrolytes. Electrolytes are stored in two external tanks. The pump helps the electrolyte to circulate between tanks and cell. A balance of plant includes heat and pH management, as well as DC-AC converter, control system. All of BOP are used to maintain system operation. A detailed schematic of a cell stack is illustrated in the Figure 7-2. Rubber gasket seals and steel tie-bolts are used to compress the cell stack in order to avoid electrolyte leakages. Two inert conductors in the liquid are used to conduct the current. The electrodes only provide platforms for charging transfer, which contributes to a long cycle life of flow batteries. Typical electrodes used in RFBs are made of carbon-based composites or inert metallic materials. The bipolar plate is designed for cells to stack together easier.

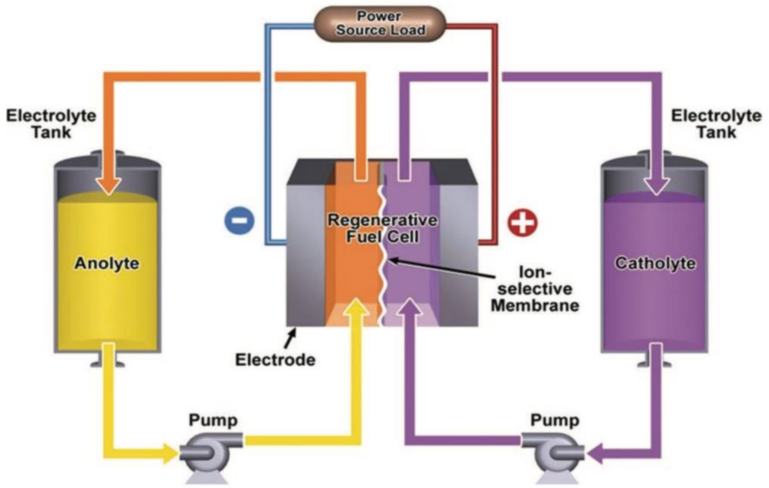


Figure 7-1 Schematic of a Flow Battery System [11]

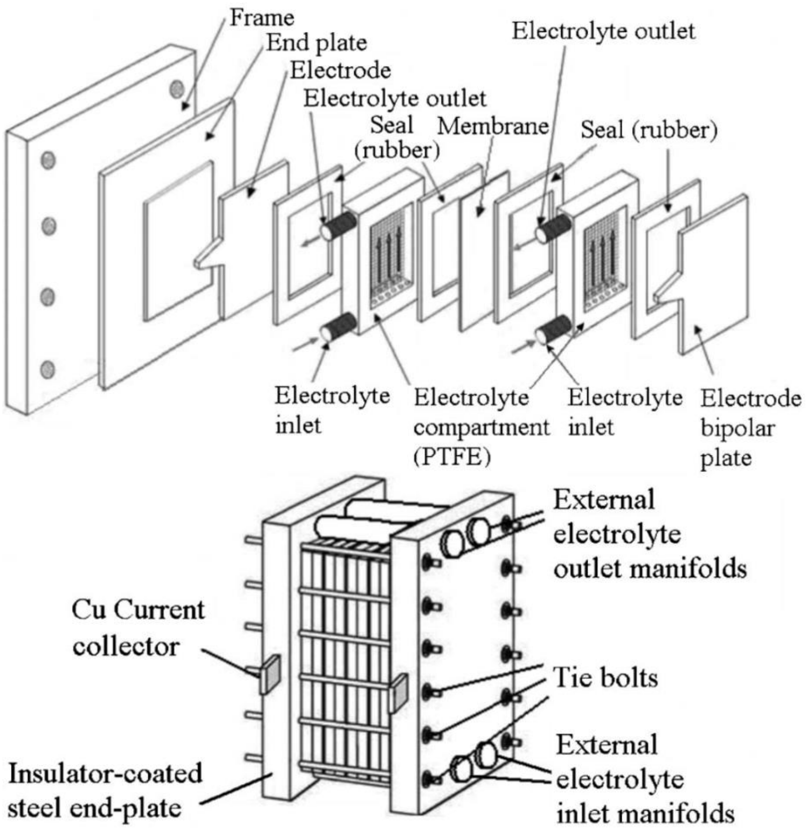


Figure 7-2 A Typical Cell Stack of a Flow Battery [64]

To make the inventory more flexible and easy to scale up separately, components for energy capacity and power capacity are built separately, as shown in Figure 7-3. The inventory datasets for this study are adopted from He [31].

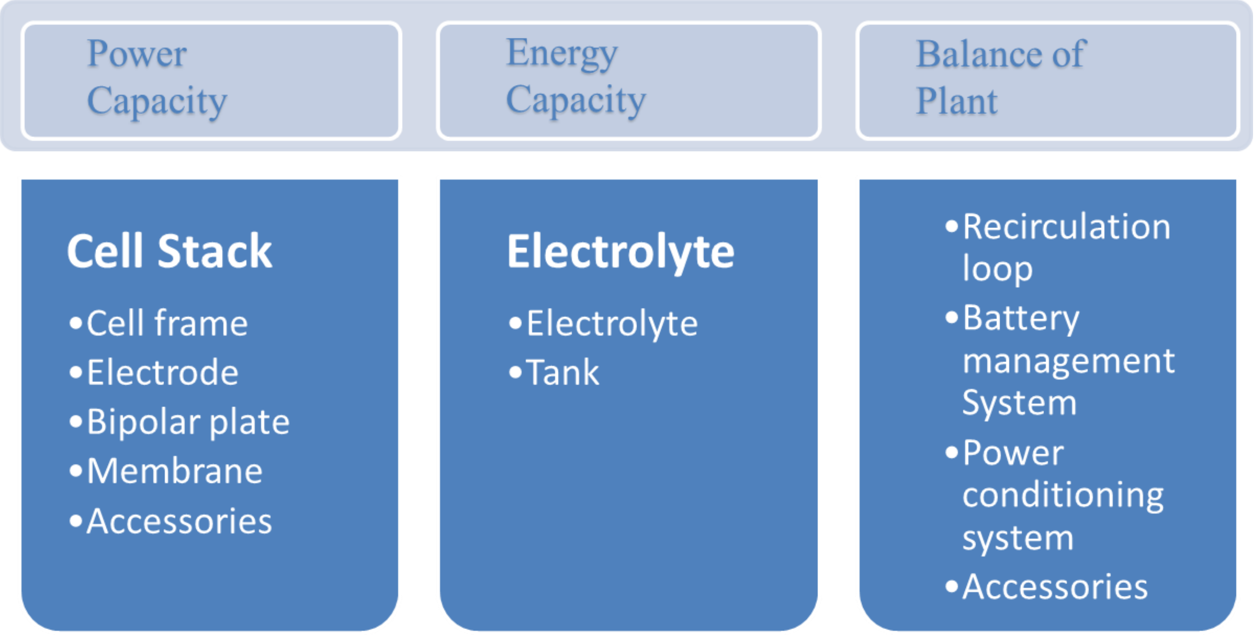


Figure 7-3 Flow Battery Components [31]

- Determine the characteristics of the three flow batteries,

The characteristics of the three flow batteries in this study are listed in Table 7-1:

Table 7-1 Flow Battery Operating Parameters

Battery type	Vanadium redox flow battery (VRFB)	Zinc bromide flow battery (ZBFB)	All Iron flow battery (IFB)
Performance	Peak power: 600kW$_{AC}$	Rated power: 25kW	Rated power: 50kW
Energy capacity	2200 kWh$_{AC}$	125 kWh	400 kWh
Round trip efficiency	65%-70% AC/AC efficiency	70% (DC, 25℃ ambient)	70% (DC, 25℃ ambient)

7.2 Comparison between the production-phase and the use-phase impacts

A case for a power capacity of 8 GW and an energy capacity of 32 GWh is selected as an example to illustrate the methodology. Recall that:

- The GWP, PM, AP impacts are decided by a LCIA method called ReCiPe 2016 (H) where H stands for hierarchy case.
- The fossil fuel CED is decided by using Cumulative Energy Demand method embedded inside the Simapro.

Figure 7-4 to 7-7 show both the production-phase global warming potential (GWP) impacts for each of the three flow-battery types based on He [31], and the use-phase impacts for the batteries. The total impact is the combination of the two. Note, all results are normalized by the functional unit (kg CO_2eq/MWh) and based on the total electricity taken in over 20 years.

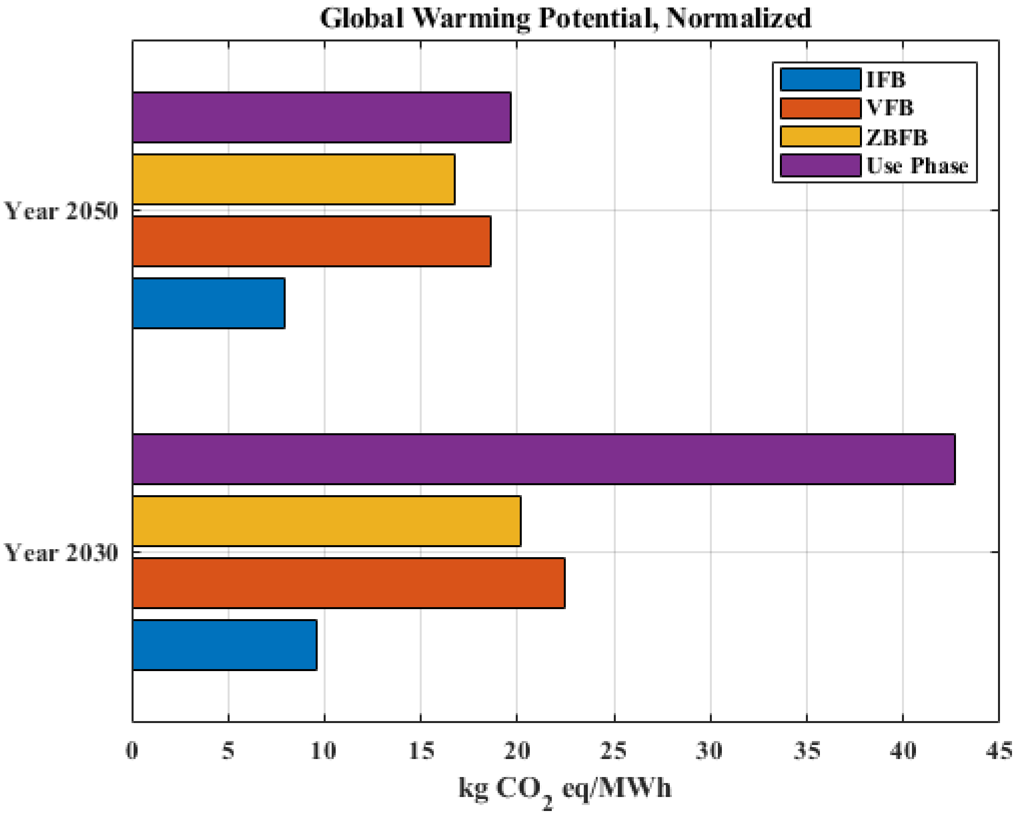


Figure 7-4 Life Cycle Impact for Three Batteries – Global Warming Potential Production phase [31] Use-phase [present thesis]

The GWP scores of all categories in 2030 are higher than in 2050. The use-phase impacts are higher than the production phase in both scenarios. The scenario with higher renewable penetration has less GWP impacts due to less fossil fuel usage. It directly induces less use-phase GWP impact than 2030 case. The total electricity taken by the battery systems has an influence on the result. For example, the electricity taken in by the batteries in 2050 is higher than 2030 as explained in Chapter 5. The two scenarios are assumed to have the same total battery storage capacity, but they are averaged by different overall electricity use, giving rise to the difference between the two scenarios.

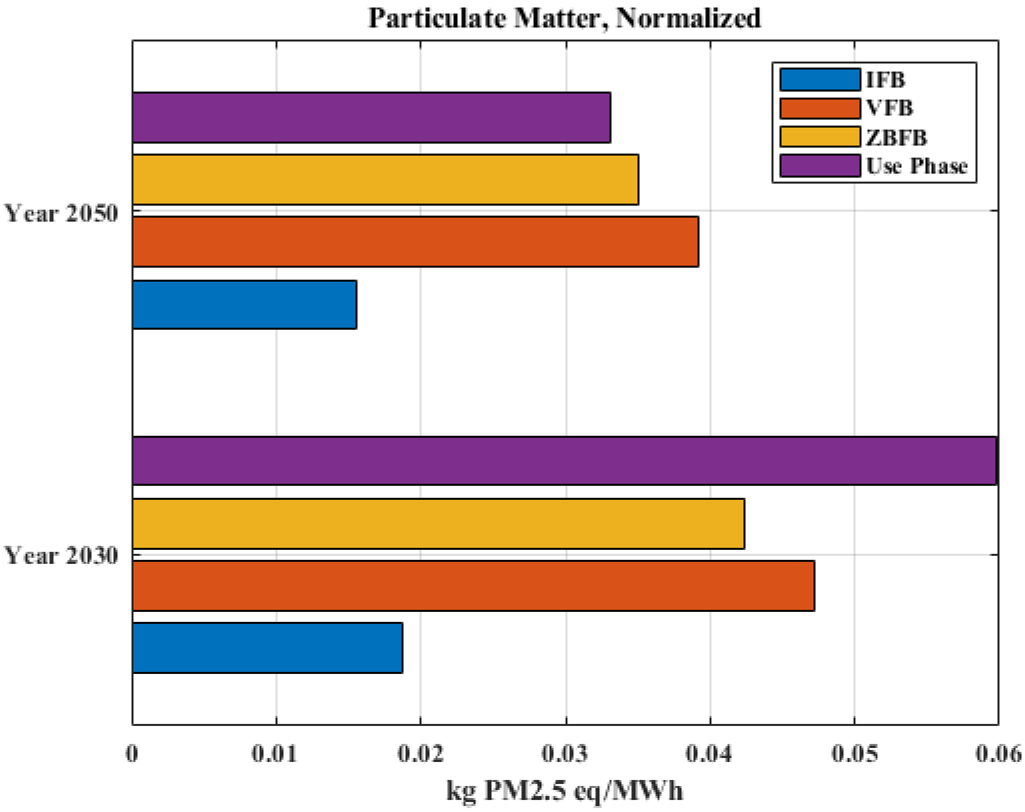


Figure 7-5 Life Cycle Impact for Three Batteries – Particulate Matter Production phase [31] Use-phase [present thesis]

The trend of PM is similar to that of GWP with one exception. In the 2050 case the use-phase impacts are smaller than two types of battery production phases. Nonetheless, the comparison of the 2050 and 2030 cases shows how significant the use-phase is in the overall life cycle of stationary batteries.

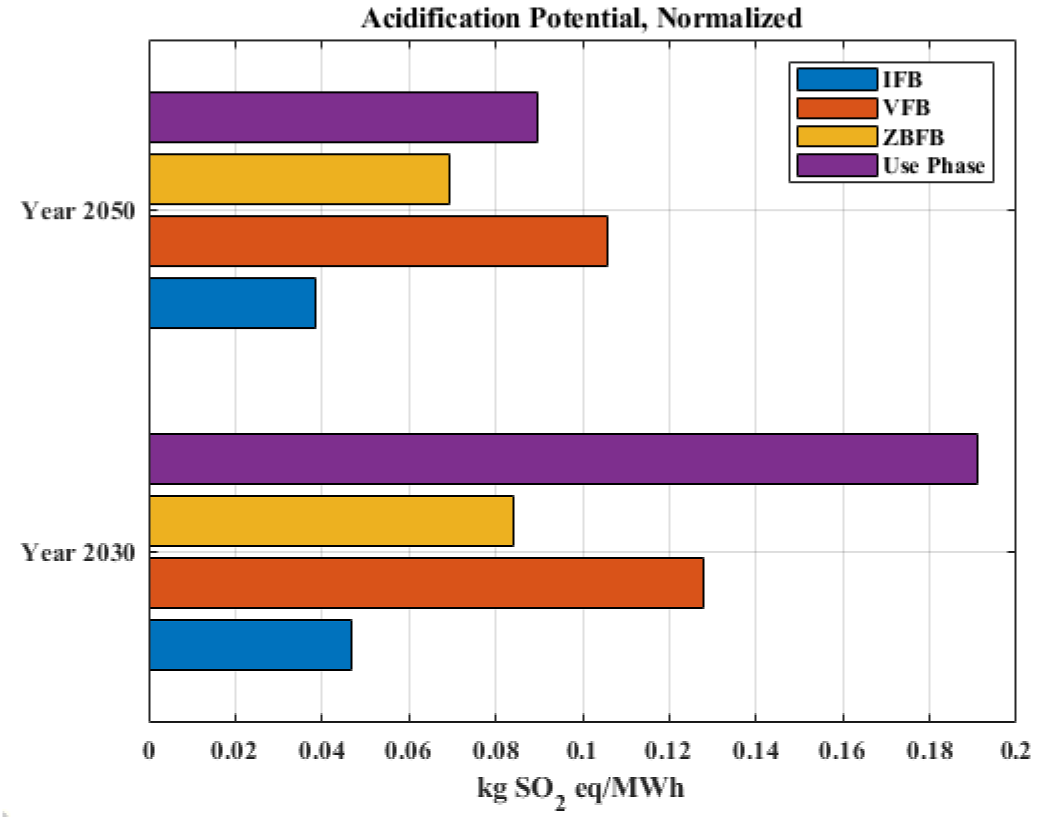


Figure 7-6 Life Cycle Impact for Three Batteries – Acidification Potential Production phase [31] Use-phase [present thesis]

For the AP impacts, the 2030 use-phase impacts are larger than all production phase impacts, and the 2050 use-phase impacts are smaller than the VRFB production phase impacts.

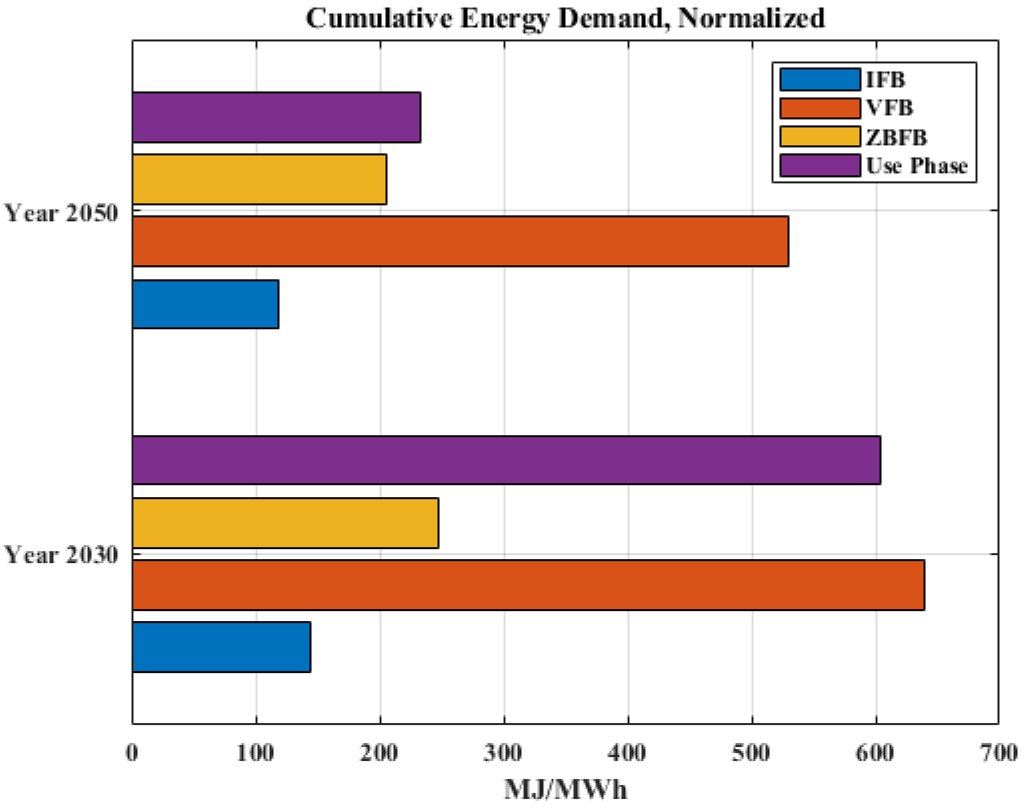


Figure 7-7 Life Cycle Impact for Three Batteries – Fossil Fuel-Cumulative Energy Demand
Production phase [31] Use-phase [present thesis]

Fossil fuel CED presents a slightly different behavior than the other three indicators. Because of the relatively high impacts from the production phase for VRFB, the use-phase impacts are smaller than the production phase even for the 2030 case. Moreover, the difference between the 2030 use-phase impacts and 2050 use-phase impacts is the largest among all indicators. The impact of 2030 is almost two times larger than for the year 2050. The reason that VFB has a high CED impact is associated with the electrolyte production process [31]. The vanadium pentoxide (V_2O_5) is a by-product of the production of steel, and steel production utilizes coal as the fuel. More discussion about this process can be found in He [31].

In order to establish the contribution to each indicator of the technology used to generate the electricity (natural gas, biogas, solar, wind, geothermal, and hydro), a detailed breakdown of the use-phase impact for each generator type is shown in the Figure 7-8:

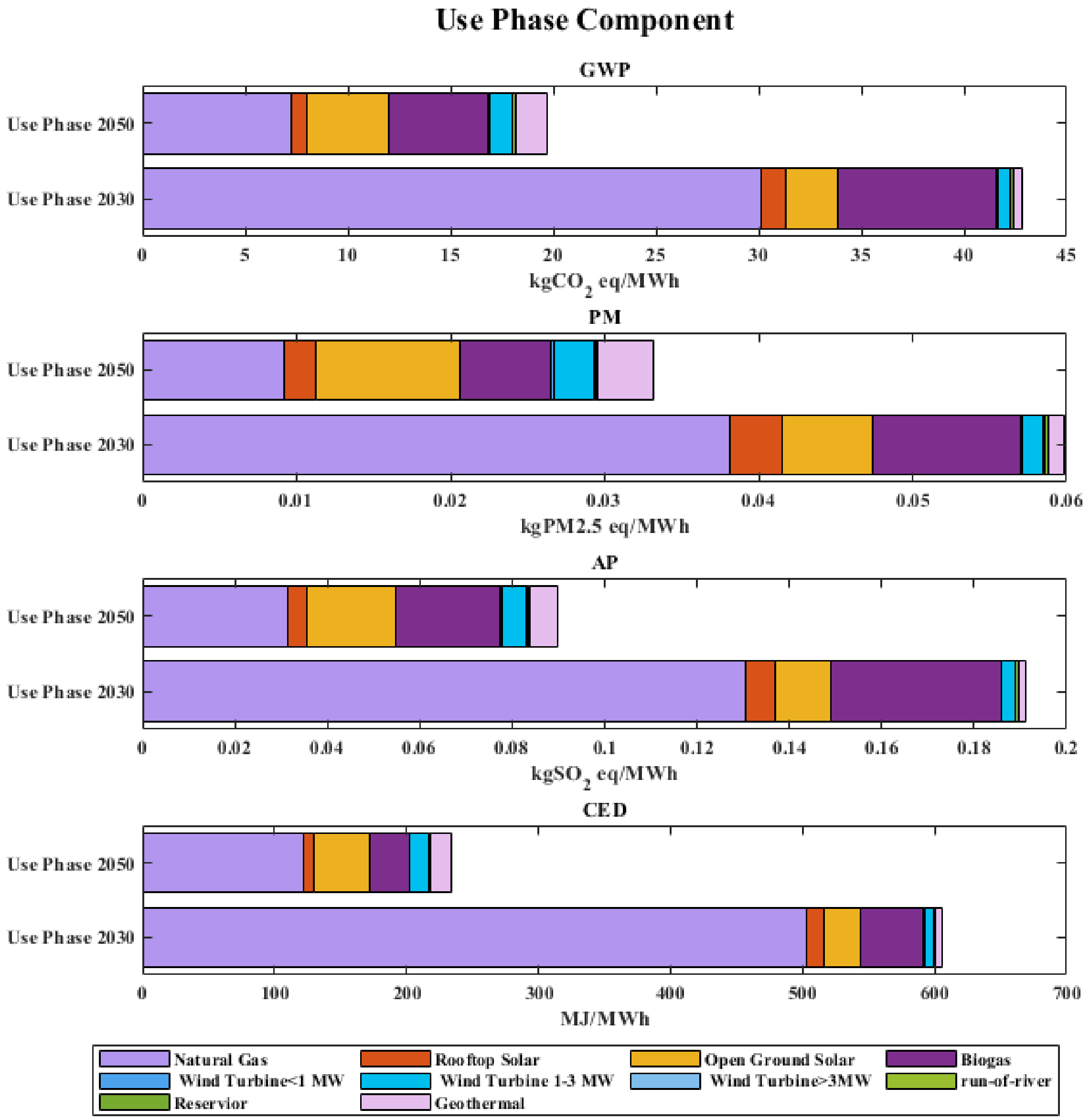


Figure 7-8 Use-Phase Detailed Explanation

Natural gas is the leading contributor for all indicators, followed by biogas. The reduction of natural gas burning substantially reduces emission GHGs and criteria pollutants. The increase in solar power results in a slight increase in emission. Even though operation of solar panels does not emit emissions, the production and material cost of the solar and wind plants contribute to the overall impacts.

7.3 Conclusions

While studies in the past tend to focus on the production phase impacts of battery systems, the use-phase impact could be as, or more significant than the production phase. For the two scenarios considered, the use-phase impacts double and, in some cases triple the environmental impacts of flow batteries.

The use-phase impacts depend on the grid composition. If applied to a clean grid (e.g., the 2050 scenario), the environmental impacts of the use-phase is generally comparative to the production phase. For the 2030 scenario, the use-phase impact is generally higher than the production phase impact. The GWP impacts of the use-phase doubles the production phase impacts. From the use-phase impacts, natural gas is the major contributor for all indicators in contrast to using a renewable source (e.g., wind, solar, hydro) for the generation of electricity.

Chapter 8: THRESHOLD OF FLOW BATTERY ESS FROM ENVIRONMENTAL ASPECTS

Task 4. Evaluate trade-offs of deploying flow batteries. Identify the existence of Maximum Allowable Energy Capacity (MAEC) and Maximum Benefit Energy Capacity (MBEC).

Chapter 5 constructed the life cycle inventory for the resources deployed in the energy system in preparation for performing a LCA, and suggested that the grid in the year 2030 with lower renewable penetration would not result in significant emission reduction by installing BESS compared to the 2050 grid. This chapter uses the 2050 grid scenario to explore benefit thresholds of flow battery systems.

- Expand VRFB and electric grid life cycle inventories with different energy-to-power ratios, and calculate the LCA impacts from both the battery side and grid side to identify the MAEC and MBEC.

8.1 LCA Expansion on the VRFBs

As shown in Chapter 6, the energy and power capacity of flow batteries can be scaled up separately. To examine the impacts of battery systems at grid-scale in the future, the inventory of VRFB with a power capacity of 500 kW and the energy capacity of 2 MWh was used as the basis for scaling up.

The size of the balance of plant is assumed to be scaled with the size of the cell stack. When the battery systems have different power and energy capacities, the electrolyte and cell stack ratio are determined by the overall energy and power capacity ratio.

Figure 8-1 shows, using PM as an example, the change of impacts with the change of energy capacity. Note that the impact of VRFB systems includes the production phase impacts as well as the use-phase impacts, and the energy capacity ranges from 0 to 2880 GWh. A closer look is shown in the next figure. Figure 8-2 presents the energy capacity change from 0 to 640 GWh, where the increment is 32 GWh. It can be seen that the use-phase impacts occupy half of the overall impacts when the capacity is small. With an increase of the energy capacity, the production phase impacts start to outweigh the use-phase impacts.

Unlike analyzing the production phase impacts of batteries, wherein the impacts are assumed to increase almost linearly with the units of batteries, the use-phase impacts behave differently. The dynamic of battery storage varies with the electric grid composition, and an increase of the BESS can induce less operation of peaker power plants and load-following power plants, which result in less natural gas consumption. For this reason, the use-phase impact is decreasing with the increase of BESS capacity. Figure 8-2 also shows that the natural gas impacts are eliminated with the growth of energy capacity, whereas the solar impacts start to be shown in large energy capacity use-phase impacts. Use-phase impacts play minor roles with the increase of energy capacities.

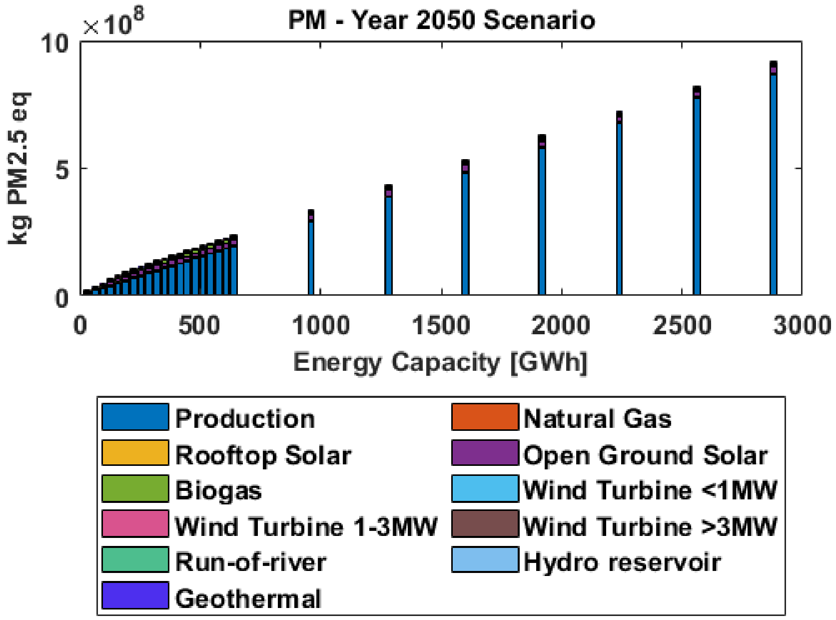


Figure 8-1 Particulate Matter Impacts Change with the Energy Capacity Change

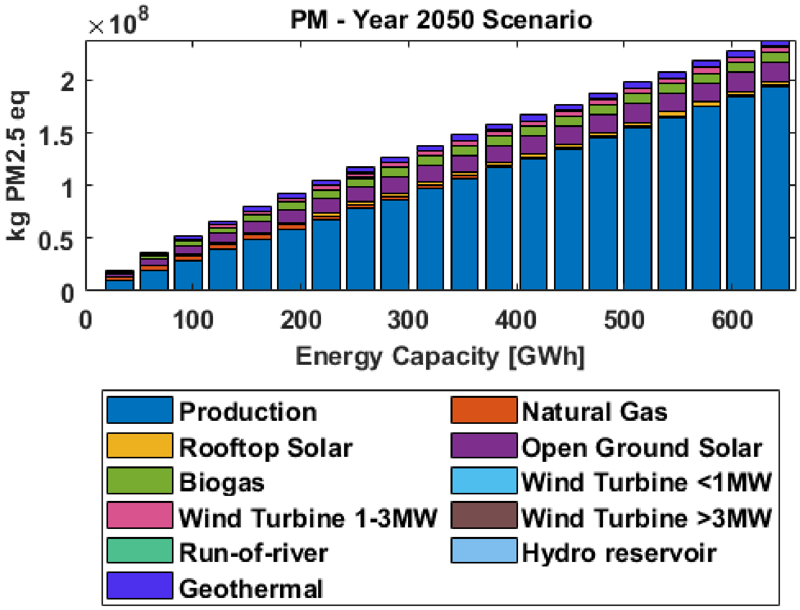


Figure 8-2 Impacts Change with Energy Capacity: 0 to 640 GWh

It is noteworthy that the open ground solar impact is increasing while the natural gas impact is decreasing. The impact of solar plants is associated with the wafer of the photovoltaic panel. Solar grade silicon is a primary source for the PM 2.5 [65]. The results also show that, for a high renewable penetration electricity grid, solar energy contributes a higher portion of total generation and that the production of metallurgical grade silicon contributes to the emission from the solar PV.

8.2 LCA on the electricity generation technologies

The benefit to the grid with battery energy capacity change is shown in Figures 8-3 and 8-4. The reduction in environmental impacts results from the decrease in natural gas and biogas use and the concomitant uptake of solar and wind energy stored by batteries. Various indicators have different trends in terms of benefits gained from the reduction of emissions. The benefits rise at first, and slow down as energy storage capacity grows above the lower bound of capacity. This behavior occurs since the majority of the increased renewable uptake is provided by the installation of the first units of energy storage capacity. Less and less surplus renewable energy is captured by every unit energy storage installed and the additional uptake of renewable energy does not significantly reduce the total emission releases. Additionally, the environmental impact of the grid is related to not only the emission from unit electricity produced from different technologies, but new installations of renewable energy. Although the emissions from fossil fuel generators are higher than renewable technologies, the electricity generated from solar and wind energy takes a more significant portion than that from biogas and natural gas combined cycle power plants in the future grid mix. In the dataset used in the inventory, the impact of solar or wind installation was averaged to electricity that they produced over lifetime. The large scale renewable capacity would influence the overall electricity emissions when taken the installation impact into consideration.

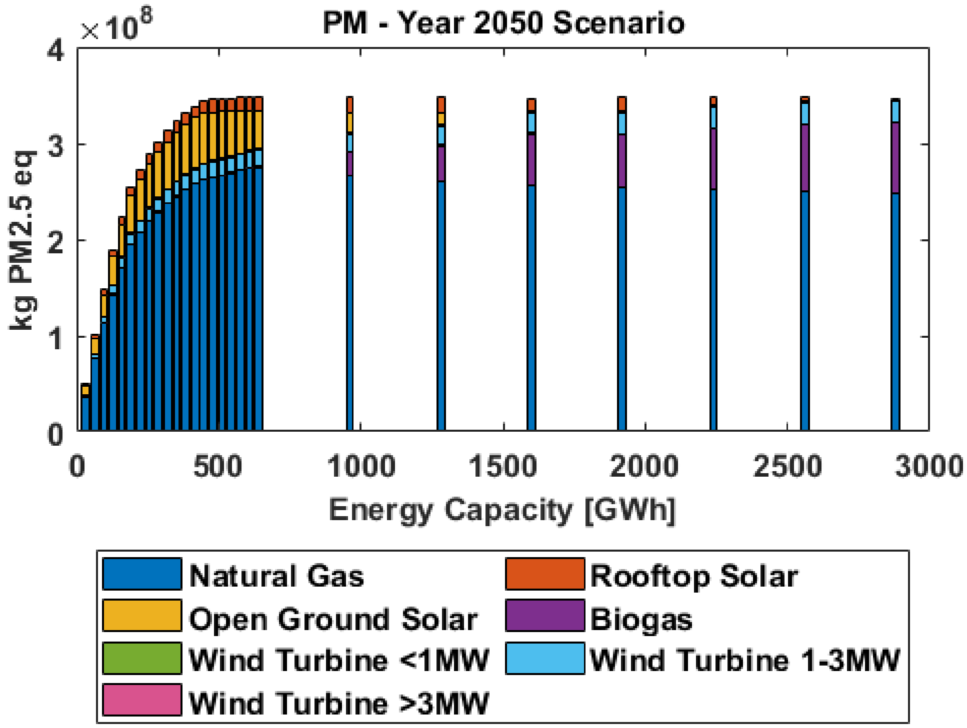


Figure 8-3 Electricity Grid Benefit Change with Energy Capacity Change

From Figure 8-4, the natural gas benefit tends to level off when the biogas reduction begins. The energy storage takes over a large portion of load-follower role so that natural gas usage is low.

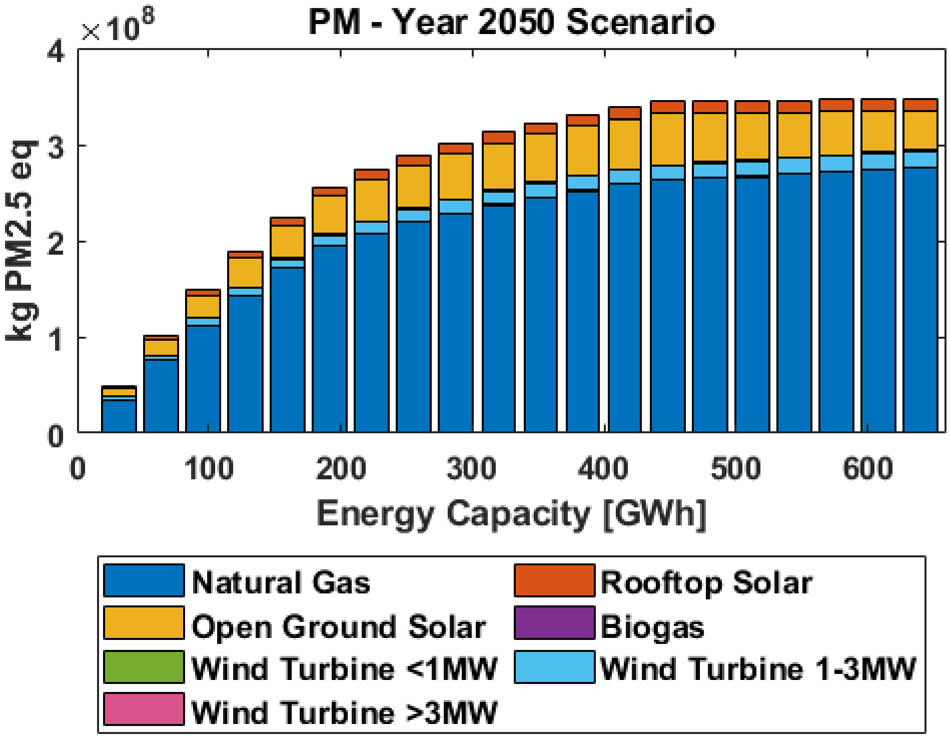


Figure 8-4 Electricity Grid Benefit Change with Energy Capacity Change 0-640 GWh

8.3 Maximum Allowable Energy Capacity (MAEC) and Maximum Benefit Energy Capacity (MBEC).

This section presents the comparison of the grid benefits against the environmental impacts associated with VRFB deployments as the capacities of battery systems scaled up. The net environmental effects for each environmental impact indicator – defined as the difference between the benefit and battery life cycle impact – is calculated for a fixed power of 36 GW and varied energy capacity for the energy storage system.

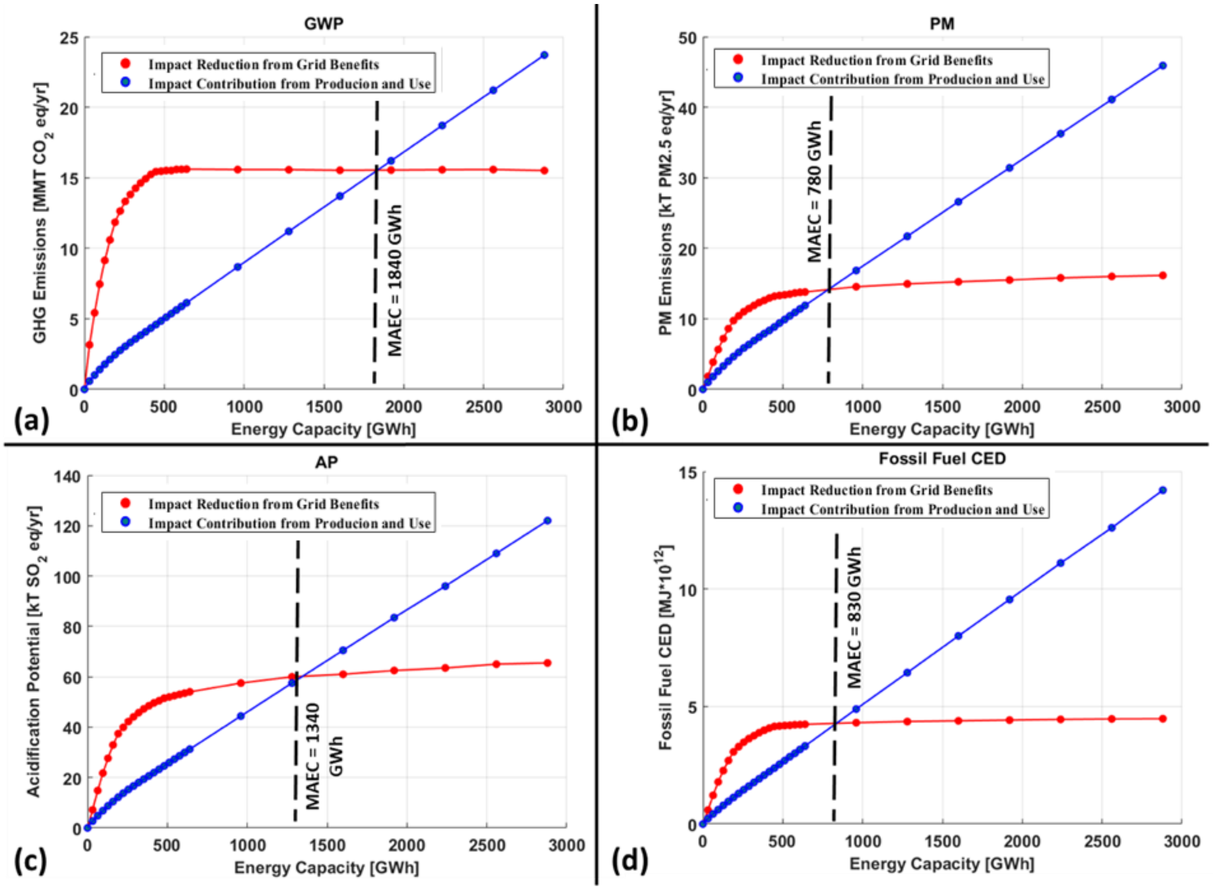


Figure 8-5 Threshold Trend for VRFB Systems of Power Capacity of 36 GW

Overall, the results reveal thresholds of battery capacities. Four impact categories considered show trade-off points where the benefit from the grid and the environmental impacts from the production + use phases cross over. The environmental impacts from the production + use phase increase almost linearly with the energy capacity of batteries. An increase in the energy to power ratio will result in the raise of the overall impacts.

The results presented in Figure 8-5 show two critical characteristics for all four environmental impact indicators. First, an energy capacity threshold occurs where the environmental impacts of the production + use phase equal the reduction in environmental impacts from improvements in electric grid operation. Referred to as the Maximum Allowable Energy Capacity (MAEC), this energy capacity value represents the amount above which deploying additional energy storage capacity results in a net environmental detriment for each indicator. Second, an energy capacity value occurs where the difference between the environmental benefits and environmental impacts reaches a maximum value. Referred as the Maximum Benefit Energy Capacity (MBEC), this energy capacity value represents the amount of energy storage that should be installed to maximize the net environmental utility of energy storage systems. The specific capacity value of the MAEC and the value of the MBEC varies among different environmental impact indicators. Because of different environmental impacts associated with the battery production + use phase and the grid, the trends and magnitudes of the net benefits vary for each indicator. To maximize the environmental benefit of installing batteries, the energy capacity should be approximately the thresholds of maximum “net benefit” for most of impact indicators. At the same time, the energy capacity should not exceed any indicator benefit limit or MAEC. Although all four of the indicators cannot reach the maximum value at a single value, a range of capacities occurs where the benefits can be optimum among all indicators. The range from 256 to 400 GWh is the suggested MBEC range for the grid studied in this power capacity (Figure 8-6). The gap between the MAEC and the MBEC threshold is generally more than 600 units of energy capacity. The MAEC energy capacity should be selected between 640 and 780 GWh to ensure to gain benefits among all indicators. For example, the PM threshold is around 780 GWh, and the CED threshold is around 960 GWh.

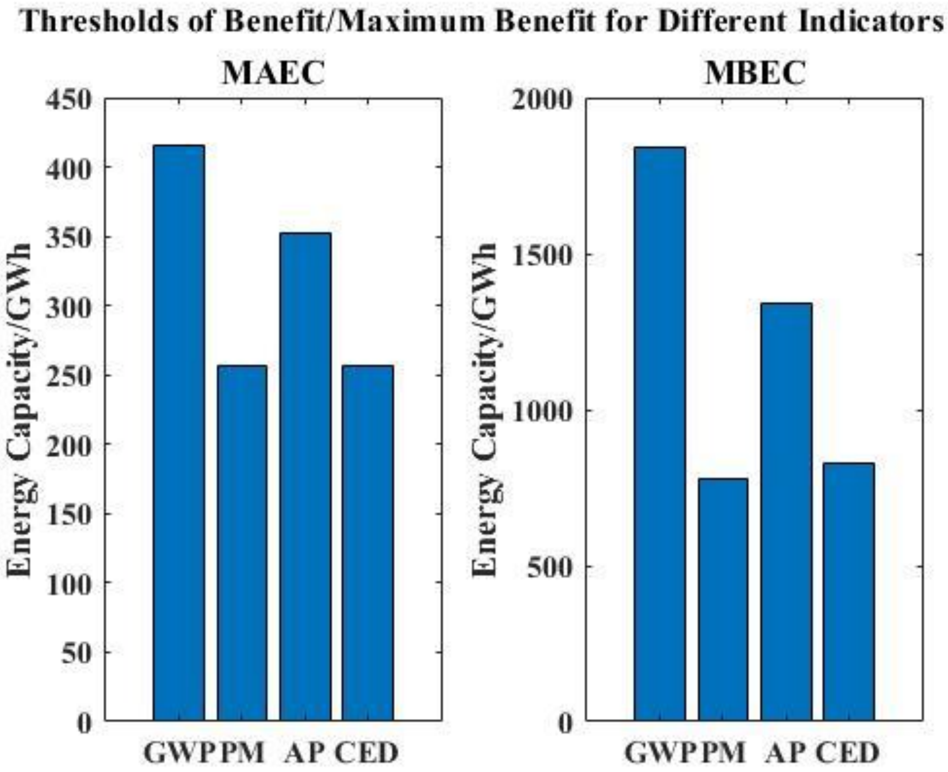


Figure 8-6 Thresholds of MAEC/MBEC for Different Indicators

8.4 Conclusions

Even in a grid with the same renewable capacity, the deployment of BESS will change the electric grid composition and change thereby the use-phase impact of the battery LCA. The use-phase impact of batteries is not only influenced by the grid, but also by the scale and size of the battery applied to the grid. The dynamic of grid must be considered in the use-phase analysis of batteries.

Different functions that battery may be assigned will give rise to different impacts as well.

The MBEC and MAEC varied among the four indicators. The range from 256 to 400 GWh is the suggested MBEC range for the grid studied in this power capacity. The MAEC energy capacity should be selected between 640 and 780 GWh to ensure to gain benefits among all indicators.

The MBEC and MAEC are influenced by many factors such as the grid composition and the LCI of batteries.

Chapter 9: POWER AND ENERGY THRESHOLD FOR VRFB IN CALIFORNIA GRID

Task 5. Determine the Maximum Allowable Energy Capacity (MAEC) and Maximum Benefit Energy Capacity (MBEC) for VRFB deployment in California.

In the last section, thresholds were shown to exist for a given power capacity of battery systems. The MBEC and MAEC were introduced to identify the point at which energy storage systems can bring net benefits to the environment. One of the main characteristics of flow batteries is that the power capacity and the energy capacity are decoupled. Different components in the battery are responsible for providing power and energy capacity so that they can be scaled up independently. The net environmental effect change with two independent variables is studied in this section. Two-dimensional contour maps of the net environmental effect for each indicator are presented. The energy and power capacity comprise the two independent variables selected, while the net environmental effect comprises the contour levels. The goal is to establish (1) whether a contour corresponding to a value of zero for the net environmental effect exists and if so, (2) at what power and energy capacity values does this occur. The contour represents the maximum threshold values for the power and energy capacities of the aggregated energy storage system beyond which installing more capacity would cause a net environmental detriment. Therefore, a maximum threshold should be set as the limiting capacity for energy storage deployment in sustainable energy system planning.

Note that the primary questions addressed in this thesis are the grid benefits and associated life cycle environmental impacts of flow batteries as the energy storage capacity increases to 2050 with 90% renewable penetration. While maintenance and replacement of battery components should be included during the lifetime of batteries, the lack of data on flow battery maintenance precludes this consideration in the present case.

9.1 Power and Energy Thresholds Maps

The results of mapping the benefit from the electric grid and the detriment from the production + use phases are presented below:

9.1.1 Global Warming Potential

The map of GWP net benefit presents the influence of expanding the power capacity and the energy capacity separately (Figure 9-1). As shown before, a significant GWP net benefit by large scale flow battery placement exists. The benefit increases sharply with every unit of the power capacity installed, before reaching the power capacity of 36 GW. It is similar to the trend of energy capacity, and the benefit increases relatively faster than that after the peak of 386 GWh. This behavior is associated with early uptakes and allows shifting of significant amounts of excess renewable energy. As more batteries are deployed, the amount of available excess energy for shifting is reduced, and the next incremental battery unit does not provide as much additional benefit. Simultaneously, the emission keeps increasing as more batteries are produced and deployed. Therefore, the net benefit has a limit as the energy capacity of the battery increases. If the energy capacities go beyond this limit, the GHG emissions from battery production and use exceed the GHG reductions from the additional renewable energy uptake. The net GHG emissions start to increase. The energy capacity limit raises with the increase of the power capacity when it is smaller than 50 GW, after which the limit becomes independent from the power capacity. Depending on the power capacity, the energy capacity coordinate for this threshold varies from 500 GWh to 1900 GWh. On one hand, the GHG reduction does not change with the power capacity increase. On the other hand, the unique configuration of the flow batteries determines that the environmental impacts of components in charge of the energy capacity out weight that of the parts corresponding to the power capacity.

Similar to the maximum net benefit shown in the fixed power capacity scenarios, an area of maximum benefit (most significant GHG reduction) is formed by the power capacity range from 32 to 116 GW and the energy capacity between 250 and 530 GWh on the map.

The color maps presented in Figures 9-2 (a), (b) examine the extent to which the GHG reductions due to energy storage application on the grid and GHG emissions due to production and use of storage devices, respectively, change with different combinations of power and energy capacity.

Figures 9-2 (a) shows the GHG emissions reduction due to the installation of flow batteries on an electric grid with a high penetration of renewable resources. The electric grid GHG reductions increase significantly as the first units of energy storage capacity are installed. With the increase of energy capacity and power capacity, the reductions level off as higher energy storage capacities are reached. It is shown that the impact of increasing energy capacity is more significant than the influence of power capacity.

Figures 9-2 (b) illustrates how GHG emissions from production and use as a function of energy storage capacity. These emissions are assumed to increase linearly with energy capacity. Increasing power capacity does not have a significant contribution to the production and use impacts for GWP.

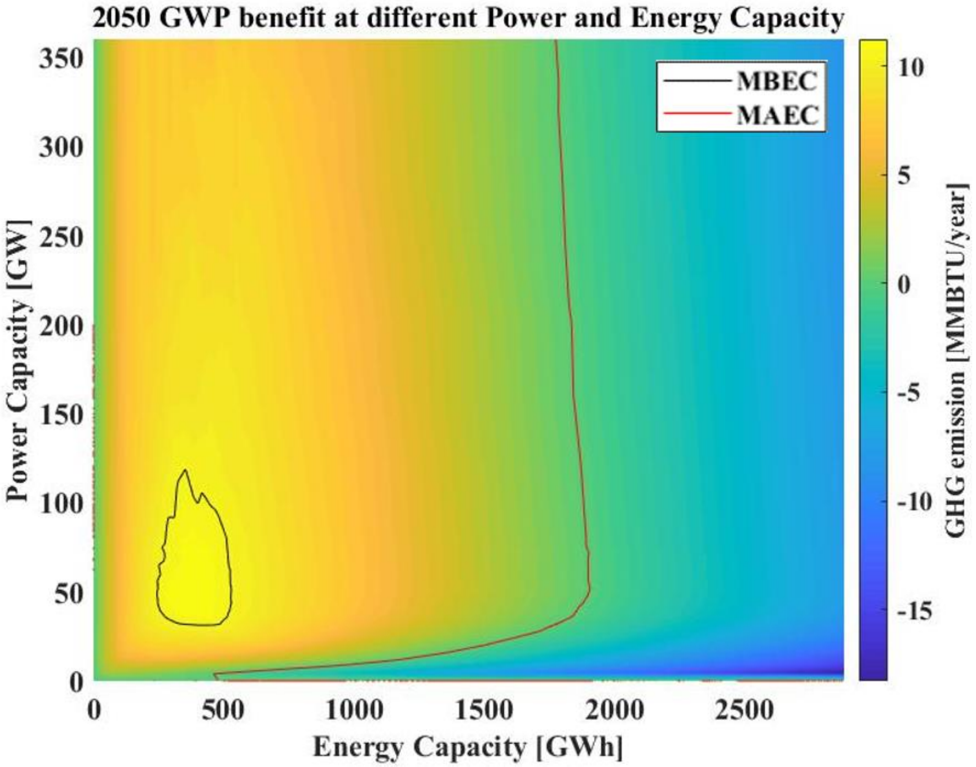
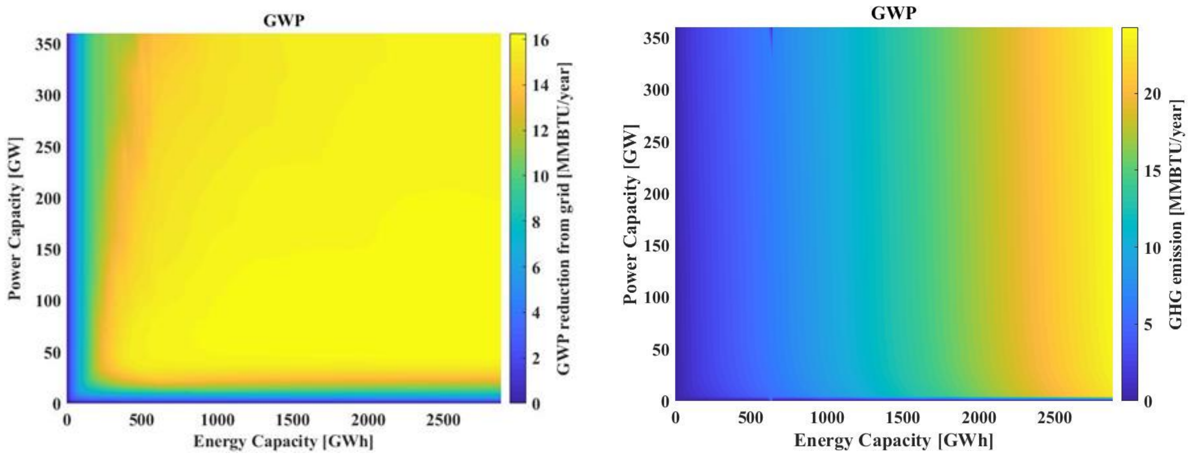


Figure 9-1 Map of Global Warming Potential Benefits



(a)

(b)

Figure 9-2 (a) Benefits from Global Warming Potential Reduction from the Grid; (b) Production + Use Emissions.

9.1.2 Particulate Matter

PM has a lower threshold in terms of the MAEC (Figure 9-3). The majority of fossil fuel used in the California electric grid is natural gas. The emission of particulates < 2.5 is 3.12e-06 kg/kWh; it is smaller than the PM from coal [66]. The lignite used in the Western Electricity Coordinating Council (WECC) has an emission of particulates < 2.5 as high as 0.0088 kg/kWh [67]. However, the most significant impact on the production and use phases corresponds to the V_2O_5 production process [31], which is a by-product in the steel making process, and is associated with a large amount of coal consumption. The PM 2.5 emission is high in the production + use phase so that the MAEC is relatively low compared to GWP. The difference in the GHG emission per kWh between natural gas and coal usage is not as big as it is for PM 2.5. For carbon dioxide, lignite coal burning will emit 1.19 kg/kWh while it is 0.34 for natural gas [67]. While the emissions are in the same order of magnitude, the difference for PM 2.5 is two orders of magnitude and explains why the threshold for GWP is higher than PM 2.5. For GWP, the reduction in natural gas emission can make up for the coal usage during the production + use phase.

There is an area of maximum benefit in the power capacity range from 32 to 116 GW and the energy capacity between 250 and 530 GWh. The MAEC varies from 200 to 800 GWh.

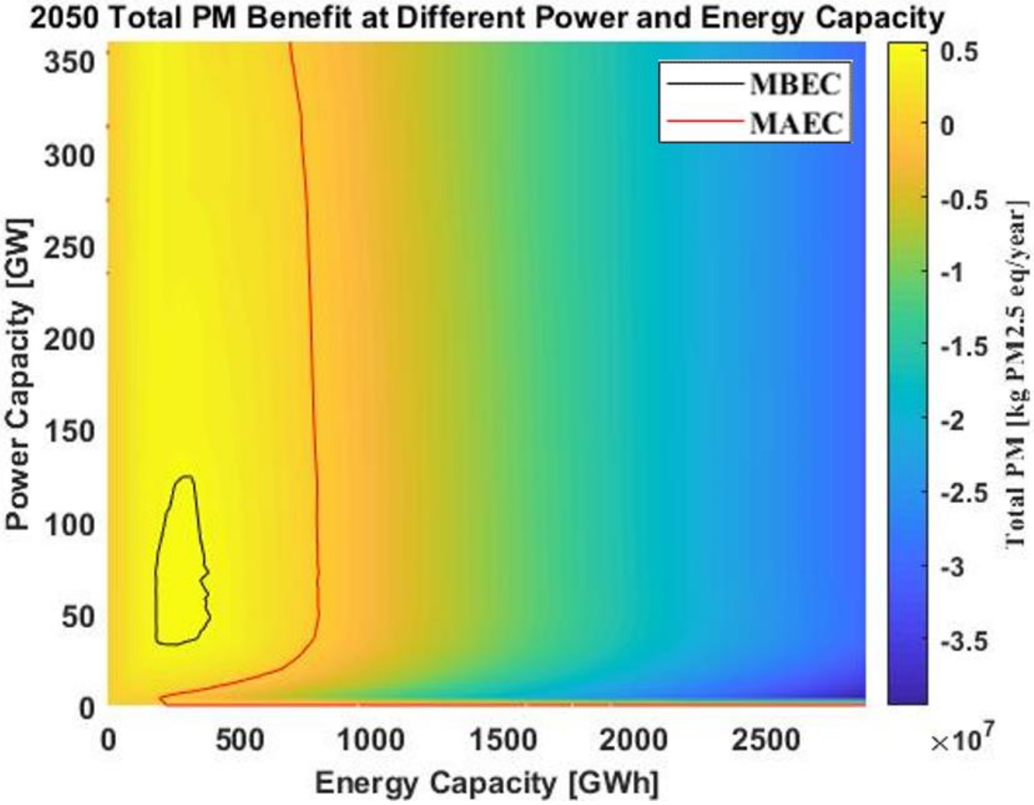
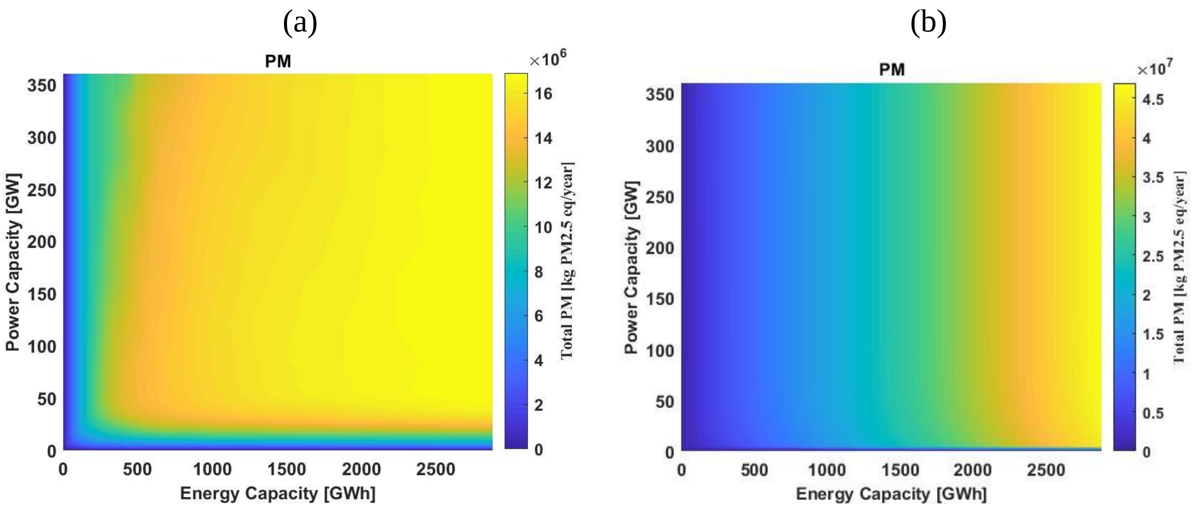


Figure 9-3 Map of Particulate Matter Benefits


(a)

(b)

Figure 9-4 (a) Benefits from Particulate Matter Reduction from the Grid; (b) Production + Use Emissions

9.1.3 Acidification Potential

AP has similar trends to the two above. In the production+use phase shown in Figure 9-6 (b), the energy capacity dominates the overall impacts. The power capacity only affects the overall impacts on a small scale. The benefit from the grid is similar to PM, where the power capacity has an influence when it is lower than 40 GW, and the energy capacity dominates the impacts afterwards. The overall benefit shown in the Figure 9-5 states an area of MAEC and MBEC for AP.

The most significant contributor of AP is SO_2, where the natural gas has an emission of 3.64e-06 kg/kWh [68] and the coal emission can be as high as 0.001 kg/kWh [67]. The results show that the natural gas used in the California grid is relatively clean compared to the grid where the battery production and use occurs. Since the difference between those two energy resources can be as high as two to three orders of magnitude, the MAEC of AP can be lower than the MAEC for GWP.

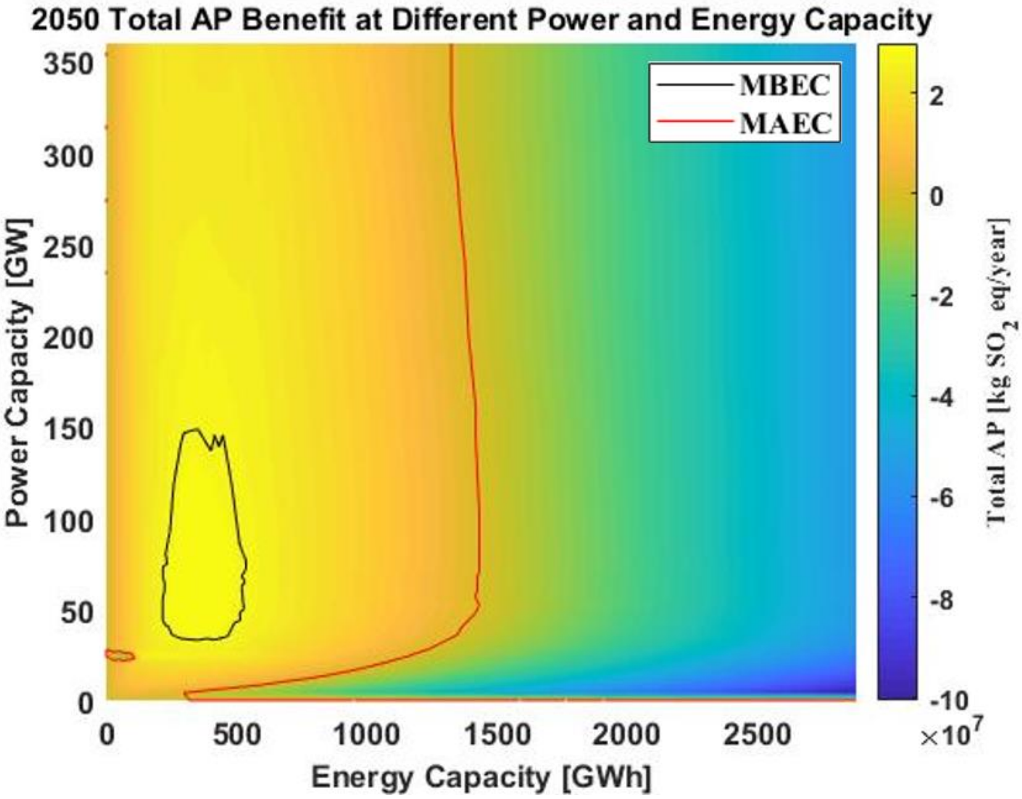


Figure 9-5 Map of Acidification Potential Benefits

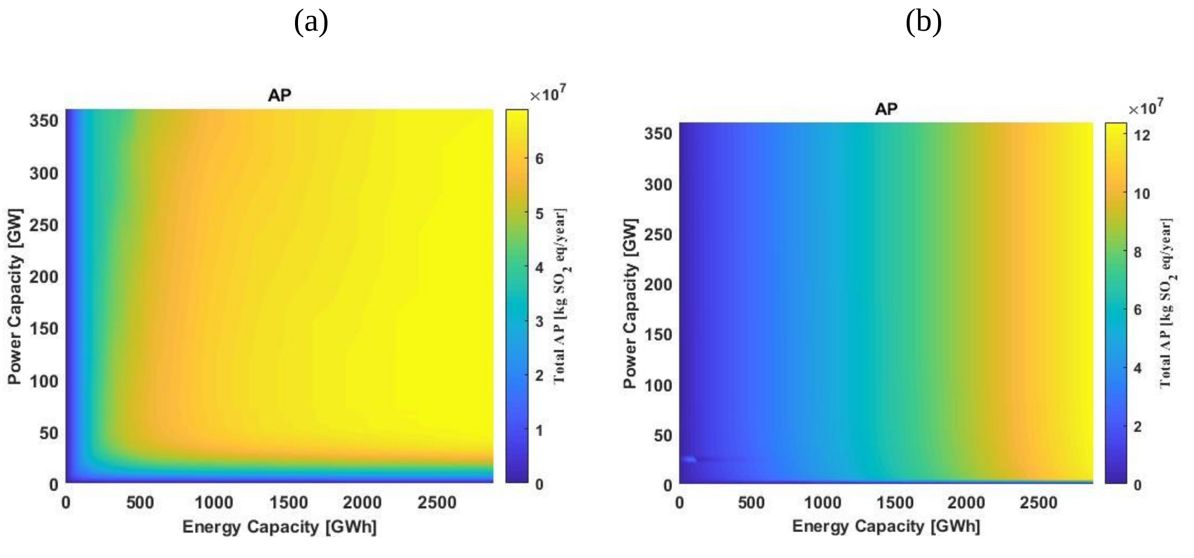

(a) (b)

Figure 9-6 (a) Benefits from Acidification Potential Reduction from the grid; (b) Production + Use Emissions.

9.1.4 Fossil Fuel Cumulative Energy Demand

As stated in Chapter 2, the fossil fuel CED is calculated by the higher heating value of the fuel. The direct coal consumption of the vanadium pentoxide production process [69] results in the CED's MAEC being relatively lower compared to other indicators. As evaluated in He [31], alternative V_2O_5 production scenarios varies significantly in terms of environmental impact [31]. As a result, the CED's MAEC could be substantially influenced by the choice of V_2O_5 process for this thesis. From the grid side, energy storage systems can bring a significant benefit in terms of cumulative energy demand. The reduction of fossil fuel has a substantial impact on the decreasing of CED since it is the only direct input for fossil fuel CED.

The trend of fossil fuel CED is similar to that of GWP (Figure 9-7). The most substantial reduction appears from 180 GWh to 420 GWh. The limit for the CED benefit is smaller than the limit of GWP. It is around 860 GWh.

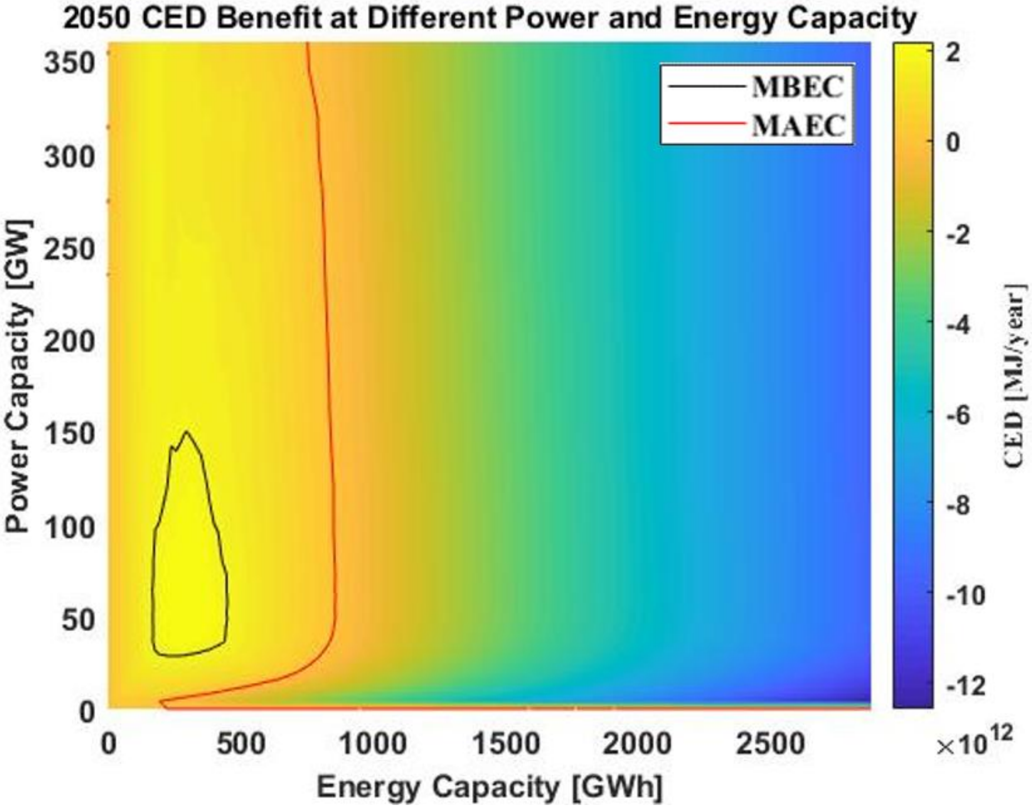
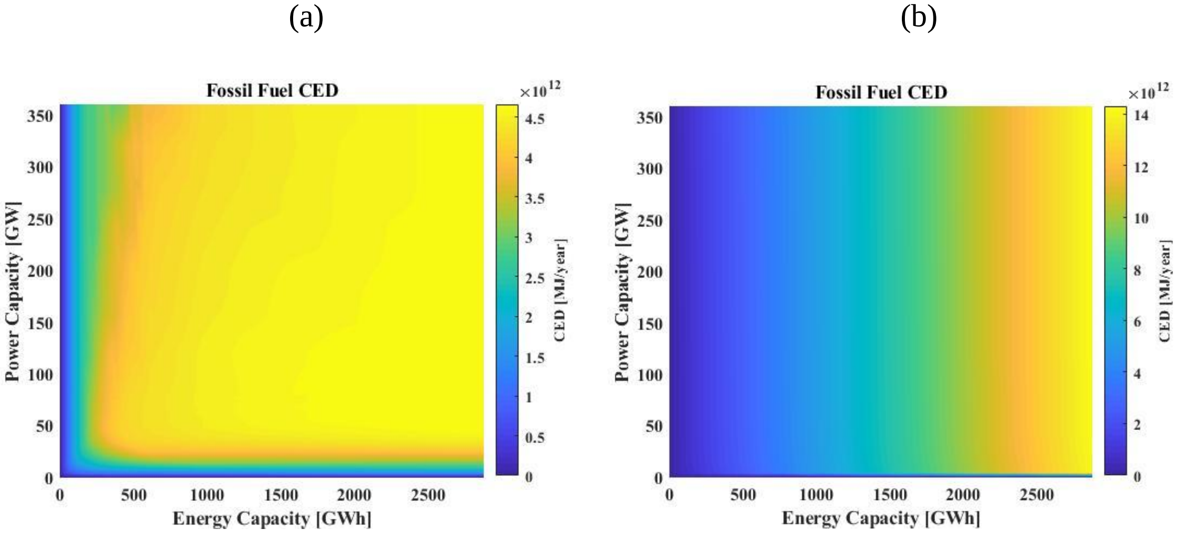


Figure 9-7 Map of Fossil Fuel-Cumulative Energy Demand Benefits


(a)

(b)

Figure 9-8 (a) Benefits from Fossil Fuel-Cumulative Energy Demand Reduction from the grid; (b) Production + Use Emissions.

9.2 Energy-and-Power Ratio Prediction

The map presented in Figure 9-9 can be used to predict the suitable energy-to-power ratio in order to obtain the most significant net benefit by installing the flow batteries. It can be used for the companies to decide the direction of enhancing energy density in the future.

Figure 9-9 indicates that the appropriate range of the energy-to-power ratio is from 3 to 15 based on the production [31] and use phase inventories assumed for the VRFB flow battery in this example. The current energy-to-power ratio is 2-8 h. It is also important to note that the range of the energy-to-power ratio in this map varies from 0.89 to 89 h, which is not practical in a real situation. However, the result suggests that there is a reasonable range for the development of VRFB. However, it needs to be kept in mind that a high energy-to-power ratio cannot ensure a significant overall environmental benefit.

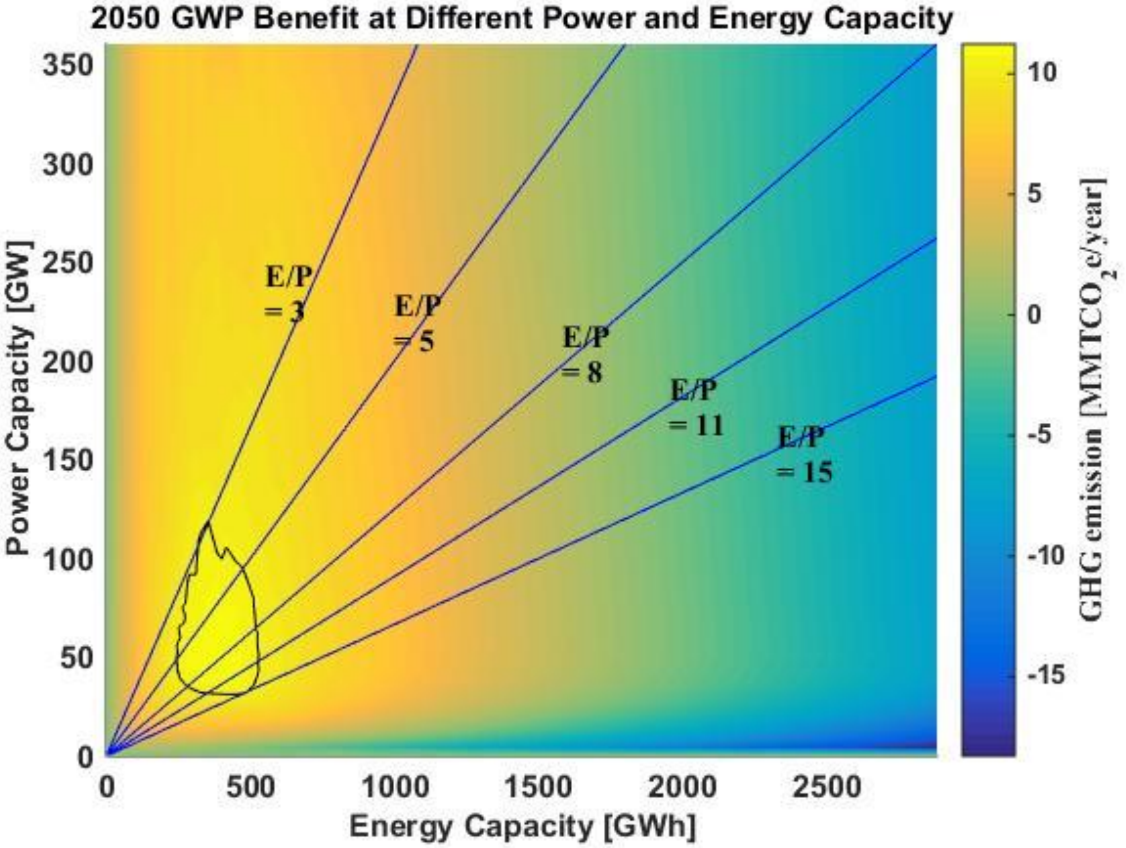


Figure 9-9 Energy-to-Power Ratio Range

9.3 Conclusions

The energy capacity dominates both the grid and the VRFB life cycle impacts within the capacities range studied. Power capacity plays a more important role when the overall power capacity is small (usually smaller than 40 GW). The range of power and energy capacities for significant overall benefits is similar for all four indicators. The power capacity of 40 to 100 GW and the energy capacity around 500 GWh is the suitable range of MBEC among all four indicators.

Technically speaking, the MBEC should be a point in the figures rather than a region since the MBEC represents the point where the combination of power capacity and energy capacity can bring the most significant net benefit to the environment. Instead, the figures present a region within which the power and energy capacities result in a large benefit and reveals, as a result, that the power capacity does not have an as strong impact as the energy capacity.

The maximum capacity thresholds exist between energy capacities of 500 to 1900 GWh for GWP, 215 to 865 GWh for CED, 200 to 800 GWh for PM, and 300 to 1425 GWh for AP depending on the power capacity. The energy capacity should be selected between 640 and 780 GWh to ensure to gain benefits among all indicators.

The threshold will be affected by improvements in both the battery production and use phases. For example, during the completion of this thesis, improvements in the VRFB were made. In addition, maintenance and replacement of battery components during the use-phase and the recycling phase will affect the capacity thresholds of the grid. While recycling can recover materials and battery components, the processing of recycled materials may increase electricity consumption and emissions.

Chapter 10: SUMMARY AND CONCLUSIONS

10.1 Summary

The work in this thesis has two contributions: 1) The dynamic of the electric grid that can reflect the battery system impact should be considered in stationary battery use-phase analysis, 2) the threshold that exists for deploying large scale battery energy storage systems from environmental perspectives. GWP, PM, AP, FF-CED impact categories were considered as examples in this case.

The impacts of the use-phase of batteries depend on the electricity mix. The grid mix with low renewable penetration results in higher use-phase impacts than its production phase impacts. A high renewable penetration grid such as 90 % renewable can reduce the use-phase impacts to be on the same order as production phase impacts. Besides renewable penetration effects, the size and scale of BESS will have influences on the use-phase impact as well. Large-scale of battery storage system deployment will change the grid configuration. The natural gas consumption drops with more renewable energy stored and discharged by battery systems. The use-phase impacts will play less essential roles in the life cycle with the increase of energy capacity of battery systems.

The comparison of VRFBs and the electricity grid LCA can assist to determine the net benefit that VRFB systems can yield. The impact of production and use of batteries should be taken into account when determining the benefit of BESS to the grid. Net benefits occur from reduced natural gas use through the capture of additional excess renewable energy provided by each additional increment of energy storage capacity installed on the grid. However, this incremental benefit diminishes as more energy capacity is installed in the system.

A Maximum Allowable Energy Capacity (MAEC) exists above which deploying additional energy storage capacity will contribute to a net environmental detriment for each corresponding indicator. There is a Maximum Benefit Energy Capacity (MBEC) to maximize the net environmental benefit from the energy storage systems. Those two thresholds would be helpful in deciding the power and energy capacity for BESS. Thresholds of BESS differs from indicators depends on the characteristic of the BESS and the grid. However, there is a range for the system to have benefit in all indicators.

10.2 Conclusions:

- The life cycle environmental impact is comprised of various phases. The use-phase impact can outweigh that of the production phase in a fossil fuel intensive grid, whereas the production phase could dominate the overall impact at high renewable penetration scenario.

  The impact from the battery use-phase depends on the role battery technology plays in the system as well as the renewable penetration of the electric grid. In a grid with 50% renewable penetration, the use-phase impact like GWP, AP could still be as high as that of the production phase. When the grid has a high renewable penetration as 90%, the environmental impacts of the use-phase is generally higher than the production phase.
- The changing dynamics of the grid with the integration of large scale of battery storage systems has to be considered when analyzing the use-phase of stationary battery systems. A large scale battery storage system will affect the dynamics of electric grid. With the same prediction of the composition of renewable capacity and fossil fuel, a large scale of BESS will change the usage of fossil fuels and affect the use-phase impact. The use-

phase analysis should consider the change that battery system would bring to the grid especially when renewable penetration of the grid is high.

- The life cycle impact of battery systems needs to be considered when determining the suitable scale of battery energy storage system in the electric grid.

  Utilizing battery energy storage systems can integrate more renewable energy and mitigate the impact of fossil fuels. However, the production of battery systems has environmental impact as well. It will deduct the overall benefit the energy storage systems can bring to the grid.
- A threshold exists above which the application of additional battery systems no longer benefits the grid.

  Thresholds of power and energy capacities exist for maximizing the benefit that flow-battery energy storage systems can (1) provide to the grid, and (2) ensure net environmental benefits.
- While the threshold of BESS differs from one indicator to another, a capacity range of BESS for the grid can have benefit among all indicators. A Maximum Benefit Energy Capacity exists to maximize the net environmental benefit from the energy storage systems.

  Given the assumptions made for the current study, the power capacity of 40 to 100 GW and the energy capacity around 500 GWh is the suitable range of MBEC among all four indicators. The maximum capacity thresholds exist between energy capacities of 500 to 1900 GWh for GWP, 215 to 865 GWh for CED, 200 to 800 GWh for PM, and 300 to 1425 GWh for AP depending on the power capacity. The energy capacity should be selected between 640 and 780 GWh to ensure to gain benefits among all indicators. The result is sensitive to the grid as well as the battery system.

10.3 Implications

This section interprets the implications of results obtained in previous chapters. There are two inferences from this thesis which can be used for academic, policymakers and so on.

As stated in Chapter 2, the use-phase definitions for stationary batteries are non-consistent in the literature. System boundaries and functional units for the use-phase are different from the production phase of products. The functional unit should not only consider the energy capacity of BESS. It could be the overall electricity that battery can output during its lifetime. The use-phase inventory is normally built by average electricity composition over a year. However, the electricity system will change with large scale of battery deployments. The combination of grid simulation tool with the life cycle assessment can be favorable to large scale battery systems analysis. The grid benefit map and the use-phase impacts with battery capacities change all reflect the importance of electricity mix variation in the determination of BESS emissions.

10.4 Limitations and Future Work

It should be pointed out that maintenance and replacement of certain parts of batteries should be included during the lifetime of batteries. This part is not included because the lack of data of flow batteries maintenance.

The primary assumption in this thesis is to scale up the flow battery using existing technology. Only one type of technology is scaled up to meet the demand of all BESS, without considering the market share and the maturity of the technology. Flow batteries are a promising technology for providing load shift and renewable self-consumption services. However, they are still at its early commercial stage. Their market share is small compared to lithium-ion batteries. The idea of combining grid simulation tools to reflect the dynamic of the grid mix within LCA and grid benefit determination could be applied to Li-ion batteries. Similar thresholds for Li-ion batteries could be decided. This method is not limited in the area of stationary batteries. It can be used in electric vehicles when the vehicle-to-grid (V2G) technology is more popular to influence the grid in the future. For a more realistic scenario, market share could be taken into consideration for each type of stationary batteries. Life cycle inventory of different batteries could be involved. As for the grid benefit side, roles that the battery storage system play can vary too. Other than renewable self-consumption, other types of energy storage technologies could serve roles like frequency regulation and other power services. This method can be implicated to much broader electric systems.

Furthermore, it should be noted that the recycling stage of battery life are not considered in this study and will affect the capacities thresholds of the grid. Recycling stages can reduce material usage by recovering the materials and battery components. Simultaneously, processing recycled materials will cost extra energy or electricity consumption and then increase the emissions. A trade-off needs to be counted if recycling data are available.

During the completion period of this thesis, the VRFB prototype used in this study has been improved for higher energy density battery products. Sensitivities study about the product or component improvement should be considered in the future study.

In the electricity grid modeling, even though the model considered the dynamic of battery systems. It does not include the aging and cycle life change of batteries and the operation parameter influence of the batteries. In the future, data could be collected to take cycle life changes of the batteries into consideration.

REFERENCES

[1] "Bill Text - SB-32 California Global Warming Solutions Act of 2006: emissions limit." [Online]. Available: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB32. [Accessed: 03-Nov-2017].

[2] "Bill Text - SB-100 California Renewables Portfolio Standard Program: emissions of greenhouse gases." [Online]. Available: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100. [Accessed: 10-Sep-2018].

[3] M. A. Gonzalez-Salazar, T. Kirsten, and L. Prchlik, "Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables," Renew. Sustain. Energy Rev., vol. 82, no. July 2017, pp. 1497–1513, 2018.

[4] California Independent System Operator, "Energy and environmental goals drive change," 2016. [Online]. Available: www.caiso.com. [Accessed: 05-Jun-2019].

[5] D. Rastler and Electric Power Research Institute, "Project Manager Electricity Energy Storage Technology Options," Epri, vol. 64, no. 2–3, p. 170, 2010.

[6] U.S. Energy Information Administration, "U.S. Battery Storage Market Trends," 2018. [Online]. Available: www.eia.gov. [Accessed: 12-Jun-2019].

[7] I. M. S. Board, "Electrical Energy Storage White Paper," Bus. Strateg. Environ., vol. 2, no. S1, pp. 1–3, 1993.

[8] Pacificorp, "Energy Storage Technology Review," 2017. [Online]. Available: http://www.pacificorp.com/content/dam/pacificorp/doc/Energy_Sources/Integrated_Resource_Plan/2017_IRP/10018304_R-01-D_PacifiCorp_Battery_Energy_Storage_Study.pdf.

[9] IRENA, "Electricity storage and renewables: Costs and markets to 2030," Electricity-storage-and-renewables-costs-and-markets, 2017. [Online]. Available: http://irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets.

[10] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," Renew. Sustain. Energy Rev., vol. 42, pp. 569–596, Feb. 2015.

[11] L. Li *et al.*, "A stable vanadium redox-flow battery with high energy density for large-scale energy storage," Adv. Energy Mater., vol. 1, no. 3, pp. 394–400, 2011.

[12] M. Hiremath, K. Derendorf, and T. Vogt, "Comparative life cycle assessment of battery storage systems for stationary applications," Environ. Sci. Technol., vol. 49, no. 8, pp. 4825–4833, 2015.

[13] A. R. Dehghani-Sanij, E. Tharumalingam, M. B. Dusseault, and R. Fraser, “Study of energy storage systems and environmental challenges of batteries,” Renew. Sustain. Energy Rev., vol. 104, pp. 192–208, Apr. 2019.

[14] E. S. Hittinger and M. L. Azevedo, “Bulk Energy Storage Increases United States Electricity System Emissions,” Environ. Sci. Technol, vol. 49, p. 3210, 2015.

[15] “ISO - ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework.” [Online]. Available: https://www.iso.org/standard/37456.html. [Accessed: 14-Jan-2020].

[16] B. Tarroja, "Characterization and Evaluation of Utility-Scale Intermittent Renewable Generation Variations and Implications for Electric Grid Load Balancing." Order No. 1493923, University of California, Irvine, 2011.

[17] U.S. Energy Information Administration, “Annual Energy Outlook 2019 with projections to 2050,” 2019. [Online]. Available: www.eia.gov/aeo. [Accessed: 30-Aug-2019].

[18] “Bill Text - AB-2514 Energy storage systems.” [Online]. Available: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200920100AB2514. [Accessed: 20-Nov-2019].

[19] “Bill Text - AB-2868 Energy storage.” [Online]. Available: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB2868. [Accessed: 20-Nov-2019].

[20] M. Bartolozzi, “Development of redox flow batteries. A historical bibliography,” J. Power Sources, vol. 27, no. 3, pp. 219–234, Sep. 1989.

[21] M. Skyllas-Kazacos, M. H. Chakrabarti, S. A. Hajimolana, F. S. Mjalli, and M. Saleem, “Progress in Flow Battery Research and Development,” J. Electrochem. Soc., vol. 158, no. 8, p. R55, 2011.

[22] Redflow, “Grid-Scale – Redflow.” [Online]. Available: https://redflow.com/applications/grid-scale/. [Accessed: 20-Nov-2019].

[23] L. W. Hruska, “Investigation of Factors Affecting Performance of the Iron-Redox Battery,” J. Electrochem. Soc., vol. 128, no. 1, p. 18, 1981.

[24] D. A. Notter *et al.*, “Contribution of Li-ion batteries to the environmental impact of electric\nvehicles,” Environ. Sci. Technol., vol. 44, no. 19, p. 43, 2010.

[25] G. Majeau-Bettez, T. R. Hawkins, and A. H. StrØmman, “Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles,” Environ. Sci. Technol., vol. 45, no. 10, pp. 4548–4554, 2011.

[26] M. Zackrisson, L. Avellán, and J. Orlenius, “Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles-Critical issues,” J. Clean. Prod., vol. 18, no. 15, pp.

1519–1529, 2010.

[27] S. Amarakoon, J. Smith, and B. Segal, “Application of Life- Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles,” pp. 1–119, 2013.

[28] C. J. Rydh, “Environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage,” J. Power Sources, vol. 80, no. 1–2, pp. 21–29, Jul. 1999.

[29] S. Weber, J. F. Peters, M. Baumann, and M. Weil, “Life Cycle Assessment of a Vanadium Redox Flow Battery,” Environ. Sci. Technol., vol. 52, no. 18, pp. 10864–10873, Sep. 2018.

[30] P. L’Abbate, M. Dassisti, and A. G. Olabi, “Small-Size Vanadium Redox Flow Batteries: An Environmental Sustainability Analysis via LCA,” Springer, Cham, 2019, pp. 61–78.

[31] H. He, “Advancing Sustainability Assessment of Renewable Energy System Production,” University of California, Irvine, 2020.

[32] S. Longo, V. Antonucci, M. Cellura, and M. Ferraro, “Life cycle assessment of storage systems: the case study of a sodium/nickel chloride battery,” J. Clean. Prod., vol. 85, pp. 337–346, Dec. 2014.

[33] M. Baumann, J. F. Peters, M. Weil, and A. Grunwald, “CO $_2$ Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications,” Energy Technol., vol. 5, no. 7, pp. 1071–1083, Jul. 2017.

[34] L. Oliveira, M. Messagie, J. Mertens, H. Laget, T. Coosemans, and J. Van Mierlo, “Environmental performance of electricity storage systems for grid applications, a life cycle approach,” Energy Convers. Manag., vol. 101, pp. 326–335, 2015.

[35] M. A. Pellow, H. Ambrose, D. Mulvaney, R. Betita, and S. Shaw, “Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues,” Sustain. Mater. Technol., p. e00120, Jul. 2019.

[36] T. S. Schmidt *et al.*, “Additional Emissions and Cost from Storing Electricity in Stationary Battery Systems,” Environ. Sci. Technol., vol. 53, no. 7, pp. 3379–3390, 2019.

[37] L. Vandepaer, J. Cloutier, C. Bauer, and B. Amor, “Integrating Batteries in the Future Swiss Electricity Supply System: A Consequential Environmental Assessment,” J. Ind. Ecol., vol. 23, no. 3, pp. 709–725, Jun. 2019.

[38] N. A. Ryan, Y. Lin, N. Mitchell-Ward, J. L. Mathieu, and J. X. Johnson, “Use-Phase Drives Lithium-Ion Battery Life Cycle Environmental Impacts When Used for Frequency Regulation,” 2018.

[39] P. Denholm and G. L. Kulcinski, “Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems,” Energy Convers. Manag., vol. 45, no.

13–14, pp. 2153–2172, Aug. 2004.

[40] H. Elzein, T. Dandres, A. Levasseur, and R. Samson, “How can an optimized life cycle assessment method help evaluate the use phase of energy storage systems?,” J. Clean. Prod., 2019.

[41] L. Oliveira, M. Messagie, J. Mertens, H. Laget, T. Coosemans, and J. Van Mierlo, “Environmental performance of electricity storage systems for grid applications, a life cycle approach,” Energy Convers. Manag., vol. 101, pp. 326–335, Sep. 2015.

[42] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” Renew. Sustain. Energy Rev., vol. 28, pp. 555–565, Dec. 2013.

[43] N. Y. Mulongo and P. Kholopane, “A sustainability assessment of electricity supply systems,” 2018 5th Int. Conf. Ind. Eng. Appl. ICIEA 2018, pp. 565–572, 2018.

[44] R. Turconi, D. Tonini, C. F. B. Nielsen, C. G. Simonsen, and T. Astrup, “Environmental impacts of future low-carbon electricity systems: Detailed life cycle assessment of a Danish case study,” Appl. Energy, vol. 132, pp. 66–73, Nov. 2014.

[45] R. Garcia, P. Marques, and F. Freire, “Life-cycle assessment of electricity in Portugal,” Appl. Energy, vol. 134, pp. 563–572, Dec. 2014.

[46] V. Kouloumpis, L. Stamford, and A. Azapagic, “Decarbonising electricity supply: Is climate change mitigation going to be carried out at the expense of other environmental impacts?,” Sustain. Prod. Consum., vol. 1, pp. 1–21, Jan. 2015.

[47] E. G. Hertwich *et al.*, “Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies,” Proc. Natl. Acad. Sci. U. S. A., vol. 112, no. 20, pp. 6277–6282, May 2015.

[48] Y. Yang, S. Bremner, C. Menictas, and M. Kay, “Battery energy storage system size determination in renewable energy systems: A review,” Renew. Sustain. Energy Rev., vol. 91, pp. 109–125, Aug. 2018.

[49] E. G. Brown, “Deep Decarbonization in a High Renewables Future Updated Results from the California PATHWAYS Model California Energy Commission.” [Online]. Available: http://www.ethree.com. [Accessed: 21-Nov-2019].

[50] B. Tarroja, B. P. Shaffer, and S. Samuelsen, “Resource portfolio design considerations for materially-efficient planning of 100% renewable electricity systems,” Energy, vol. 157, pp. 460–471, Aug. 2018.

[51] A. Mileva, J. Johnston, J. H. Nelson, and D. M. Kammen, “Power system balancing for deep decarbonization of the electricity sector,” Appl. Energy, vol. 162, pp. 1001–1009, Jan. 2016.

[52] M. M. Hand, E. Demeo, T. Mai, D. Arent, M. Meshek, and D. Sandor, “Renewable Electricity Futures Study Edited By Suggested Citations Renewable Electricity Futures Study (Entire Report).” [Online]. Available: http://www.nrel.gov/analysis/re_futures/. [Accessed: 10-Jun-2019].

[53] N. S. Goteti, E. Hittinger, and E. Williams, “How much wind and solar are needed to realize emissions benefits from storage?,” Energy Syst., vol. 10, no. 2, pp. 437–459, 2019.

[54] P. Denholm and G. L. Kulcinski, “Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems,” Energy Convers. Manag., vol. 45, no. 13–14, pp. 2153–2172, Aug. 2004.

[55] J. D. Eichman, "Energy Management Challenges and Opportunities with Increased Intermittent Renewable Generation on the California Electrical Grid." Order No. 3548685, University of California, Irvine, 2013.

[56] “Ecoinvent 3.4 – Ecoinvent.” [Online]. Available: https://www.ecoinvent.org/database/older-versions/ecoinvent-34/ecoinvent-34.html. [Accessed: 03-Mar-2020].

[57] H. Mitavachan, “Comparative Life Cycle Assessment of Stationary Battery Storage Technologies for Balancing Fluctuations of Renewable Energy Sources,” Thesis, no. March, p. 103, 2014.

[58] M. Huijbregts *et al.*, “ReCiPe 2016 : A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization,” 15-Dec-2017. [Online]. Available: https://rivm.openrepository.com/handle/10029/620793. [Accessed: 26-Feb-2019].

[59] Intergovernmental Panel on Climate Change, “IPCC Second Assessment Climate Change 1995: A Report of the Intergovernmental Panel on Climate Change.” [Online]. Available: https://www.ipcc.ch/report/ipcc-second-assessment-full-report/. [Accessed: 02-Mar-2020].

[60] World Health Organization, “Working together for health- The World Health Report 2006,” 2006. [Online]. Available: www.wma.net. [Accessed: 20-Nov-2019].

[61] E. G. Brown, “Deep Decarbonization in a High Renewables Future Updated Results from the California PATHWAYS Model California Energy Commission.” [Online]. Available: http://www.ethree.com. [Accessed: 10-Jun-2019].

[62] California Energy Commission, “Total System Electric Generation.” [Online]. Available: https://ww2.energy.ca.gov/almanac/electricity_data/total_system_power.html. [Accessed: 26-Jun-2019].

[63] K. E. Forrest, "Demonstrating a Framework to Evaluate the Impacts of Energy Storage Strategies to Meet California Sustainability Goals." Order No. 10120856, University of California, Irvine, 2016.

[64] P. Leung, X. Li, C. Ponce de León, L. Berlouis, C. T. J. Low, and F. C. Walsh, “Progress in redox flow batteries, remaining challenges and their applications in energy storage,” RSC Adv., vol. 2, no. 27, p. 10125, Oct. 2012.

[65] A. Arvesen, E. G. Hertwich -, S. Rauner, and M. Budzinski, “Environmental Research Letters Environmental impacts of high penetration renewable energy scenarios for Europe,” 2016. [Online]. Available: http://iopscience.iop.org/article/10.1088/1748-9326/11/1/014012/pdf. [Accessed: 20-Dec-2018].

[66] “ecoQuery - Dataset Details (UPR).” [Online]. Available: https://v36.ecoquery.ecoinvent.org/Details/UPR/f85332fb-ac72-4b4f-9e34-fb2a4e67bdb1/8b738ea0-f89e-4627-8679-433616064e82. [Accessed: 09-Mar-2020].

[67] “ecoQuery - Dataset Details (UPR).” [Online]. Available: https://v34.ecoquery.ecoinvent.org/Details/UPR/5a9e2dd1-0cde-4919-b461-b509cb8e6e03/8b738ea0-f89e-4627-8679-433616064e82. [Accessed: 03-Mar-2020].

[68] “ecoQuery - Dataset Details (UPR).” [Online]. Available: https://v36.ecoquery.ecoinvent.org/Details/UPR/aec7830a-2c7a-424e-beea-10a41bbe13d6/8b738ea0-f89e-4627-8679-433616064e82. [Accessed: 09-Mar-2020].

[69] S. Chen, X. Fu, M. Chu, Z. Liu, and J. Tang, “Life cycle assessment of the comprehensive utilisation of vanadium titano-magnetite,” J. Clean. Prod., vol. 101, pp. 122–128, Aug. 2015.

[70] “Yearly Average Rates & Forex History Data | OFX.” OFX.com. [Online]. Available: https://www.ofx.com/en-us/forex-news/historical-exchange-rates/yearly-average-rates/. [Accessed: 18-Nov-2019].

[71] J. S. Cooper, “Specifying Functional Units and Reference Flows for Comparable Alternatives,” International Journal of Life Cycle Assessment, vol. 8, no. 6. Springer Verlag, pp. 337–349, 2003.

APPENDIX: ECOINVENT 3.4 DATASET DOCUMENTATIONS

In this section, detailed input and output of the datasets [56] are presented:

1. Hydro:
(1) Run-of-river

Activity name	electricity production, hydro, run-of-river		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh

Inputs from technosphere	Amount
hydropower plant, reservoir, alpine region	4.04e-13 unit
lubricating oil	7.56e-06 kg
Inputs from environment	Amount
hydropower plant, run-of-river	8.07e-13 unit
lubricating oil	7.56e-06 kg
Inputs from environment	Amount
Energy, potential (in hydropower reservoir), converted	3.79 MJ
Occupation, river, artificial	0.0045 m2*year
Transformation, from pasture, man made	2.81e-05 m2
Transformation, from shrub land, sclerophyllous	2.81e-05 m2
Transformation, to industrial area	5.63e-07 m2
Transformation, to river, artificial	5.57e-05 m2
Water, turbine use, unspecified natural origin	45 m3
Emissions to water	Amount
Water	45 m3

(2) Reservoir

Activity name	electricity production, hydro, reservoir, alpine region		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh

Inputs from technosphere	Amount
hydropower plant, reservoir, alpine region	4.04e-13 unit
lubricating oil	7.56e-06 kg
Inputs from environment	Amount
Energy, potential (in hydropower reservoir), converted	3.79 MJ

Occupation, lake, artificial	0.00345 m2*year
Transformation, from unspecified	2.3e-05 m2
Transformation, to industrial area	2.3e-07 m2
Transformation, to lake, artificial	2.28e-05 m2
Volume occupied, reservoir	0.15 m3*year
Water, turbine use, unspecified natural origin	0.81 m3
Emissions to air	Amount
Dinitrogen monoxide	7.7e-08 kg
Methane, non-fossil	1.4e-05 kg
Water	0.0292 m3
Emissions to water	Amount
Water	0.781 m3

2. Solar

(1) Open ground solar photovoltaic

Activity name	electricity production, photovoltaic, 570kWp open ground installation, multi-Si		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, low voltage	no	allocable product	1 kWh

By-products	Material for treatment	Byproduct classif.	Amount
wastewater, from residence	yes	Waste	1.96e-08 m3

Inputs from technosphere	Amount
photovoltaic plant, 570kWp, multi-Si, on open ground	4.42e-08 unit
tap water	1.96e-05 kg
Inputs from environment	Amount
Energy, solar, converted	3.85 MJ
Emissions to air	Amount
Water	2.93e-09 m3

(2) Slanted roof solar photovoltaic

Activity name	electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh

By-products	Material for treatment	Byproduct classif.	Amount
wastewater, from residence	yes	Waste	3.6e-06 m3
Inputs from technosphere			Amount
photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof			8.4e-06 unit
tap water			0.0036 kg
Inputs from environment			Amount
Energy, solar, converted			3.85 MJ
Emissions to air			Amount
Water			5.4e-07 m3

3. Wind

(1) Onshore wind larger than 3MW

Activity name	electricity production, wind, >3MW turbine, onshore		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh
By-products	Material for treatment	Byproduct classif.	Amount
waste mineral oil	yes	Waste	3.32e-05 kg
Inputs from technosphere			Amount
lubricating oil			3.32e-05 kg
transport, freight, lorry 7.5-16 metric ton, EURO3			6.23e-13 ton*km
wind turbine network connection, 4.5MW, onshore			4.69e-09 unit
wind turbine, 4.5MW, onshore			4.69e-09 unit
Inputs from environment			Amount
Energy, kinetic (in wind), converted			3.87 MJ

(2) Onshore wind 1 - 3MW

Activity name	electricity production, wind, 1-3MW turbine, onshore		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh
By-products	Material for treatment	Byproduct classif.	Amount

waste mineral oil	yes	Waste	3.32e-05 kg

Inputs from technosphere	Amount
lubricating oil	3.32e-05 kg
transport, freight, lorry 7.5-16 metric ton, EURO3	1.4e-12 ton*km
wind turbine network connection, 2MW, onshore	1.05e-08 unit
wind turbine, 2MW, onshore	1.05e-08 unit
Inputs from environment	**Amount**
Energy, kinetic (in wind), converted	3.87 MJ

(3) Onshore wind smaller than 1MW

Activity name	electricity production, wind, <1MW turbine, onshore		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh

By-products	Material for treatment	Byproduct classif.	Amount
waste mineral oil	yes	Waste	3.32e-05 kg

Inputs from technosphere	Amount
lubricating oil	3.32e-05 kg
transport, freight, lorry 7.5-16 metric ton, EURO3	3.5e-12 ton*km
wind power plant, 800kW, fixed parts	2.64e-08 unit
wind power plant, 800kW, moving parts	2.64e-08 unit
Inputs from environment	**Amount**
Energy, kinetic (in wind), converted	3.87 MJ

4. Natural gas

Activity name	electricity production, natural gas, combined cycle power plant		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh

Inputs from technosphere	Amount
gas power plant, combined cycle, 400MW electrical	1.4e-11 unit
natural gas, high pressure	0.163 m3
water, completely softened, from decarbonised water, at user	0.0382 kg
water, decarbonised, at user	1.27 kg
Inputs from environment	**Amount**

Water, cooling, unspecified natural origin	0.0315 m3
Emissions to air	Amount
Acenaphthene	5.04e-12 kg
Acetaldehyde	5.09e-09 kg
Acetic acid	7.7e-07 kg
Arsenic	2.61e-10 kg
Benzene	5.74e-09 kg
Benzo(a)pyrene	3.36e-12 kg
Beryllium	1.57e-11 kg
Butane	5.89e-06 kg
Cadmium	1.44e-09 kg
Carbon dioxide, fossil	0.34 kg
Carbon monoxide, fossil	1.4e-05 kg
Chromium	1.83e-09 kg
Cobalt	1.09e-10 kg
Dinitrogen monoxide	6.21e-06 kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	1.84e-16 kg
Ethane	8.71e-06 kg
Formaldehyde	2.05e-07 kg
Hexane	5.04e-06 kg
Lead	6.55e-10 kg
Manganese	4.97e-10 kg
Mercury	4.38e-10 kg
Methane, fossil	6.18e-06 kg
Nickel	2.74e-09 kg
Nitrogen oxides	0.000162 kg
PAH, polycyclic aromatic hydrocarbons	5.09e-08 kg
Particulates, < 2.5 um	3.12e-06 kg
Pentane	7.31e-06 kg
Propane	4.48e-06 kg
Propionic acid	1.02e-07 kg
Selenium	3.12e-11 kg
Sulfur dioxide	3.64e-06 kg
Toluene	9.54e-09 kg
Water	0.000714 m3
Emissions to water	Amount
Water	0.0321 m3

5. Biogas

Activity name	heat and power co-generation, biogas, gas engine		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount

electricity, high voltage	no	allocable product	2.34 kWh
By-products	Material for treatment	Byproduct classif.	Amount
heat, central or small-scale, other than natural gas	no	allocable product	12 MJ
waste mineral oil	yes	Waste	0.000682 kg

Inputs from technosphere	Amount
biogas	1 m3
heat and power co-generation unit, 160kW electrical, common components for heat+electricity	1.14e-07 unit
heat and power co-generation unit, 160kW electrical, components for electricity only	1.14e-07 unit
heat and power co-generation unit, 160kW electrical, components for heat only	1.14e-07 unit
lubricating oil	0.000682 kg
Emissions to air	**Amount**
Carbon dioxide, non-fossil	1.9 kg
Carbon monoxide, non-fossil	0.00109 kg
Dinitrogen monoxide	5.68e-05 kg
Methane, non-fossil	0.000523 kg
NMVOC, non-methane volatile organic compounds, unspecified origin	4.55e-05 kg
Nitrogen oxides	0.000341 kg
Platinum	1.59e-10 kg
Sulfur dioxide	0.000568 kg

6. Geothermal

Activity name	electricity production, deep geothermal		
Geography	WECC, US only (Western Electricity Coordinating Council, US part only)		
Reference products	Material for treatment	Byproduct classif.	Amount
electricity, high voltage	no	allocable product	1 kWh

Inputs from technosphere	Amount
benzene	3.05e-06 kg
geothermal power plant, 5.5MWel	5.78e-10 unit
Inputs from environment	**Amount**
Energy, geothermal, converted	7.14 MJ
Emissions to air	**Amount**
Benzene	3.05e-06 kg